Permafrost in steep rock walls in Norway

Céline Steiger
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Master Thesis in Geosciences
Discipline: Physical Geography, Hydrology and Geomatics
Department of Geosciences
Faculty of Mathematics and Natural Sciences

University of Oslo
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Cover photo: The North face of Otertinden close to Hatteng, Northern Norway during field work on 11 August 2014.
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Abstract

Permafrost in mountainous areas is particularly sensitive to increasing air temperatures; degradation of permafrost may lead to destabilization of steep rock walls, trigger natural hazards, and thereby represent a threat to down-valley infrastructure and settlements. The scope of this thesis was to study the spatial distribution of permafrost in steep rock walls in Norway and subsequently conduct a hazard assessment emerging from these walls.

Firstly, a map of steep rock walls potentially underlain by permafrost in mainland Norway was created. This is achieved by combining interpolated air temperature data from the seNorge data and a digital elevation model (DEM) with a resolution of 10 m. The thresholds for mean annual air temperature (MAAT) and a slope steepness were set to \( \leq -2 \, ^\circ\text{C} \) and \( \geq 60^\circ \), respectively. Based on this map, the spatial distribution of steep rock walls was analyzed. By applying a regression analysis based on ground temperatures from temperature loggers installed on steep rock walls in Jotunheimen, central southern Norway, the seasonal influence of solar radiation was investigated. By using a simple empirical-statistical method, possible rock fall paths with starting zones in steep permafrost rock walls were identified.

In most of Norway, steep rock walls potentially underlain by permafrost were found in mountainous areas. In southern Norway minor occurrences were found close to the northwestern coast line, on mountain plateaus and along the Swedish border. The lower limit of permafrost in steep rock walls decreases in southern Norway from west to east from c. 1500 m asl to 1200 m asl. The lowest permafrost occurrence in steep rock walls was found in Finnmark at 660 m asl. During spring, sun-exposed rock wall temperatures were up to 7°C higher than the air temperature. During winter elevation explains most of the variation, whereas during the other seasons it is solar radiation. The map overestimates permafrost occurrence in sun-exposed rock walls in the Jotunheimen region by 380 m. It was concluded that the generated map from this thesis provides a good first-order representation of potential permafrost occurrence in north-facing rock walls in central southern Norway.

Results reveal that in mountainous areas in southern Norway, north-facing slopes are possibly exposed to rock falls. In northern Norway infrastructure, such as houses and roads can be hit by possible rock falls. In addition, the danger of rock falls into lakes and fjords was calculated for northern Norway.
Acknowledgements

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Studying permafrost let us travel around the world. During our studies we have had the incredible opportunity to attain courses in Svalbard at UNIS, where we also learned how to drive a snow-scooter and protect ourselves from polar bears. In northern Norway and Finnland during the PermaNordnet course we met other permafrost-students and could enjoy the finnish sauna. Even though while running around in Finnmark, we got a little wet feets. One of the most incredible experiences was to travel to Sapporo, Japan for CryoEAST. Sushi, powder skiing in almost never ending snowfall, signs hard to read, drinks in a ice-glass in a ice-bar with a polar ice bear, hot onsens, and very nice Japanese people made this journey unforgettable. All of this was possible through the immense initiative of Bernd - takk for det!

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1 Introduction

1.1 Motivation

Permafrost is particularly sensitive to climatic changes and has warmed across the northern Hemisphere (Haeberli and Beniston, 1998; Romanovsky et al., 2002). In Scandinavia and Svalbard, a significant warming at the permafrost surface by 0.04 °- 0.07 °C per year was measured, with greatest warming in Svalbard and Northern Scandinavia (Isaksen et al., 2007).

Due to the absence of an insulating interface of snow, vegetation and soil material, air and ground temperatures are highly coupled to steep rock walls (Gruber et al., 2004b; Harris et al., 2009). Permafrost affects the geotechnical properties of the ground (Gruber et al., 2004b; Haeberli, 1992; Krautblatter et al., 2013) and a thawing may lead to significant landscape response (Berthling and Etzelmüller, 2011; Harris et al., 2009). Amongst other factors such as geology, hydrology, glaciers, topography and geomechanics, permafrost represents one of the main factors contributing to the stability of a rock wall (Fischer and Huggel, 2008; Krautblatter et al., 2013). A warming of permafrost in steep rock walls could lead to a reduced stability of the slope (Davies et al., 2001; Dramis et al., 1995; Haeberli, 1992; Isaksen et al., 2007). A possible degradation of permafrost could lead to potentially hazardous events on cold mountain slopes and increase the risk for people and infrastructure in affected regions (Haeberli, 1992; Harris, 2003; Isaksen and Blikra, 2011).

Rock falls originating from permafrost areas were reported in the Alps (Dramis et al., 1995; Gruber and Haeberli, 2007a; Noetzli et al., 2003; Ravanel and Deline, 2011). Extremely high temperatures, as during the warm summer of 2003, increased the measured occurrence of rockfalls in the Alps (Gruber et al., 2004a). A spatial relationship between rockfalls and degradation of permafrost in the European Alps was detected by Noetzli et al. (2003) and by Allen et al. (2009) in the Southern Alps, New Zealand. The exact factors and processes of destabilizing rock walls due to permafrost degradation is a complex process that still needs
to be investigated further (Harris et al., 2009). Many rock slopes in Troms, northern Norway, show signs of large-scale movements (Blikra et al., 2006; Nordvik et al., 2010). A possible large rock slide of e.g. Nordnes, located along Storfjord, northern Norway could lead to a catastrophic tsunami (Nordvik et al., 2010). In western Norway, in the last 100 years, 170 people have lost their lives because of tsunamis caused by rock avalanches into fjords (Blikra et al., 2005). Because of the above mentioned reasons, an investigation on the distribution of permafrost in steep rock walls in Norway is necessary.

1.2 Objectives

The scope of this thesis is to describe and quantify the spatial distribution of permafrost in steep rock walls in Norway, and to conduct a hazard assessment for selected sites to define possible objects at risk.

For this purpose, the main objectives are:

1. What is the spatial distribution of steep rock walls underlain by permafrost in Norway?

2. What is the influence of solar radiation on the distribution on permafrost in steep rock walls?

3. Are settlements, water bodies or infrastructures at risk of possible rock falls originating from steep rock walls underlain by permafrost?

The first point of the objectives is addressed through the creation of a map of steep rock walls potentially underlain by permafrost in Norway. This map is created based on a digital elevation model and an interpolated seNorge data set at a resolution of 10 m². To analyze the distribution of permafrost, the altitude of the lower limit of permafrost, the aspect and elevation distribution, and the surface area and its warm fraction are studied.

The second point is analyzed through a regression analysis, where data from temperature loggers installed in steep rock walls are used. The aspect dependency of the lower limit of
permafrost and the surface offset are defined for a small extraction of the map of steep rock walls potentially underlain by permafrost. The seasonal influence of solar radiation and the seasonal surface offsets are then investigated in more detail.

The third point is analyzed through the use of a relative hazard assessment, using a simple empirical-statistical approach.

1.3 Thesis structure

In Chapter 2 the distribution of permafrost worldwide and in Norway, along with its thermal condition is revealed. The possible investigation techniques to detect permafrost are shown. Furthermore, the factors and processes determining the thermal condition of steep rock walls are explained in more detail. In Chapter 3 the study area is presented.

In section 4.1 the input data is shown, followed by section 4.2 where the methods of the generation of the map of steep rock walls potentially underlain by permafrost in Norway are explained. This is followed by a description of the methods applied for the analysis of the spatial distribution of permafrost in steep rock walls in Norwegian counties (4.3), the influence of solar radiation (4.4) and the validation of the created map (4.5). The methods of the relative hazard assessment are presented in section 4.6.

The results from the mapping are presented in section 5.3, followed by a presentation of its spatial distribution in section 5.4. The seasonal influence of radiation on the lower limit of permafrost and the temperature distribution is analyzed in more detail in section 5.5. Section 5.6 presents the results of the validation from existing permafrost maps through a regression analysis, where solar radiation was included, along with fieldwork observations. Finally, in section 5.7 the path of rock falls at different sites is shown.

A discussion of the obtained results is provided in Chapter 6 and a conclusion is drawn in Chapter 7.
2 Scientific background

2.1 Definition of permafrost

Permafrost is described as sub-surface material having a temperature of less or equal to 0°C during at least two consecutive years (Brown and Péwé, 1973). Its definition is therefore based on the factors temperature and time. Permafrost underlies about 24% of the southern Hemisphere and extends from the Himalayas (26°N) to northern Greenland (84°N) (Zhang et al., 1999) (Figure 1). In Europe permafrost occurs mainly in mountainous regions, bedrocks, superficial sediments, block fields and sometimes with glaciers (French, 2007).

![Permafrost distribution on the northern Hemisphere](image)

Figure 1: Permafrost distribution on the northern Hemisphere (Rekacewicz, 1998).

The thickness of permafrost can vary from a few decimeters up to several hundred meters (King, 1986). Its thickness does not need to represent the today’s climate but may be a result of former cold periods (Harris and Brown, 1982). Its response time is dependent on thermal
conductivity, ice content and the thickness of the frozen ground (Osterkamp, 1983). The authors Harris and Haeberli (2001) mention the dependency of ground surface temperatures to climatically induced time scales, that range from daily to millennial cycles. In this thesis mountain permafrost is analyzed.

2.2 Permafrost distribution in Norway and its thermal condition

In Norway permafrost appears mostly in mountainous areas (Isaksen et al., 2007; Ødegård et al., 1996). In general the lower limit of mountain permafrost in Scandinavia decreases from the western coast towards Eastern Norway and north-western Sweden (Etzelmüller et al., 1998; King, 1982, 1986). This because along the coast a maritime climate, while in in the eastern part of Norway a more continental climate, expressed by lower winter precipitation and higher summer temperatures prevails (see section 3.3). In southern Norway the lower limit of discontinuous permafrost decreases from c. 1600 m asl in the west to c. 1200 m asl on the east (Etzelmüller et al., 2003). In central Norway in the Jotunheimen and Dovrefjell areas a lower limit of permafrost was defined at c. 1550 m asl (Isaksen et al., 2002). On wind-blown sites in Dovrefjell permafrost can be found down to 1350 m a.s.l. (Sollid et al., 2003). Studies in Troms and Finnmark, northern Norway revealed a widespread occurrence of permafrost (Gisnås et al., 2013). The permafrost limit is at about 800 - 900 m asl in the western mountains of Troms and 200 - 300 m lower in the more continental areas.

During the International Polar Year (2007-2009) a permafrost monitoring in the polar regions of the Northern Hemisphere was conducted (Romanovsky et al., 2010). In this study 575 boreholes in North America, the Nordic countries and Russia were involved. The study states that the warming has commenced two or three decades ago and has continued during the IPY. Warming rates were smaller for warm permafrost at 0 °C than for colder, ice-richer permafrost where latent heat effects are prevalent. In Northern Europe a long-term database for permafrost monitoring through a transect from northern to southern Europe was analyzed (Harris et al., 2009). Here, a warming of permafrost was found. In Scandinavia
and Svalbard a significant warming at the permafrost surface by 0.04 °- 0.07 °C per year was measured, with greatest warming in Svalbard and Northern Scandinavia (Isaksen et al., 2007). The authors conclude that this is a result of surface warming during the last decades. Christiansen et al. (2010) conclude that permafrost in the Nordic area is close to 0 °C. This makes permafrost sensitive to climatic change in this region.

2.3 Permafrost detection

Permafrost can be detected and monitored with boreholes instrumented with temperature loggers (e.g. Christiansen et al. (2010)). Further, Bottom Temperatures of Snow (BTS) measurements (Haeberli, 1973) and geophysical methods, such as resistivity surveys (Electrical Resistivity Tomography, Electromagnetic induction techniques, Ground Penetrating Radar), refraction seismic tomography and ground temperature measurements can be conducted (Harris et al., 2009; Hauck et al., 2004). To drill boreholes in mountainous terrain is tedious and expensive and therefore modeling is useful (King et al., 1992).

In mountainous areas the surface climate and subsurface conditions vary greater than on lowlands (Risenborough et al., 2008). The spatial variability of climate variables in mountainous regions is defined by physiographic features, which depend on the scale of interest (Daly, 2006). At larger scales, elevation is the most important factor and for medium to smaller scales additional terrain-related factors need to be included (Risenborough et al., 2008). Different modeling approaches exist and these can be categorized into empirical-statistical and physical based models. The chosen model depends on the aim and the scale of the study. Statistical-empirical permafrost models describe permafrost occurrence by topoclimatic factors (altitude, slope and aspect, mean air temperature or solar radiation). It assumes equilibrium conditions and generally depend on BTS, temperature measured through miniature temperature data loggers, geophysical investigations or inventories such as rock glaciers to verify the existence of permafrost. Energy fluxes are not included in such models. These models are useful for large study areas. Physical-numerical models are
process-based and calculate energy balances of the surface. An overview of recent and past development on permafrost modeling are given in the studies of Risenborough et al. (2008), Harris et al. (2009) and Etzelmüller (2013).

2.3.1 Spatial interpolation of air temperature

Ødegård and Sollid (1992) suggest a linear relationship between mean annual ground temperature (MAGT) and MAAT. To map permafrost at small scale and for an area with heterogeneous surface conditions, such as in mountain areas, the MAAT is frequently used as the only predictor for permafrost occurrence and gives a good approximation of permafrost distribution (Hoelzle et al., 2001). Hereby, a spatial interpolation of air temperature from a common reference elevation (generally sea level) and the successive calculation of the near-surface MAAT using a DEM and a lapse rate is conducted (Risenborough et al., 2008). Several studies show that in southern Norway a MAAT of -3 to -4 °C for the regional limit of lower mountain permafrost limit in southern Norway, if accounting for snow (Etzelmüller et al., 2003; Haeberli et al., 2010; King, 1986; Ødegård et al., 1996).

To interpolate air temperature a altitudinal lapse rate of air temperature (ALRT) has to be used. The ALRT is defined as the normalized temperature difference between a lower and a higher location and is measured in (Fang and Yoda, 1988). It is expressed in °C m$^{-1}$ and usually decreases with increasing altitude and is commonly negative. It may becomes positive if an inversion prevails. Inversions can be observed in sheltered areas such as in valley bottoms and sinks (Tveito and Førland, 1999). A rapid decrease in temperature is named a steep ALRT and a slow decrease a shallow ALRT, respectively (Pepin, 2001). Especially in the lower troposphere, the ALRT varies spatially and temporally (Holden, 2005). The dry adiabatic ALRT) it is about -0.98 °C 100 m$^{-1}$ and for very warm saturated air (the saturated adiabatic ALRT) it is about -0.4 °C 100 m$^{-1}$. This difference appears because when the atmosphere is saturated, latent heat of condensation will be released when the air is rising.
2.3.2 Logistic regression analysis

Logistic regression is often used to evaluate the relationship between modeled BTS values and the pit data on the presence or absence of permafrost (Brenning et al., 2005; Pereira and Itami, 1991). Logistic regression estimates the probability of a certain condition occurring by calculating changes in the dependent itself. This method does not assume linearity for relationships between BTS, potential incoming solar radiation (PISR) and elevation. Furthermore, it does not require normally distributed variables, does not assume homoscedasticity, and generally has less stringent requirements than ordinary linear regressions (Kleinbaum et al., 1998).

2.4 Permafrost in steep rock walls: factors and processes

Differences in thermal regimes of air and rock temperatures were observed in the Alps (Gruber et al., 2004b), Norway (Hipp et al., 2014) and Canada (Lewkowicz, 2001). Etzelmüller (2013) mentions the studies of Farbrot et al. (2011), Lewkowicz and Bonnaventure (2011) and Hasler et al. (2011), which show that ground surface temperature in mountain permafrost varies highly and is dependent on aspect and snow variability. The study of Gubler et al. (2011) demonstrated a temperature difference of 6°C along a elevation band of 300 m. Hoelzle et al. (2001) state that temperatures of steep rock walls mainly depend on aspect (short-wave radiation), altitude (sensible heat and long-wave incoming radiation) and lithology. The study by Noetzli et al. (2007) examined the 3D patterns of temperatures on mountain peaks. Results showed a complex 3D pattern of temperature distribution and heat flow density below mountainous topography for equilibrium conditions that are additionally perturbed by transient effects. The temperature on the surface of complex topographies differs with aspect, but is not dependent on the geothermal heat flux.

The investigation of the stability of steep rock walls is difficult, because of the complicated acquisition of data and the complexity of factors influencing the slope stability (Fischer and
Huggel, 2008). According to Davies et al. (2001) ice in discontinuities has a stabilizing effect. Laboratory results show that ice filled fractures have a minimum strength between -1.5°C and 0°C. A phase change from ice to water leads to two effects; (1) a loss in joint bonding, which is given by ice/rock interlocking and adhesion of the ice to the rock and (2) a release of water which, if it does not drain leads to an increase in water pressure in the joint which then in turn decreases the effective stress and results in a reduction of shear strength. An increase of ground temperatures would lead to a reduction of the factor of safety and a slope failure could occur.

Krautblatter et al. (2013) developed a model that relates the destabilization of thawing permafrost rock slopes to temperature-related effects on rock- and ice-mechanics. They established a modified Mohr-Coulomb failure criterion for ice-filled fractures that incorporates fracturing of rock bridges, friction of rough fracture surfaces, ductile creep of ice and detachment mechanics along rock-ice interfaces.

2.5 Definition rock falls

A rock fall is "a relatively small landslide confined to the removal of individual and superficial rocks from a cliff face (Selby, 1982, in: Dorren, 2003)". The phenomenon of rockfall is a common process and a particularly significant hazard in mountain environments. Especially in highly populated mountain areas, where slopes are long and steep and where human-made infrastructures are situated at the bottom of valleys (Azzoni et al., 1995; Dorren and Seijmonsbergen, 2003). To protect areas and infrastructure from rock falls, it is important to understand its risk. According to Dorren and Seijmonsbergen (2003), a cause for a rockfall is a chemical or physical weathering of a bedrock slope which then leads to fracturing, opening of joints and as a result in promotion of rockfall. Other trigger mechanics include e.g. frost-thaw activity, seismic activity, rapid snowmelt or rain storms. Generally said, a rockfall is a result of a combination of topographical, geological and climatological factors. In this report only the topographical factor is taken into account. (Azzoni et al., 1995) emphasize
that rockfall prediction is a very difficult task because of the prevalent randomness. The complexity originates from the different involved stages of rockfall motions: free fall, toppling, rolling and sliding. Those also vary in time and space and depend on the size, shape and mass of the falling particle (Keylock and Domaas, 1999).
3 Study area

3.1 Geographical settings

This thesis analyzes the permafrost distribution in steep rock walls in mainland Norway. Norway is located in northern Europe and covers the western part of the Scandinavian Peninsula (Leksikon, 2015). It boarders with Sweden in the east and Finland and Russia in the north. It has a surface area of 385 186 km$^2$ and is situated between 58°N and 71°N and 5°E to 31°E (with Svalbard). The Scandinavian Mountains are the main mountain range in Norway. They range from southern to northern Norway, while in the northeast they curve towards Sweden. The highest mountain is Galdhøppigen in Jotunheimen (2469 m asl).

3.2 Geology and geomorphology

The Norwegian bedrock consists mainly of Precambrian bedrock, which was strongly deformed during the Caledonian folding or the Permian and Tertiary faulting (Münster Strøm, 1948). Devonian rocks prevail in the western part (Vestlandet) and north and south of Trondheim (counties Nord-Trøndelag and Sør-Trondelag). In the Oslo region, Cambro-Silurian sediments and Permian eruptives are filled in a faulted depression. In Norway the main morphological component are the elevated Tertiary surfaces, which are cut by late Tertiary and Pleistocene erosion. The country was highly impacted by the last glaciation (2.6 million years - 0.9 million years BP) and is still rising due to isostatic uplift (Ramberg et al., 2007). Steep rock walls can be detected in alpine reliefs, coastal mountains and overdeepened glacial valleys (Etzelmüller et al., 2007). In southern Norway this topography can mainly be found along the west coast (e.g. Sunnmørsalpene, Tafjordfjella) and in the center of the country (e.g. Jotunheimen, Skarvheimen, Dovrefjell, Rondane and Trollheimen). In the north, mountainous topography prevails along the coast (Narvikalspene, Indre Troms, Ytre Troms). One of the main erosion forms created by cirque glaciers. These glaciers were able to break apart and destroy mountain massifs (Münster Strøm, 1948).
3.3 Climate

The climate in Norway is highly diverse since it is influenced by the sea and the Scandinavian Mountains, which act as an orographic barrier (met.no, 2015b). The climate is temperate compared to other places in same latitudes because of the warm North Atlantic current that follows along the western coast. Along the coast, a maritime climate with mild and humid winters prevails. While in central and eastern Norway a continental climate is found, which leads to a colder and drier climate, in northern Norway is situated in a continental to subarctic climate zone. During winter months average temperatures at the coast are close to 0 °C and decrease towards the east (e.g. Østlandet: -18 - -12 °C) (met.no, 2015a). Also during early spring along the coast temperatures are higher than in the rest of the country. First in May the warmest temperatures are measured in southern Østlandet. In summer the highest temperatures are recorded in southern Norway, but also in northern Norway temperatures are relatively high due to the continental climate. In Autumn the inland has again lower temperatures than in coastal areas. The mean annual precipitation sum varies strongly across the country. Highest amounts of precipitation are found c. 50 km away from the West coast in autumn and winter. In the west frontal and a orographic precipitation dominates, where warm and moist air masses coming from the Atlantic Ocean are lifted at the mountains along the coast which leads to high amounts of orographic precipitation. Rain shadow areas are located in inner parts of Østlandet, the Finnmark plateau and some areas along the Swedish boarder.
4 Methodology

This Chapter presents all the used methodology in this thesis. First, the used input data is described (4.1). Then the methods for the generation of a map of potential permafrost occurrence in steep rock walls with a resolution of 10 m$^2$ is presented (4.2). Subsequently, the methods for obtaining the spatial distribution pattern in Norwegian counties is presented (4.3). The obtained map is validated through existing permafrost maps (4.5.1), to a regression analysis (4.5.2) and during fieldwork (4.5.3). In (4.6) the applied method for the hazard assessment is presented.

4.1 Input data

4.1.1 The seNorge data

The seNorge data set (Figure 2) was developed by the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Meteorological Institute (met.no) and the Norwegian Mapping Authority (Statens Kartverk) (available via www.senorge.no, hereafter referred as seNorge data). It contains daily climate data since the year 1957 until present over all Norway. In this thesis a data set for the period from 1961 - 1990 was used. The data set is based on daily temperature and precipitation measurements, which are interpolated to 1 km $\times$ 1 km. The grid is interpolated from about 200 stations for temperature and 400 for precipitation. The measured daily mean values are first projected to sea level (Tveito et al., 2000) and regression coefficients based upon monthly mean temperature data are used. These are based on monthly mean temperatures data from 1152 stations in northern Europe using stepwise linear regression. For the spatial interpolation of the de-trended temperatures residual kriging is applied. The interpolated temperatures were then readjusted to terrain altitude by applying a lapse rate that differed for each month (Table 1). At higher elevations meteorological stations are sparse and the extrapolation method strongly dependent on the temperature lapse rate (Tveito et al., 2005).
Figure 2: Mean annual air temperature (MAAT) 1961 - 1990 in Norway (available at www.senorge.no).

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Table 1: Monthly temperature lapse rates used for the extrapolation of the seNorge data (in °C/100m) (Tveito et al., 2000).

4.1.2 Digital elevation models

Two digital elevation models (DEM) of whole Norway produced by the Norwegian Mapping Authority and are available on a resolution of 1 km and 10 m, respectively (Statens Kartverk, 2011). The two DEMs are based on contour lines, elevation point and water surface polygons. Populated areas are covered by contour lines of 5 m and unpopulated areas
by 20 m respectively. Depending on location and quality of the underlying data the elevation information has a uncertainty of 2 - 6 m.

4.2 Mapping potential occurrence of permafrost in steep rock walls

In this section the methods for the creation of a map of steep rock walls potentially underlain by permafrost is explained (Figure 3). First, a spatially varying lapse rate of air temperature (ALRT) was recalculated by using the seNorge data set and a DEM of 1 km² resolution (section 4.2.1). This lapse rate was then used to down-scale the seNorge data set to a resolution of 10 m (section 4.2.2). The result was then combined with steep slopes (section 4.2.3). This lead to the map of steep rock walls potentially underlain by permafrost.

4.2.1 Recalculation lapse rate of air temperature

Interpolation of near-surface air temperatures from climate stations by applying a linear ALRT is commonly used to generate temperatures at locations where measurements are not available (Régnière, 1996). The global mean ALRT is -0.65 °C 100 m⁻¹ and it is sufficient for most purposes (Barry and Chorley, 1987). According to Bruun (1957) a ALRT of -0.65 °C 100 m⁻¹ is not representative to calculate annual mean temperatures for Norway. Furthermore, the ALRT is dependent on topography (Tveito and Førland, 1999). In northern England, the Italian and Austrian Alps near-surface ALRTs varied both diurnally and seasonally, respectively (Pepin, 2001; Rolland, 2003). Steeper ALRTs are found in summer and during the day, whereas in winter and during the night shallower ones prevailed. Also in Norway, the ALRT shows lowest gradients in winter and highest in summer (Tveito, 2007). To generate the seNorge data set a seasonally varying mean ALRT is applied (Table 1).
In section 4.2.1 the applied spatially varying lapse rate is explained, followed by section 4.2.2, where the creation of a MAAT on a high resolution of 10 m is revealed. Together these two information lead to a map of rock walls potentially underlain by permafrost, which is explained in section 4.2.3.
The lapse rates in \textit{seNorge} are based on the altitude of the climate station. To account for the local terrain, the two topographical parameters (Tveito et al., 2000) mean altitude within a 20 km radius around a climate station, as well as the minimum altitude within the same circle, are included. The resolution in their work is $1 \times 1 \text{ km}^2$. According to the authors, these two topographical parameters satisfy the fact that stations on high levels (e.g. hill tops) have different topographical features than stations on low levels (e.g. kettles). To define temperatures of steep rock walls in Norway, in this thesis, a mean altitudinal lapse rate of air temperature (ALRT) had to be calculated first (Figure 3). To account for spatial variations due to topography and climate, a ALRT for each single grid cell over whole Norway at a resolution of $1 \times 1 \text{ km}^2$ km is recalculated by using the \textit{seNorge} air temperature data set over a period from 1957 - 2013 and a DEM of a resolution of $1 \times 1 \text{ km}^2$. By applying a $3 \times 3$ moving window, calculating for each cell the annual mean ALRT towards its’ eight neighboring cells (Eq. 1). The result were then averaged over the study period (1957 - 2013). It is expected to get the same lapse rates as applied in the \textit{seNorge} data set.

$$\text{lapse rate} = \frac{\Delta MAAT}{\Delta \text{Elevation}}$$  \hspace{1cm} (1)

4.2.2 Interpolation of the \textit{seNorge} data set

In order to define permafrost occurrence in steep rock walls, a temperature data set at high spatial resolution of 10 m is necessary. For this purpose the \textit{seNorge} data are interpolated from 1 km to 10 m. Hereby, the \textit{seNorge} data is first adjusted to sea level with the spatially varying ALRT (see section 4.2.1) (Eq. 2, in brackets the resolution of the specific raster layer).

$$\text{MAAT}(10\text{ m}) = \text{MAAT}(1\text{ km}) + \text{lapse rate}(10\text{ m}) \times (\text{DEM}(1\text{ km}) - \text{DEM}(10\text{ m}))$$  \hspace{1cm} (2)
4.2.3 Map of potential occurrence of permafrost in steep rock walls

Based on the DEM (resolution 10 m, section 4.1.2) and the interpolated scNorge data set (resolution 10 m, section 4.2.2), a map of steep rock walls potentially underlain by permafrost in Norway at a resolution of 10 m was created. The term ”potentially” indicates that the sites have not been verified of having permafrost. Further factors that influence the occurrence of permafrost, such as radiation, were not incorporated in the permafrost map.

Permafrost was defined to occur where a MAAT of $\leq -2^\circ$C persists over the period from 1961 - 1990. This threshold temperature accounts for higher temperatures on the rock wall surface compared to the air temperature (Gruber et al., 2004b; Hipp et al., 2014), but it is higher than as in the studies mentioned above (section 2.3). The reason for this higher threshold is that in steep rock walls only a limited surface offset can be observed. Rock walls are directly coupled to atmospheric condition.

The resulting map is divided into three areas: a) southern, b) central and northern, and c) northern Norway. Different regions indicate the main and minor occurrences of permafrost in steep rock walls.

Sites where permafrost was found, were checked on aerial images (NorgeiBilder, 2015).

4.3 Spatial distribution of permafrost in Norwegian counties

To analyze the spatial distribution of steep rock walls potentially underlain by permafrost, the beforehand created map (section 4.2) was analyzed for each of the 12 Norwegian counties (see following list). By using a principal component analysis and a cluster analysis of series of mean annual temperatures from 1876-1997 (Hanssen-Bauer and Nordli, 1998) defined 6 temperature regions in Norway. In this analysis the counties were divided into 6 regions used by Hanssen-Bauer and Nordli (1998). Finnmark, which is located in several regions was assigned to region 4. For the cells containing permafrost in steep rock walls for each county following was defined: elevation, aspect, area of permafrost ($\text{km}^2$), altitude of lower
limit of permafrost (-3 °C ≤ MAAT ≤ -2 °C) and the fraction of warm permafrost. For the compilation of the elevation and aspect see Figure 3.

It has to be mentioned that not the true surface area but an indication of it was calculated. This since steep rock walls are not well represented in the used DEM. Therefore, the mentioned surface area is only a very rough estimation.

Region 1

- Buskerud: Hardangervidda, Hallingskarvet
- Oppland: Jotunheimen, Breheimen, Reinheimen, Rondane, Dovrefjell
- Telemark: Hardangervidda
- Hedmark: Knutshø, Flåman

Region 2

- Hordaland: Hardangervidda
- Sogn og Fjordane: Jostedalsbreen, Jotunheimen
- Møre og Romsdal: Eikesdalsvatnet, Trollheimen, Tafjord-Reindalen

Region 3

- Sør-Trøndelag: Trollheimen, Dovrefjell
- Nord-Trøndelag: Blåfjellet, Børgefjell

Region 4

- Nordland: Børgefjell, Saltfjellet
- Troms: South of Narvik, South of Setermoen, Lyngen Alps
- Finnmark: Altacanyon
4.4 Influence of solar radiation

In this section the methods for analyzing the influence of solar radiation in Jotunheimen, southern Norway are explained. A linear regression analysis was done to explain rock wall temperatures based on the independent factors PISWR (section 4.4.1) and elevation (section 4.1.2). The method is explained in section 2.3.2.

4.4.1 Potential incoming short-wave radiation

The potential incoming short wave radiation (PISWR) is modeled in ArcGIS (ESRI, 2014), based on the algorithm of Fu and Rich (1999). This algorithm calculates in a first step an upward-looking hemispherical viewshed based on topography (ESRI, 2015a). A viewshed represents the visible sky that is seen from a specific location. In a second step the direct radiation is calculated by overlaying the viewshed on a direct sunmap. A sunmap is representation of the sun track, which varies depending on the hours of day and days of the year. Then the diffuse radiation is calculated by overlaying the viewshed on a diffuse skymap. A diffuse skymap represents the diffuse radiation from all sky direction that results due to scattering by atmospheric components (clouds, particles, etc.). The process of combination of the viewshed with a direct sunmap and a diffuse skymap is repeated for the whole raster and creates a insolation map. A default sky size of 200, and a hour interval of 0.5 hours was chosen.

4.4.2 Rock wall temperatures

Temperature series from loggers installed in steep rock walls in Jotunheimen, southern Norway (Figure 4) and Signaldalen, northern Norway (Figure 5) were used (section 4.4.2). Regression equations for each season were calculated (section 4.4.3) and continuous raster of surface temperature compiled. After defining the isotherm of MAAT 0°C in each raster, a map of potential occurrence of permafrost in steep rock walls was created. It is assumed
that this is the lower limit of permafrost in steep rock walls. The threshold for steepness was set to $\geq 60^\circ$.

Figure 4: Placement of the loggers RW1 in Hurrungane and RW2 to RW5 in Juvasshøe, Jotunheimen (Hipp et al., 2014). The two lakes Juvvatnet and Skagastolsvatnet are treated in section 5.7.
Figure 5: Overview map and temperature logger locations on Sauenakken in Signaldalen. The loggers A51180 and A5117D are installed on a large rock boulder and the loggers A5117E and A5117F on a small rock.

In Jotunheimen the temperature loggers record the temperature in 10 cm from the surface at a temperature resolution of 2 hours (Hipp et al., 2014). The data set from the loggers in rock wall RW1, RW4 and RW5 covers 3 years from September 2010 - September 2013 and for
the loggers in RW2 and RW3 the data set covers 4 years from September 2010 - September 2014 (Figure 6). For northern Norway data from four temperature loggers (Geoprecision, Erdingen, Germany) installed on Sauenakken in Signalndalen were used (Regula Frauenfelder, NGI) (Figure 5). Sauenakken is a saddle between two mountains Polvartinden in the South and Otertinden in the north and is located east of Signalndalen and on the west it adjoins to a plateau with a slight depression (Table 2). The data set for these loggers covers 3 years from September 2011 - August 2014 and a temperature resolution of 30 minutes (Table 7). Two of the loggers are installed on a large rock boulder and two on a small rock.

The mean air temperature at the PACE borehole Juvasshøe (1894 m asl) recorded during the period from 2010 - 2014 was -3.7 °C and during the year 2014 -2.2 °C (eKlima.no, 2015). From 2010-2014 the air temperature was therefore warmer than the 1961-90 climate normal of -4.3 °C and almost equal to the climate normal 1981-2010 of -3.8 °C. The temperature data of Signalndalen is not compared to climate normals.
<table>
<thead>
<tr>
<th>Datalogger</th>
<th>Elevation m asl</th>
<th>Comment</th>
<th>Exposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jotunheimen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RW1</td>
<td>1595</td>
<td>Steep rock face (90°)</td>
<td>N</td>
</tr>
<tr>
<td>RW2</td>
<td>2204</td>
<td>Steep rock face (90°)</td>
<td>E</td>
</tr>
<tr>
<td>RW3</td>
<td>2226</td>
<td>Steep rock face (90°)</td>
<td>SE</td>
</tr>
<tr>
<td>RW4</td>
<td>2180</td>
<td>Steep rock face (90°)</td>
<td>NW</td>
</tr>
<tr>
<td>RW5</td>
<td>2320</td>
<td>Steep rock face (85°)</td>
<td>E</td>
</tr>
<tr>
<td>Signaldalen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A51180</td>
<td>640</td>
<td>Logger on a rock boulder</td>
<td>NE</td>
</tr>
<tr>
<td>A5117D</td>
<td>657</td>
<td>Logger on a rock boulder</td>
<td>NW</td>
</tr>
<tr>
<td>A5117E</td>
<td>630</td>
<td>Logger on a small rock</td>
<td>E</td>
</tr>
<tr>
<td>A5117F</td>
<td>632</td>
<td>Logger on a small rock</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 2: Placement details about the installed temperature data loggers in Jotunheimen and Signaldalen. The slope was 90° on all of the loggers.
Figure 6: Rock wall loggers RW1 to RW5 for 2010-2013. For RW2 and RW3 the data series cover one year longer (2010-2014) (for logger placement see Figure 4).
4.4.3 Regression equations

To describe the relationship between rock wall temperature $T_{RW}$ ($^\circ$C) and the explanatory variables elevation (m asl) and PISWR (W m$^{-2}$), regression coefficients were calculated (Eq. 3). The coefficients were calculated for each season of the year (September 2010 - August 2014). The data sets were divided into the four seasons winter (December - February), spring
(March - Mai), summer (June - August) and autumn (September - November). For the winter, spring and summer seasons 51 data points and for autumn 47 are given, respectively. The coefficients a is the intercept (the value of $T_{RW}$ when elevation or PISWR = 0), the coefficients b and c are the slopes or the amount by which $T_{RW}$ changes when either the elevation or PISWR increases. The coefficient c is therefore the lapse rate (ALRT).

$$T_{RW} = a + b \times PISWR + c \times elevation$$  \hspace{1cm} (3)

For each temperature logger the mean monthly temperature, elevation and PISWR were calculated. The elevation, slope and aspect were extracted from a digital elevation model (DEM) with a resolution of 10 m (Statens Kartverk, 2011). To calculate a continuous seasonal $T_{RW}$ and mean $T_{RW}$, the regression coefficients were applied to a spatial raster. Subsequently, the seasonal $T_{RW}$ of the cells with a mean $T_{RW} \leq 0^\circ$ and a slope $\geq 60^\circ$ were selected. From these cells the elevation, aspect and temperature was extracted. This leads to five maps of potential permafrost in steep rock walls; one for each season and one of the whole study period. The mean temperature over the study period was calculated by averaging the seasonal data.

### 4.4.4 Seasonal surface offset

The surface offset, defined as the difference between rock wall temperature and mean air temperature (MAT) (Risenborough et al., 2008) is calculated for each season and for the study period 2010-2014. The seasonal mean temperature at the closest climate station Juvasshøe was extrapolated with a seasonal ALRT according to Farbrot et al. (2011).

### 4.4.5 Hierarchical partitioning

In relation to understand the relative importance of the independent variables PISWR and elevation during the different seasons a hierarchical partitioning was conducted (Walsh and
Mac Nally, 2008). The applied function takes the list of goodness of fit measures, and applies the hierarchical partitioning algorithm of (Chevan and Sutherland, 1991) to return an output, where each variable, its independent contribution (I) and its conjoint contribution with all other variables (J).

4.5 Validation

The generated map of steep rockwalls in permafrost was then validated against existing permafrost maps (4.5.1) and against the maps from the regression analysis (4.5.2).

4.5.1 Validation with existing permafrost maps

In their study Gisnås et al. (2013) modeled the distribution of permafrost with the equilibrium model CryoGRID1.0 for whole Norway on a resolution of 1 km². In their study forced gridded data on daily air temperature and snow cover were applied. Thermal properties for different bedrock types and sediment covers were used to determine distributions of thermal conductivity, heat capacity and water content. Results reveled that most permafrost can be found within exposed bedrock or covered by coarse-grained sediments. To compare the map created in the framework of this study, the results from CryoGRID1.0 from the year 1961-1990 were used.

Rock glaciers are well visible geomorphological features, which can be classified into intact (active and inactive) and relict forms. Intact rock glaciers indicate permafrost occurrence, and relict ones non-permafrost condition (Barsch, 1996). For Norway an inventory of rock glaciers was established by Lilleøren (2011). The rock glacier inventory from the study of (Lilleøren, 2011) is compared to the before hand produced map of permafrost in steep rock walls, and are a independent validation.
4.5.2 Validation with regression analysis

The generated map of rock walls potentially underlain by permafrost is validated against the permafrost map created through the regression analysis in Jotunheimen, which included solar radiation (section 4.4). This was done, to see how much solar radiation influences the outcome of the created map.

Firstly, the maps are compared visually. This is followed by an analysis of the altitudes of the lower limits of permafrost in both maps. Finally, the surface offset between both maps is calculated. To define the lower limit of permafrost of the rock walls generated through the regression analysis a range of $-1 \, ^\circ C \leq T_{RW} \leq 0 \, ^\circ C$ and for the earlier created permafrost map through the interpolation of the seNorge data a range of $-3 \, ^\circ C \leq T_{RW} \leq -2 \, ^\circ C$ was chosen. To define the surface offset between the interpolated seNorge air temperature and the modeled rock wall temperatures (Figure 36), both raster layers were subtracted from each other.

4.5.3 Fieldwork validation

To validate the generated permafrost map, selected sites were visited during fieldwork. In northern Norway from 7th - 15th of August 2014 in the regions around Narvik and Bardu and from 26th - 30th of August 2014 in Lyngen Alps and Tamokdalen. In southern Norway on 18th - 20th of September 2014 in Jotunheimen, from 27th - 29th of September 2014 in the region of Vang and Gjendesheim, on 16th of October in Stryn and on 1st of Mai 2015 in Hurrungane. The following scheme was followed during fieldwork:

1. Date and place of the site and aspect of the wall.

2. Geomorphology of the wall: Definition of the geological structures (fracture and joints sets, weakness zones, weathering, water condition), vegetation growth, presence of snow, perennial snow patches, and glaciers.
3. Geomorphology under the wall: Scree slopes, deposits and/or single boulders.

4. Rock mass movement that had taken place recently or in longer time ago and a rough age estimation. According to Grotzinger (2010) mass movements can be divided into rockfalls, rockslides and rock avalanches and involve either small blocks or larger masses of bedrock. A rock fall is a free fall from a steep mountain side. Velocities are fastest and travel distances are shortest compared to the other mass movements. A rockslide is characterized through a down-ward sliding of a rock unit. Rock avalanches are large masses of rock material and can reach high velocities and travel distances compared to rock slides.

5. Taking pictures of the site and the wall and make sketches.

4.6 Relative hazard assessment: the alpha-beta method

After UNISDR (2015), the definition of a hazard is: A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. A degradation of permafrost in steep rock walls can lead to a destabilization of rock walls underlain by permafrost. This could lead to a hazardous transformation of geomorphologic activity and may lead to damage on infrastructure (Harris et al., 2001).

In this section the hazard of failure of steep permafrost rock walls potentially reaching infrastructure and water bodies was investigated, by conducting a simple runout model to define areas exposed to a potential rock fall, which originate from steep permafrost rock walls. Elements at risk are buildings, roads and water bodies located within a radius of 1,5 km from steep permafrost rock walls. The run out modeling was conducted by using a model of Sætre (2014). This model is based on the alpha-beta model by Keylock and Domaas (1999), which contains empirical data of 121 extreme rock falls in Norway. The model correlates travel distance are correlated with simple topographic parameters. Keylock and Domaas
(1999) define extreme rock falls as boulders that travel beyond the foot of the talus slope, which typically forms at the foot of a mountain side. The runout length is determined by the geological energy gained between the point of initiation (point A) and the point where a slope angle of 23° is reached (point B). The geological energy is calculated by the tangent of the line between A and B. The $\beta$-angle is the angle between the line A-B and the horizontal plane. With equation (4) the angle $\alpha$, which is the angle between a horizontal line and the line of sight. The angle $\alpha$ defines the maximal runout length.

$$\alpha = 0.77\beta + 3.9^\circ \quad (4)$$

Figure 8: The alpha-beta method after Keylock and Domaas (1999). Point B is defined as the point where the slope is equal to 23°. Alpha (Eq. 4) is the line of sight between point A (source cell) and the point where the rock fall ends.

Sætre (2014) applied the Horn’s method and the D8-algorithm to calculate aspect and slope of the DEM. The source layer are the cells with permafrost occurrence. Cells with permafrost get the value 1 the others value 0. Then the slope in every cell along the flow path against the B-point angle is checked. The default value is 23° and this value was also used in this thesis. Detecting B-point one has to be sure that it is not a local flat. If it is less than a true value, it is rejected and one continues to search for the B-point. Only one
local flat cell is allowed (equivalent to 10 m). If the next cell is not a local flat, the further rock fall path is calculated. Then the alpha-angle is given by equation (Eq. 4). The script stops when the angle between the A-B line and a horizontal plane at point B is less than the alpha-angle. The resulting matrix consists of cumulative values, where each rock fall adds a value 1 to the matrix cell. Further analysis in the code includes a sink identification and a overlap analysis of sink cells with source and run out maps.

The procedure to conduct the hazard assessment is given in a chart (Figure 9). In a first step, a layer with a buffer is compiled with a radius of 1.5 km around each cell, which had been defined as a steep permafrost rock wall. This layer was then overlaid with shapefiles of infrastructure (buildings, roads) and water bodies (NVE, 2015). The result was examined visually (red boxes in Figure 9), to check if a rock fall is possible. Permafrost cells can be on a lower altitude than the elements at risk or only some single cells or widely scattered permafrost-cells were calculated. However, only large scale permafrost rock walls, were defined as source for runout modeling. A slope angle of release was defined to be $\geq 60^\circ$ and $\beta = 23^\circ$ were defined. The result is a raster layer which depicts the cumulative cell values for each time a rock fall enters a cell. 6 classes were defined (1-2, 3-10, 11-50, 51-100, 101-250 and $>250$ counts). The higher the count, the higher the occurrence of rock fall. The result was also compared with the online available Norwegian avalanche data base (skrednett.no, 2015) to check whether rock avalanches have already occurred at these spots.
Figure 9: Flow chart for hazard analysis. The blue boxes are input data, the white ones the conducted processes and the green boxes the generated output. After the green boxes a "Visual examination" was conducted (red boxes). The two white boxes on the right side of the boxes "Visual examination ArcGIS" and "Object at risk" explain in more detail the procedure.
5 Results

5.1 Recalculated raster of mean ALRT

The recalculation of the spatially varying mean ALRTs revealed that for most of Norway a ALRT of around -0.45°C (100 m)^{-1} prevails (Figure 11). Along mountain ranges and the coast line the ALRTs showed high variability, which are most probably artifacts (for discussion see section 6.1.1). The resulting map of the mean ALRT showed before the applied spline interpolation mostly on flat areas missing values. To interpolate the missing values, the spline method was chosen, since it is efficient and passes exactly through the input points (ESRI, 2015b).

The histogram of the ALRT values show a clear symmetric distribution with a positive kurtosis of both the ALRT before and after the interpolation (Figure 10). After the spline interpolation the histogram showed values mostly ranging between -0.53 to -0.37°C (100 m)^{-1}. The mean value after the interpolation is -0.37°C (100 m)^{-1}. For the calculations of the mean ALRT only the values between -1 to 1°C (100 m)^{-1} were included in the analysis.

Figure 10: Histogram of ALRT distribution (in°C (100 m)^{-1}) before (brown bins) and after (blue bins) the spline interpolation. The most frequent values is in both cases -0.45°C (100 m)^{-1}. For the calculations of the mean ALRT only values between -1 to 1°C (100 m)^{-1} were considered in the analysis.
Figure 11: Spatially varying temperature ALRT with a resolution of 1 km, recalculated based on the MAAT of the seNorge data of each year from 1957 to 2013 (Statens Kartverk, 2011). This is the used raster layer, which was used for further calculation of MAAT. Values of ALRT are mostly between -0.3 and -0.6°C (100 m)$^{-1}$. The lower box depicts the Jotunheimen region, which is zoom into the region. In the upper box the Lyngs Alpene can be seen, where several red dots along the coast were recalculated. These are most probably artifacts.
5.2 Interpolated seNorge data set

A MAAT of \( \leq -2^\circ C \) is mostly found in mountainous regions, on high-mountain plateaus and in continental areas of Norway (Figure 12). The overall coldest temperatures were found in Hallingskarvet, Jotunheimen, Dovrefjell, Rondane, in the Narvikfjellene and Finnmarksvidda.

Figure 12: MAAT of \( \leq -2^\circ C \) at a resolution of 10m based on the seNorge data. Especially the mountainous areas in southern Norway (Jotunheimen, Rondane, Dovrefjell) show a MAAT \( \leq -2^\circ C \). In northern Norway, continental areas along the Swedish border and in Finnmark show temperatures below (Kartverket, 2015). The lower box shows the temperature regime in Jotunheimen and the box in northern Norway the Lyngen Alpes and surroundings.
5.3 Map of steep rock walls potentially underlain by permafrost

This section provides the mapping of permafrost in steep rock walls (Figure 13). Subsequently, extracts of southern (5.3.1), central (5.3.2) and northern Norway (5.3.3) is shown.

Figure 13: Map of steep rock walls potentially underlain by permafrost in Norway. To define permafrost in steep rock walls, a MAAT of $\leq -2^{\circ}$C for the period from 1961-1990 (seNorge.no) and a 10 m digital elevation model were combined. The red dots represent permafrost rock walls with a buffer of 1.5 km around each single pixel with permafrost (Kartverket, 2015).
5.3.1 Southern Norway

Figure 14 presents a map of steep rock walls potentially underlain by permafrost in southern Norway. The main occurrence is estimated to extend from Hallingskarvet in the south up to Trollheimen in the north (a distance of c. 340 km). From west to east the map extents from Jostedalsbreen to Rondane (c. 200 km). Areas with large occurrence are: Hallingskarvet, Reineskarvet, Jotunheimen, Rondane and Dovrefjell (Figure 15). Minor occurrences exist in Rjukan and Hamrefjellet in southern Hardangervidda and north of Hemsedal. Around the ice caps Jostedalsbreen and Hardangerjökulen (Figure 16) permafrost was found. In the east, along the Swedish border in Femunden, Sylan and Guevtele area some small permafrost patches are found. North of Trondheim, some permafrost can be found in Bøorgefjell.

Artefacts were generated close to the coast through the applied ALRT, such as in Nordfjord on the west coast (Figure 14).

In Rondane large areas with permafrost in steep rock walls were depicted (Figure 15). Below the modeled walls much debris can be found. Permafrost above an active rock glacier (Lilleøren, 2011) was modelled (see box in Figure 15). In Dovrefjell steep rock walls with permafrost mostly appear in glaciers cirques (Figure 15). In these two regions the temperatures are low and range from -2 to -6°C.

In Figure 16 the two mountains Kjenndalskruna, northwest of Jostedalsbreen and Skarfellet and Trolla, located in Møre og Romsdal are shown. These two sites have compared to Rondæ and Dovrefjell warmer temperatures in the rock walls (-2 - -3.9°C).
Figure 14: Potential permafrost occurrence in steep rock walls in southern Norway. The squares depict the different regions with permafrost in steep rock walls. Most permafrost was found to be in the areas Hallingskarvet, Jotunheimen, Rondane and Dovrefjell. Artifacts are the red dots, which are close to the coast line, e.g. the red dot in Nordfjord, and most probably the dots in the northwest of the square of Møre og Romsdal. (Kartverket, 2015).
Figure 15: Permafrost in steep rock walls in Rondane (above, with an aerial image on the right) and Dovrefjell (below), extracted from Figure 14. In Rondane permafrost was modeled in the steep rock wall on the mountain Storsmeden (red dot, 2016 m asl) above a rock glacier. In Dovrefjell the mountain Snøhetta (2278 m asl) and several glacier cirques showed permafrost occurrence. In both regions low temperatures were compiled (Kartverket, 2015; NorgeiBilder, 2015).
Figure 16: Permafrost in steep rock along Jostedalsbreen (above) and the mountains Skarfjelle (north of the image 1790 m asl.) and Trolla (1800 m asl) in the county Møre og Romsdal (Kartverket, 2015; NorgeiBilder, 2015).
5.3.2 Central and northern Norway

From Saltfjellet to Laksev, steep rock walls potentially underlain by permafrost was found mostly in mountainous areas and along the Swedish border (Figure 17). Considerable areas with permafrost are in the mountains southeast of Narvik, south and east of Bardufoss, Tamokdalen, Lyngen Alps and in the municipalities Storfjord (Kitdalen, Signaldalen, Elsnes-dalen), Kåfjord (Manndalen, Skardalen, Kåfjorddalen), Nordreisa (Skibotndalen, Kidalen). South of Narvik permafrost is found in along the glaciers Okstindsbreen and the ice caps Svartisen, Blåmannsisen and Sulitjelmaisen. A close-up of Lyngen Alps (Figure 18) and Kåfjord (Figure 19) is given.
Figure 17: Map of permafrost walls in northern Norway. A buffer of 1.5 km was set around each pixel with permafrost. The squares depict the different regions with permafrost in steep rock walls. Artifacts are the red dots, which are close to the coast line. (Kartverket, 2015).
Figure 18: Permafrost in steep rock in the Lyngen Alps, extracted from Figure 17. Most mountain
tops and steep valley sides show permafrost occurrence. The black box in the upper image depict
Langdalstindane (1487 m asl) in the lower part and Ellendaltinden (1345 m asl) in the upper part
of the box. (Kartverket, 2015; NorgeiBilder, 2015).
Figure 19: Permafrost in steep rock walls in Kåfjord, extracted from Figure 17. In most of the steep mountain rock walls permafrost at a temperature of -2 to -5°C were found. In box nr. 1 the mountain Normannviktinden (1355 m asl) with several rock glaciers is shown. In box nr. 2 the mountain Isfjellet (1299 m asl) is presented, where rock falls can be seen and the main road E6 close to the fjord (Kartverket, 2015; NorgeiBilder, 2015).
5.3.3 Northern Norway

A less steep mountainous topography exist in this part of Norway. Therefore, less permafrost in steep was modelled. In northern Norway steep permafrost rock walls can be found around Øksfjordjøkelen and along the canyon vallex sides of the Altariver. The sites which show permafrost on the islands, are seen as artifacts and are therefore not included in further analysis.

Figure 20: Map of permafrost walls in Finnmark, northern Norway. In box nr. 1 the Altacanyon is shown, where permafrost was observed along the canyon sides. In box nr. 2 a site 2 km south of Austertana is shown. Both sites show large debris cones and have rather “warm” permafrost of around -2°C. To make each rock wall more visible, a buffer of 1.5 km was set around each pixel with permafrost. (Kartverket, 2015; NorgeiBilder, 2015).
5.4 Spatial distribution of permafrost occurrence in Norwegian counties

A map shows all the Norwegian counties and the climate regions after Hanssen-Bauer and Nordli (1998) (Figure 21). The total and relative area of permafrost in steep rock walls and its warm fraction in each Norwegian county is presented (Table 3). The lower limit of permafrost for each county varies between 660 and 1500 m asl (Table 4). In Figure 22 the histograms of the elevation and aspect distribution of the county of Troms is shown (all histograms are in the Appendix). An overview of the statistics is given in Figure 23.

Figure 21: Map of the Norwegian counties (grey colored) and the regions (numbers 1-6) from which the data set of the steep permafrost rock walls has been divided in (adjusted after Hanssen-Bauer and Nordli (1998)).
In southern Norway the counties Telemark, Hordaland, Buskerud, Oppland, Sogn og Fjordane, Møre og Romsdal, Hedmark, Sør-Trøndelag and Nord-Trøndelag have permafrost in steep rock walls. Most permafrost occurrence in steep rock walls was found in the county of Troms (41.42 km$^2$) followed by Oppland (13.18 km$^2$), Nordland (7.7 km$^2$), Sogn og Fjordane (4.91 km$^2$) and Buskerud (3.66 km$^2$) (Table 3). Minor occurrence were found in Møre og Romsdal (1.2 km$^2$) and Finnmark (c.1 km$^2$). The other counties had less than 1 km$^2$ of permafrost. Troms and Oppland have compared to the size of the whole county the most permafrost occurrence. Most “warm” permafrost, which was defined to be the cells in the range of $-3^\circ C \leq MAAT \leq -2^\circ C$ appeared in Troms (14.0 km$^2$), Nordland (4.6 km$^2$), Sogn og Fjordane (2.25 km$^2$), Oppland (2.1 km$^2$) and Møre og Romsdal (1.5 km$^2$). For the counties Telemark, Hordaland, Møre og Romsdal and Finnmark more than 70% of the permafrost was warm. The counties Sør-Trøndelag, Nord-Trøndelag, Sogn og Fjordane and Nordland had around 40% warm permafrost. The counties Buskerud, Oppland, Hedmark an0d Troms had least warm permafrost (<33%) (Figure 23).
<table>
<thead>
<tr>
<th>County</th>
<th>Total area (km²)</th>
<th>Area with Permafrost (km²)</th>
<th>Permafrost -2 to -3 °C (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Region 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buskerud</td>
<td>14’910</td>
<td>3.66 (0.02)</td>
<td>0.84 (22)</td>
</tr>
<tr>
<td>Oppland</td>
<td>25’192</td>
<td>13.18 (0.05)</td>
<td>2.1 (15)</td>
</tr>
<tr>
<td>Telemark</td>
<td>15’296</td>
<td>0.28 (0.001)</td>
<td>0.27 (96)</td>
</tr>
<tr>
<td>Hedmark</td>
<td>27’397</td>
<td>0.58 (0.002)</td>
<td>0.089 (15)</td>
</tr>
<tr>
<td><strong>Region 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hordaland</td>
<td>15’436</td>
<td>0.79 (0.005)</td>
<td>0.55 (70)</td>
</tr>
<tr>
<td>Sogn og Fjordane</td>
<td>18’619</td>
<td>4.91 (0.03)</td>
<td>2.25 (45)</td>
</tr>
<tr>
<td>Møre og Romsdal</td>
<td>15’099</td>
<td>1.9 (0.01)</td>
<td>1.5 (78)</td>
</tr>
<tr>
<td><strong>Region 3</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sør-Trøndelag</td>
<td>18’839</td>
<td>0.45 (0.002)</td>
<td>0.2 (44)</td>
</tr>
<tr>
<td>Nord-Trøndelag</td>
<td>22’415</td>
<td>0.24 (0.001)</td>
<td>0.1 (41)</td>
</tr>
<tr>
<td><strong>Region 4</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nordland</td>
<td>38’481</td>
<td>7.7 (0.02)</td>
<td>4.6 (59)</td>
</tr>
<tr>
<td>Troms</td>
<td>25’862</td>
<td>41.42 (0.16)</td>
<td>14.0 (33)</td>
</tr>
<tr>
<td>Finnmark</td>
<td>48’631</td>
<td>1.03 (0.002)</td>
<td>0.86 (83)</td>
</tr>
</tbody>
</table>

Table 3: Area of permafrost in steep rock walls in each Norwegian county.

5.4.1 Lower limit of permafrost, elevation and aspect distribution

The lower limits for each county is the average of all cells in the range of -2 to -3°C. In southern Norway the lower limit of permafrost in steep rock walls decreases from the west to the east from around 1500 to 1200 m asl (Table 4). In region 3 no pattern can be determined. In region 4 the lower limit of permafrost in rock walls is around 870 m asl, with the lowest
in Finnmark (661 m asl). Table 4. The coldest MAAT is observed in Oppland and Hedmark (c.-5°C).

<table>
<thead>
<tr>
<th>County</th>
<th>MAAT of steep rock walls (°C)</th>
<th>Lower Limit of Permafrost in Rock Walls (m asl)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Region 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buskerud</td>
<td>-3.7</td>
<td>1284</td>
</tr>
<tr>
<td>Oppland</td>
<td>-5.0</td>
<td>1285</td>
</tr>
<tr>
<td>Telemark</td>
<td>-2.4</td>
<td>1350</td>
</tr>
<tr>
<td>Hedmark</td>
<td>-4.5</td>
<td>1033</td>
</tr>
<tr>
<td><strong>Region 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hordaland</td>
<td>-2.9</td>
<td>1507</td>
</tr>
<tr>
<td>Sogn og Fjordane</td>
<td>-3.4</td>
<td>1518</td>
</tr>
<tr>
<td>Møre og Romsdal</td>
<td>-2.6</td>
<td>1584</td>
</tr>
<tr>
<td><strong>Region 3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sør-Trøndelag</td>
<td>-2.9</td>
<td>1385</td>
</tr>
<tr>
<td>Nord-Trøndelag</td>
<td>-3.2</td>
<td>962</td>
</tr>
<tr>
<td><strong>Region 4</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nordland</td>
<td>-3.0</td>
<td>1092</td>
</tr>
<tr>
<td>Troms</td>
<td>-3.5</td>
<td>860</td>
</tr>
<tr>
<td>Finnmark</td>
<td>-2.6</td>
<td>661</td>
</tr>
</tbody>
</table>

Table 4: MAAT and lower limit of permafrost in steep rock walls in Norwegian counties divided by temperature regions defined by Hanssen-Bauer and Nordli (1998). In the more continental region 1 the lower limit of permafrost is lower than in region 2 where a maritime climate prevails. In region 3 the lower limit of permafrost for Nord-Trøndelag is low (962 m asl) since the walls are located in continental sites. In region 4 the lowest permafrost occurrence was found.

In Figure 22 the histograms of the elevation and aspect distribution of all rock walls potentially underlain by permafrost of Troms is presented.
In region 1 the lower most cells with permafrost could be found c. 1000 m asl. In Oppland two peaks (at 1400 and 1900 m asl) could be detected, which most probably depict the Hurrungane and Galdhøppigen area. In Telemark the topography is less mountainous than in inner Norway and therefore the highest cells were located at around 1600 m asl. In region 2 most frequently cells appear to be at an elevation of 1500 m asl. In Sogn og Fjordane permafrost was modeled to elevations up to 2400 since it is also part of the Jotunheimen region, where the highest mountains can be found. In region 3 most frequently elevation at c. 1400 and 1200 m asl appear. In the northern regions (region 4) most permafrost cells can be found at elevations of c. 1000 m asl and in Finnmark at c. 800 m asl.

The aspect of all the regions differ highly and no a distinct pattern could be determined. It seems that in northern Norway more cells are oriented towards east and north. But it appears that not many steep rock walls are oriented towards the west. A peak in rock walls facing south were detected in Buskerud and Sogn og Fjordane (see Appendix).
Permafrost in steep rock walls in Norwegian counties

![Map of Norway with areas highlighted for permafrost in steep rock walls]

- **Troms**: 25'862 km², 41.0 km² (33%), 860 m asl, N, NE
- **Buskerud**: 14'910 km², 3.6 km² (22%), 1284 m asl, N, NE
- **Oppland**: 25'192 km², 13.0 km² (15%), 1285 m asl, N, E, S
- **Telemark**: 15'296 km², 2.0 km² (78%), 1570 m asl, N, NE
- **Møre og Romsdal**: 18'619 km², 0.3 km² (15%), 1584 m asl, N, NE
- **Nordland**: 38'481 km², 7.7 km² (59%), 1090 m asl, N, SW
- **Sogn og Fjordane**: 18'839 km², 1.0 km² (53%), 1385 m asl, S, SW
- **Hordaland**: 15'436 km², 0.3 km² (15%), 1033 m asl, N, S, SE
- **Nord-Trøndelag**: 22'145 km², 0.2 km² (9%), 962 m asl, S, SW
- **Sør-Trøndelag**: 18'802 km², 1.0 km² (5%), 1362 m asl, E
- **Hedmark**: 27'397 km², 0.6 km² (22%), 1033 m asl, E, W
- **Finnmark**: 48'631 km², 1 km² (83%), 661 m asl, NE

**Table of Characteristics**

<table>
<thead>
<tr>
<th>County</th>
<th>Total area of county (km²)</th>
<th>Total area of permafrost in steep rock walls (km²)</th>
<th>Lower limit of steep permafrost rock walls (m asl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Troms</td>
<td>25'862</td>
<td>41.0</td>
<td>860</td>
</tr>
<tr>
<td>Buskerud</td>
<td>14'910</td>
<td>3.6</td>
<td>1284</td>
</tr>
<tr>
<td>Oppland</td>
<td>25'192</td>
<td>13.0</td>
<td>1285</td>
</tr>
<tr>
<td>Møre og Romsdal</td>
<td>18'619</td>
<td>0.3</td>
<td>1584</td>
</tr>
<tr>
<td>Nordland</td>
<td>38'481</td>
<td>7.7</td>
<td>1090</td>
</tr>
<tr>
<td>Sogn og Fjordane</td>
<td>18'839</td>
<td>1.0</td>
<td>1385</td>
</tr>
<tr>
<td>Hordaland</td>
<td>15'436</td>
<td>0.3</td>
<td>1033</td>
</tr>
<tr>
<td>Nord-Trøndelag</td>
<td>22'145</td>
<td>0.2</td>
<td>962</td>
</tr>
<tr>
<td>Sør-Trøndelag</td>
<td>18'802</td>
<td>1.0</td>
<td>1362</td>
</tr>
<tr>
<td>Hedmark</td>
<td>27'397</td>
<td>0.6</td>
<td>1033</td>
</tr>
<tr>
<td>Finnmark</td>
<td>48'631</td>
<td>1.0</td>
<td>661</td>
</tr>
</tbody>
</table>

**Figure 23**
5.5 Influence of solar radiation

5.5.1 Regression equations

The following regression equations for each season were generated for Jotunheimen (Table 5) and for Signaldalen (Table 6). The ALRTs are steeper for winter, spring, autumn and in average than the ones from the seNorge data set (Table 1), except for summer. The data set of the earlier created spatially varying ALRTs (section 5.1), showed for the same region a lower value of -0.42°C (100m)^{-1}. The p-values for PISWR and elevation are statistically significant for all seasons, except for summer. The R^2 is satisfying for spring (0.73), winter (0.5) and autumn (0.49). In summer both the p-values and the R^2 are not satisfactory. However, all the regression equations are used in the further study. In Table 6 it can be seen that the results from the regression analysis in Signaldalen is statistically not significant. Therefore, the results from this analysis not used further on.

<table>
<thead>
<tr>
<th>Multiple regression equation</th>
<th>adjusted R^2</th>
<th>p-value PISWR</th>
<th>p-value elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{RW} = 1.407323 + 0.161 \times PISWR - 0.6601 \times elevation )</td>
<td>0.50</td>
<td>7.14e-05</td>
<td>5.95e-08</td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{RW} = 15.172122 + 0.12142 \times PISWR - 1.2822 \times elevation )</td>
<td>0.73</td>
<td>1.31e-15</td>
<td>8.70e-09</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{RW} = 8.4546249 + 0.03841 \times PISWR - 0.29466 \times elevation )</td>
<td>0.20</td>
<td>0.003302</td>
<td>0.13056</td>
</tr>
<tr>
<td>Autumn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{RW} = 8.224704 + 0.1118 \times PISWR - 0.7114 \times elevation )</td>
<td>0.49</td>
<td>5.46e-08</td>
<td>0.000699</td>
</tr>
</tbody>
</table>

Table 5: Multiple regression equations for Jotunheimen. The mean ALRT is -0.73°C (100m)^{-1}.
Table 6: Multiple regression equations for Signaldalen. Since the results are statistically insignificant, the data set was not used for further studies.

<table>
<thead>
<tr>
<th>Season</th>
<th>Multiple regression equation</th>
<th>adjusted $R^2$</th>
<th>$p$-value</th>
<th>$p$-value</th>
<th>PISWR</th>
<th>elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Winter</strong></td>
<td>$T_{RW} = -22.84040 - 1.68226 \times PISWR + 2.443 \times elevation$</td>
<td>-0.04</td>
<td>0.888</td>
<td>0.408</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spring</strong></td>
<td>$T_{RW} = 26.69970 + 0.32229 \times PISWR - 5.244 \times elevation$</td>
<td>0.73</td>
<td>2.89e-11</td>
<td>0.129</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Summer</strong></td>
<td>$T_{RW} = 0.52289 - 0.01236 \times PISWR + 1.769 \times elevation$</td>
<td>-0.06</td>
<td>0.871</td>
<td>0.734</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Autumn</strong></td>
<td>$T_{RW} = 16.54408 + 1.26125 \times PISWR - 2.852 \times elevation$</td>
<td>0.78</td>
<td>1.21e-12</td>
<td>0.352</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.5.2 Seasonal permafrost maps

In this section the seasonal permafrost maps of the Hurrungane region are presented. Figure 24 gives an overview over Hurrungane and its mean annual rock wall temperature. Since permafrost in rock walls is a phenomenon that is small-scaled, the mountain Vetle Skarstølstindane (2340 m asl) was chosen, as an example of the seasonal thermal condition on rock walls in Jotunheimen.

Figure 24: Overview over the Hurrungane area. The black box shows the mountain Vetle Skarstølstindane (2340 m asl), of which is presented in the following seasonal maps.
Figure 25: In winter all the rock walls show temperatures below freezing point. No aspect dependency can be seen. The lowest temperatures were measured to be -14.6°C and the highest -6.5°C (mean = -10.5°C). On the mountain tops temperatures between -10 and -15°C and further in the valley of -6°C and -9°C. (Kartverket, 2015).

Figure 26: In spring the mountain tops are still very cold but most rock walls in the valley seem to have warmed up. A aspect dependency can be seen, where rock walls on same altitudes, but more sun-exposed, have higher temperatures. Here, the temperatures range from 3.0°C in valleys to -13.7°C on mountain tops (mean = -3.5°C) (Kartverket, 2015).
Figure 27: In summer no negative temperatures were modeled in the study area and range from 2.5 - 7.9°C (mean = 5.5°C). Sun-exposed rock walls are warmer than sun-averted walls on same altitudes (Kartverket, 2015).

Figure 28: In autumn the temperatures range from -8.4 to -3.5°C (mean = -3.5°C). Mountain tops show low temperatures compared to valley sides. Sun-exposed walls are warmer (Kartverket, 2015).
The mean surface offset at the rock wall was for both the study period from 2010-2013 (Hipp et al., 2014) and 2013-2014 approximately the same for sun-exposed rock walls (3°C). For the sun-adverted rock walls no data is available for the period 2013-2014. If the looking at the seasons following was revealed: In winter a minimal offset exists for sun-exposed walls (Figure 29). In spring and summer the sun-exposed rock walls are up to 7°C warmer than air temperature. In sun-adverted walls in spring, and in autumn a negative offset can be seen. The largest amplitudes are seen in sun-exposed walls. Outliers (red crosses in Figure 29) are present in all the bins, but mostly appear in summer.

![Surface Offset Winter](image1)

![Surface Offset Spring](image2)

![Surface Offset Summer](image3)

![Surface Offset Autumn](image4)

**Figure 29:** Seasonal offset between the modeled rock surface temperature generated through the regression analysis and the seasonal MAT at Juvasshoe (1894 m asl). The stars depict the mean values. In winter a minimal offset can be seen. In spring the offset is in sun-exposed walls up to 7°C. In summer a larger offset on sun-exposed wall exists, but many outliers can be seen. In autumn the difference becomes negative.
5.5.3 Hierarchical partitioning

In Table 7, through the results of the hierarchical partitioning, it becomes evident that in winter elevation explains most of the variance (78%), whereas in the other seasons it is the PISWR. In spring and autumn PISWR explains 82% of the variance and in summer 75%, respectively.

<table>
<thead>
<tr>
<th>Season</th>
<th>multiple R²</th>
<th>I PISWR (in %)</th>
<th>I elevation (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0.56</td>
<td>0.12 (21.7)</td>
<td>0.44 (78.3)</td>
</tr>
<tr>
<td>Spring</td>
<td>0.74</td>
<td>0.60 (82.1)</td>
<td>0.13 (17.9)</td>
</tr>
<tr>
<td>Summer</td>
<td>0.23</td>
<td>0.17 (74.9)</td>
<td>0.06 (25.1)</td>
</tr>
<tr>
<td>Autumn</td>
<td>0.51</td>
<td>0.41 (82.1)</td>
<td>0.10 (17.9)</td>
</tr>
</tbody>
</table>

Table 7: Results of the hierarchical partitioning. I represents the independent contribution of an independent variable to the overall $R^2$. In brackets the values of I as a percentage of the total explained variance.

The information about the influence of radiation of steep rock walls was not included in the earlier produced map of potential permafrost occurrence in steep rock walls. This because the here achieved outcomes are appropriate for the area of study where the temperature loggers have been installed. In Norway on the same latitude different climatic conditions exist which influence the both the solar radiation and the air temperature condition (see 3.3). Isaksen et al. (2002) write that the influence of radiation is higher in continental areas of Norway, since there the cloudiness and air humidity is reduced.
5.6 Results of validation

5.6.1 Existing permafrost maps

Generally, the generated map in this thesis shows similar results of permafrost distribution compared to the TTOP map from 1961-1990 from the study of Gisnås et al. (2013). In the following regions this study estimated colder temperatures: In southern Norway in the regions of Haukelifjell, in the area of Hardangerjøkulen, close to the coast and in Trollheimen. In northern Norway in the regions close to the sea on the Lyngen Alps less permafrost was estimated.

Figure 30: MAGT (1961-1990) modelled by Gisnås et al. (2013) by using a equilibrium model CryoGRID1.0.

If comparing the regional inventory of rock glaciers (Lilleøren, 2011) it seems that in the Lyngen Alps intact and relict rock glaciers and permafrost in steep rock walls seem to
occur on similar sites (Figure 31). In Finnmark mostly relict glaciers were found, and on these sites the map of potential occurrence of permafrost in steep rock walls most probably shows artifacts. In the area south-east of Narvik and in Jotunheimen several intact rock glaciers were depicted and here several steep rock wall potentially underlain with permafrost were estimated to exist, too. During the analysis steep rock walls potentially underlain by permafrost were found above two presumably active rock glaciers (Lilleøren, 2011) in Rondane (Figure 15) and in Lyngen Alps (Figure 18).

Figure 31: Comparison between a map of registered active (blue) and relict (red) permafrost landforms (left, (Lilleøren, 2011)) and the produced permafrost map of steep rock walls in the Lyngen Alps, northern Norway.
5.6.2 Validation with maps including solar radiation

In this section the *map of steep rock walls potentially underlain by permafrost* (further on also defined called *interpolated seNorge data set*) is validated against the map generated through the regression analysis based on rock wall temperature. First the maps are compared visually against each other, followed by a presentation of the altitude of lower limit of permafrost, and the surface offset.

Comparing both maps reveals that overall, a similar distribution of permafrost in steep rock walls results. A visible difference is that the isotherm of MAAT of $\leq 2^\circ$C that was calculated with the *seNorge* data, is lower in sun-exposed rock walls, than the isotherm of the regression analysis (Figure 32). This is not only visible in this specific extract of the map, but in the whole region. On sun-averted rock walls colder temperatures were modeled than on sun-exposed rock walls in the map of the regression analysis (Figure 32). Also, on mountain tops colder temperatures were modeled, than lower in the valley. To satisfy the fact that air temperature is generally lower than rock wall temperature (Hipp et al., 2014) the same coloration was applied, where a rock wall temperature of 0$^\circ$C corresponds to an air temperature of -2$^\circ$C. The *seNorge* data (Figure 33) showed lower temperature in all cardinal directions.
Figure 32: Average temperatures in steep rock walls in Hurrungane (in °C) for the period 2010-2014. Depending on aspect different rock walls were calculated. This as a result of solar radiation (NorgeiBilder, 2015).

Figure 33: Modeled temperatures in steep rock walls in Hurrungane through seNorge air temperature data (in °C). The dashed line depicts the lower limit of permafrost (= 0°C) for the rock wall temperatures calculated from the installed temperature data loggers. The straight line shows the lower limit of permafrost for the air temperature (MAAT = -2°C). On most east and north facing slopes both lines are on same altitudes.
The altitude of lower limit of permafrost modeled through the regression analysis is for south-facing rock walls between 1750 and 2000 m asl and for north-facing walls between 1200 and 1400 m asl (Figure 34). If using the medians the difference is c. 550 m. The values are distributed symmetrically, which means that for east and west facing slopes the values are similar. The altitude of the lower limit of permafrost generated through the interpolated seNorge data set ranges in all aspects between 1350 and 1490 m asl. Compared to the results of the regression analysis the lower limit of permafrost was lower in east, southeast, south, southwest and west by c. 400 m. In north and northeast a higher lower limit of permafrost in by c. 200 m was detected. Almost the same altitude of lower limit of permafrost resulted for northwest aspect. If looking at the histograms of the aspect distribution (Figure 35) it becomes visible that there are more permafrost cells in the northeast (50°) and southwest (220°). Both data sets show a similar frequency distribution. The histogram of the elevation distribution depicts for the interpolated seNorge data set most permafrost cells appear at 1400 m asl. For the data from the regression analysis two peaks are visible, one at 1400 and

![Figure 34: The elevation of the 0°C isotherm of the modeled rock wall temperature through the regression analysis (blue bins) and the elevation of the -2°C isotherm of the interpolated seNorge data set (red bins) are shown. The altitude of south facing rock walls is between 1750 and 2000 m asl, and for north facing slopes between 1200 and 1400 m asl. This is a aspect difference of c. 550 m. The interpolated seNorge data showed values between 1350 and 1490 m asl.](image-url)
Figure 35: The histograms show the frequency distribution of elevation (left) and aspect (right) of the lower limit of permafrost in rock walls. The two peaks in the elevation histogram depict the Hurrungane and the Galdhøppigen regions.

The calculation of the surface offset revealed that for rock walls exposed towards north, northeast, east, west and northwest positive offsets were calculated, which indicates that in these cells a rock wall temperature colder than the interpolated seNorge data set was calculated (Figure 36). The stars in each box show the mean value. An mean difference in south-facing rock walls of c. 4.4°C and 0.5°C and on north-facing ones was found (Figure 36). On southwest and southeast facing slopes the difference was c. 4°C and on east and west facing slopes c. 2.5°C. On northwest and northeast facing rock walls the difference becomes smaller again (c. 1.3°C).
Figure 36: Surface offset between air (interpolated *seNorge* data set) and rock wall temperature depending on different aspects. The stars depict the mean values of each box. Largest differences were calculated on south exposed rock walls. In north, northeast, east, west and northwest exposed rock walls some cells were calculated to have a colder rock wall temperature than the interpolated *seNorge* data set.

5.6.3 Observations during fieldwork

In total 66 rock walls have been visited and c. 3000 images taken, therefore only an extract of the most typical rock walls will be presented. To check whether there is permafrost or not was not possible on site, since this would need direct temperature measurements or geotechnical investigations of the steep rock walls. But during field work it was possible do define if the modeled sites were actually steep, and in a surrounding where permafrost can form. To describe the geological structures was often difficult, since the walls were often not reachable by foot and showed quite complex structures. Vegetation such as trees and bushes could be spotted well. The presence of water could be seen, when the walls were darker because they were wet or even a river flowed down.

Three major rock wall Types were defined (see below Type A, B, C). This characterization is based on (1) fracturization of the wall, (2) recent rock mass movement observations, (3) proximity to a glacier. Often it was not possible to assign a rock wall to a single Type, either
because it was not seen well enough or because several Types were true for the site. Most frequent sites of Type A and B were visited, since Type C is a phenomenon, which appears only on high mountainous surroundings and could not be reached easily by foot. Mostly rock walls of Type A were visited (27 in total), followed by Type B (16), Type C (9) and mixtures of Type A/B (7) and A/B/C (1).

- **Type A**: Rock wall that shows many recent rock avalanches and has a lot of deposits under the steep part. It could occur that in cracks and fractures of the rock wall vegetation grew.

- **Type B**: Rock wall that seems quite stable and have ancient deposits below or not have any recent deposits. The deposits are often covered by vegetation (moss, bushes, small trees).

- **Type C**: Rock wall above or encircling a glacier (so-called cirque glaciers).

A database of all the visited rock walls was produced (see Appendix). All images taken during field work were categorized. In the header of the table the mountain name, its elevation and aspect, snow, ice, water and vegetation details and if recent rock avalanches were released are given. In Figure 37 the sites visited in southern Norway are shown, and three selected sites presented. On Bergfjellet (1500 m asl), a mountain assigned to Type A is situated close to Vang (Figure 37). The upper most meters were depicted as permafrost in the map and had a temperature of around -2 - -3°C. Bergfjellet is highly fractured. Below the rock wall much debris and several large and small-scale rock avalanches observed. On the mountain Skorsnøsa (1453 m asl) on the blocks lying below the steep rock wall many lichens had grown and the rocks were weathered. It was thereof assigned to Type B. Here a temperature of around -2 - -3°C was calculated. On Store Smørrstabstinden (2200 m asl), a temperature of around -6°C was modeled. The rock wall is above a glacier and no mass movements were seen here. Thereof, it was assigned to Type C.
Figure 37: In the above figure visited field sites in southern Norway are shown. In the lower three images the different Types of rock walls are shown (for exact location see upper map). Along Bergfjellet many recent rock mass movements were seen. Below this wall a road, settlement and a lake are situated. In the middle Skorsnøsa is shown, which is located close to Tyinkrysset. It is assumed that this is a old rock avalanche, because quite big lichens had already grown on the deposits of an old rock avalanche. Below Store Smerstabbstinden no rock avalanches were found. More details about the sites are given in the text above and in the Appendix.
Figure 38: In the above figure visited field sites in the area around Narvik are shown (extract from Figure 17). In the lower three images the different Types of rock walls are shown (for exact location see upper map). On Elvegårdstinden a recent large scale rock avalanche was seen (left). The wall seemed quite dry. Stetinden has potential permafrost occurrence in the upper most north and west facing rock walls. No debris was seen below. Below Istinden (right subimage) a glacier is situated and only little debris was found. More details about the sites are given in the text above and in the Appendix.
The area around Narvik had according to the *map of steep rock walls potentially underlain by permafrost* much permafrost occurrence in the mountains. Here the mountain Elvegårdstinden (1448 m asl) was visited (Figure 38). Recently there has been a large rock avalanche. The detachment zone was in the upper most part of the mountain. The date of the rock avalanche remains unknown. The rock wall seems dry and not too fractured. The temperature here was modeled to be around -2°C. Stetinden (1391 m asl) was visited, since permafrost was modeled to be around the peak area (c. -2°C). No mass movements or debris were observed. The mountain seems to be quite stable, and not too fractured. It was therefore assigned to Type B. On the north- and east-facing mountain top of Vestre Istinden (1489 m asl) permafrost was modeled. On its north-facing wall a glacier exists. On this glacier some boulders originating from the above wall were seen. In the joints in the wall, snow and ice was observed (images not shown here). The temperature of the north-facing wall is around -5°C.

In northern Norway, sites in Tamokdalen, Signaldalen, Manndalen, Kåfjorden and Lyngs Alpene were visited. Here, many rock walls were assigned to Type A. As an example in Figure 40 rock walls from this study area are shown. Mannfjellet (1552 m asl) showed according to the created map, permafrost occurrence in the upper most mountain parts. On Oksfjellet (1143 m asl) several recent rock avalanches were seen. This does also account for Otertinden (1354 m asl), were the north-facing wall had permafrost. Below Lemetfjellet (1435 m asl) a glacier is located, where deposits of rock avalanches were seen. The temperatures of all presented sites is around -3 to -5°C.
Figure 39: Sites visited during fieldwork in Lyngen Alps and surroundings in northern Norway (extract from Figure 17).
Figure 40: Sites visited during fieldwork in Lyngen Alps and surroundings in northern Norway (extract from Figure 17). Nr. 1 shows Mannfjellet (1552 m asl), which is located in Signaldalen. Here many rock avalanches with detachment zones in modeled permafrost zones were seen. Nr. 2 is Oksfjellet (1143 m asl) in Kåfjorden, where many recent rock avalanches were observed. Nr. 3 shows Lemetfjellet (1435 m asl), where permafrost was modeled above the glacier. Nr. 4 is Otertinden (1354 m asl), which showed in the upper part of the mountain fresh detachment zones.

5.7 Hazard Analysis: Objects at risk

In total a runout modelling of 25 regions was done. In southern Norway 8 road parts, 20 lakes and 1 house was reached by a runout path (Figure 41). In northern Norway 22 road parts, 9 lakes and 3 houses were reached by a runout path (Figure 42). It has to be mentioned
that the information of the Norwegian avalanche data base skrednett.no (2015) includes also snow avalanches. Specific sites were extracted and compared to skrednett.no (2015) and to aerial images NorgeiBilder (2015). In southern Norway most rock avalanches occurred in mountainous sites and mostly lakes were hit. The only house that was directly hit, was a hut close to Jostedalsbreen. An example of northern Norway is given in Figure 43 and from Kåfjord in Figure 44.

It could appear that the modeled paths were not following the steepest slope gradient or were just straight lines. Below Polvartinden, a large rock avalanche occurred in 2008 (Figure 43). When comparing the run outs with the satellite images of (NorgeiBilder, 2015) existent rock fall paths below steep rock walls were depicted. In southern Norway, less infrastructure was modeled to be exposed to possible rock falls. Rockfalls into fjords were not modeled neither. But mostly lakes of different scales were hit. In northern Norway, more rock fall occurrence was modeled. Here especially in the main valleys Signdaldalen, Manndalen and Kåfjord, rock falls were modeled.

Most of the rock walls in southern Norway, where a risk was modeled, were south-facing. Two sites, that were north-east facing were: Juvvatnet close to Juvasshøe (permafrost temperature: -6°C) and the lake Skagastølsvatnet in Hurrungane (permafrost temperature: -2 to -4°C) (location: Figure 6). In northern Norway, the detachment zones were in all different cardinal directions.

Since most of the runout paths were modeled in mountainous areas, the rock avalanche data base (skrednett.no, 2015) could not be used for southern Norway (see discussion section 6.3). The data base reports mostly rock falls along main roads. In northern Norway several occurrences of rock falls were reported by skrednett.no (2015). The details of each registered rock fall were not analyzed in more detail.
Figure 41: Map of objects at risk in southern Norway. Jotunheimen is located in the center of the map. Several sites exposed to possible rock falls were modeled in mountainous areas. Mostly, lakes were hit. (Kartverket, 2015; NorgeiBilder, 2015; skrednett.no, 2015).
Figure 42: Map of objects at risk in northern Norway. Most runouts were modeled in the main valleys, such as Signaldalen, Kåfjorden and Manndalen, and in mountainous areas (Kartverket, 2015; NorgeiBilder, 2015).
Figure 43: Run out modeling in Signaldalen, northern Norway (location: Figure 39). In the south of the image the mountain Polvartinden, northeast Mannfjellet (Figure 40) and in the northwest Otertinden (Figure 40). The large rock avalanche which occurred on the north facing slope of Polvartinden in 2008 is visible in the white circle (NorgeiBilder, 2015).
Figure 44: Runout modeling along Kåfjorden (exact location: Figure 42). At the end of the fjord, the village Birtvarre is located. Several rock avalanches, with detachment zones in possible permafrost areas were modeled. Especially the mountain Oksfjellet seemed to be a source of rock avalanches (Figure 40) a Some of which reach the fjord or roads and houses in the valley bottom.
6 Discussion

In this Chapter the thesis is discussed. In section 6.1 the limitations and uncertainties of the generated map (6.1.1), the regression analysis (6.1.2) and the hazard assessment (6.1.3) are discussed. In section 6.2 the spatial distribution of permafrost in steep rock walls is discussed. The results of the potential hazard is discussed in section 6.3.

6.1 Limitations and uncertainties

6.1.1 Map of steep rock walls potentially underlain by permafrost

The provided map gives a first-order estimation of sites with steep rock walls potentially underlain by permafrost in Norway. The applied method determines permafrost occurrence on a small scale, but may on a local scale not be precise enough. This since important feedback mechanisms such as atmospheric, snow and permafrost interaction and non-stationary transitions at depth (Hoelzle et al., 2001) were not included in the map.

The assumptions are that on rock walls only a limited surface offset can be observed. However, snow influences the ground thermal regime also on steep rock walls (Hasler et al., 2011). Snow in cracks can have both a cooling or a warming effect. The ground temperatures are influenced by the maximum snow depth and the timing of snow cover in autumn (Goodrich, 1982). Snow in cracks, fissures and joints was observed during field work in Vang in September 2014, in Stryn in October 2014 (Figure 45) and in Hurrungane in Mai 2015 (Figure 45). In late September 2014, at the RW3 site (Galdhøppigen region, Figure 45), a thin layer of rime was found in cracks and fissures in the wall. Snow patches and firn below permafrost rock walls were found in cracks, joints and fractures that were oriented towards north and lied in the shadow (Durmålsfjellet, Figure 46) and on east facing slopes Lakselvstindane (Figure 45). Along vertical fractures snow patches remained. These snow patches could be also remnants of snow avalanches in winter. In northern Norway fresh snow
was not observed during field work in the summer months.

Figure 45: In a) RW3 (Galdhøppigen region, site location in Figure 4) with rime in cracks and fissures in late September 2014. b) Tomefjellet close to north-west of Jostedalsbreen in late October 2014 with thin snow accumulation especially in horizontal cracks. c) Lakselvtindane in Lyngsalpene in August 2014 (site location in Figure 39) with perennial snow patches under the rock wall on talus slopes and in vertical funnels along the rock wall. d) Austanbotstindane in May 2015 with ice and snow in cracks in the rock wall (site location in Figure 37).

Blocky material below steep rock walls can influence the above situated steep rock wall by cooling it (Prof. Ole Humlum, personal communication). In talus slopes and on block glaciers a so-called chimney effect (air advection) can appear (Morard et al., 2008). It contributes to a cooling of the ground, especially in the lower and deeper parts of the affected landforms, by aspiration of cold air into the ventilated terrain during winter, while warmer air is raised towards the upper part of the slope. An increase of the efficiency of air circulation with
decreasing sealing by ice appears. Thus, ground ice can also be preserved in inactive rock glaciers and talus slopes, where climatic conditions otherwise are unfavorable for permafrost.

During fieldwork on Durmålsfjellet, a mountain close to Narvik, northern Norway (location: Figure 38) several of the above mentioned geomorphological phenomenon were seen (Figure 46). Subtle fissures and cracks on top of a mountain (subfigure 1), larger joint and fractures (subfigure 2), talus slopes (subfigure 3) and water percolating out of the mountain (subfigure 4). These are all site-specific details that most probably influence the local permafrost occurrence.

Another assumption was that on steep rock walls of $60^\circ$ no debris can accumulate. During fieldwork this was found to be true, even if in some couloirs in the walls thick debris layer existed, which probably influenced the local permafrost occurrence. Another factor that has not been included is vegetation.

An other efficient effect that influence temperature and stability of a rock walls is advective heat transport, which is highly efficient (Hasler et al., 2011). During field work it was tried to determine how "wet" the rock wall was (see Appendix). In several steep rock walls rivers were spotted. This could lead, depending on the season, to ice formation in the wall. What has not been included in the map, was the geological properties of the steep rock wall. The geomorphology of the rock wall itself and the deposits are most probably dependent on the geological and glacial history of the area and the geology prevailing in the region.

A site where it is supposed to have permafrost in cracks is at the Nordnes rockslide, northern Norway (Nordvik et al., 2010), no permafrost in steep rock walls has been modeled. This since by definition this site is neither a steep rock wall or has a MAAT of below -2 °C. The created map of steep rock walls does not account for permafrost in cracks, which is essential for any rock slide and rock fall analysis.
Figure 46: Durmålsfjellet (1408 m asl, facing northeast), is located southeast of Narvik (Figure 38). The upper 120 meters of the wall along 1 km long section and has in the lower part a temperature of -2 °C and on the upper part -3 °C. Subfigure 1: The surface on top of the mountain seemed to be recently eroded since lots of the rocks were of brighter color than the rocks in near proximity; 2: Most sliding had occurred along the bedding planes.; 3: Talus field below the rock wall; 4: Water percolated, which was originated from cracks.
The influence of snow, perennial snow patches, talus slopes, fractures, energy transfer, geologies and vegetation have to be investigated further in future studies. Snow characteristics could be determined by the use of remote sensing. Most other factors need to be modeled or investigated on-site by experts.

The temperature and precipitation observation for the compilation of the *seNorge* data is biased towards lower altitudes (Tveito, 2007). In Norway 85% of the climate stations are installed below 500 m asl, whereas 50% of the terrain is above this level. Inversions affect the temperature regime at higher elevations. Therefore, both the recalculated spatially varying lapse rate and the interpolated *seNorge* data set have temperatures that are biased towards lower altitudes. This influenced the outcome of this study to a high extent, since both the ALRT and the interpolated *seNorge* data set are based on the original seNorge data set.

The decision of setting the MAAT threshold to \( \leq -2^\circ C \), to define permafrost occurrence, is rather conservative. Since the surface offset on steep rock walls is almost nonexistent (Boeckli et al., 2011; Gruber and Haeberli, 2007b; Harris et al., 2009). The created map was compared to a regression analysis that includes solar radiation, and a difference of 4°C in sun-exposed rock walls and by 1°C in sun-averted rock walls was found. The difference was larger than if comparing the extrapolated air temperature from the Juvasshøe climate station and the rock wall temperature (Hipp et al., 2014). Possibly, because the study period 2013 - 2014 was warmer than the *seNorge* data (1961-90), a larger offset was calculated. The chosen threshold of MAAT = \( \leq -2^\circ C \), is therefore, for the aim of this study acceptable. Due to different PISWR in other regions of Norway, different thresholds may have to be applied.

During fieldwork it was confirmed that the chosen slope angle threshold is accurate enough to define steep rock walls. Even if the given DEM with a resolution of 10 m (Statens Kartverk, 2011) showed deviations of 2 - 6 m, this represents a draw-back in regions with minor permafrost occurrence, but in areas with permafrost on a large extent, this can be neglected.

The spatially varying ALRT was recalculated by the use of the *seNorge* data set. The
information about the exact applied spatially varying lapse rates by (Tveito et al., 2000) are not available and therefore the generated results could not be compared. If only comparing to the mean ALRT of seNorge, then a similar mean ALRT was recalculated. On flat areas or along the coast, where minimal differences in topography exist, artifacts probably arise due to a spatial interpolation of the climate stations and not due to changes in the DEM. At the same time, to calculate a lapse rate in flat areas is rather useless.

For regions in Dovrefjell Isaksen et al. (2002) calculated a ALRT of -0.44 °C (100 m)^{−1} and for Jotunheimen -0.42 °C (100 m)^{−1}. For Femunden (eastern Norway) a ALRT of -0.31 °C (100 m)^{−1} was calculated (Heggem et al., 2005). The recalculated ALRTs are similar for the same study areas, except for the Femunden area: In the Dovrefjell region a ALRT of -0.42, for the Jotunheimen area -0.46 and for Femunden -0.44 °C (100 m)^{−1} was obtained. Inversions were calculated in Femunden too, but these are mainly seen as artifacts. As mentioned earlier, not many climate stations are installed on high altitudes, and thereof, the temperatures in high altitudes biased towards lower altitudes. Furthermore, the seNorge data is based on interpolations and errors added (Tveito et al., 2000). The recalculated ALRT is probably accurate enough on steep topographies, but not on flat areas. Which is not a draw-back, since areas with steep rock walls underlain by permafrost are not located in these areas. The used method was a simple approach and accurate enough for the purpose of this study.

6.1.2 Regression analysis

Linear regression analyses do not account for heat transfer processes but may used to show a simple map of permafrost occurrence in a region (Brenning et al., 2005). There exist other factors that may influence the thermal regime on the rock wall (for more detail see section 6.1.1).

In Jotunheimen data series of 3 years are available for 3 loggers and over 4 years for 2 temperature loggers. This time period might be too short, to define average temperature
conditions on rock walls. Rolland (2003) estimated air temperature, by using simple linear regression for several regions in northern Italy. According to this study, results from previous studies did not represent characteristic ALRTs because of two reasons: An insufficient number of climate stations in high altitudes and too short data periods. These problems can be reduced when more than 60 stations and data of 30 years are used (Paul, 1976). Therefore, longer data series and more temperature loggers are needed. In northern Norway, the regression analysis did not show significant results. During winter months the temperature data curves did not show a typical daily variability, but the curve was smoothed (Figure 7). Probably snow covered the loggers, since the loggers were not installed on steep rock walls but on a boulder and on a small hill. In their study in Spitsbergen, Ødegård and Sollid (1993) measured rock temperatures on a cliff, but their loggers got covered by snow which lead to no insulation before snow melt. The same could have occurred in Signaldalen. Furthermore, the temperature loggers in Signaldalen were all installed on similar elevations, whereas the installed loggers in Jotunheimen had a elevation difference of 725 m (Table 2).

In future studies, temperature loggers need to be installed in different aspects and elevations and on steep rock faces to avoid snow coverage. To install temperature loggers in a steep rock wall is a difficult task, which demands safety requirements. Moreover, reading out the temperature loggers at a later state can be challenging. Therefore, temperature loggers are often installed on easy accessible locations.

The calculated PISWR, does not include cloudiness (Fu and Rich, 1999). However, it is considered in the output, when calculating transmittivity and diffuse proportion. Clouds are difficult to model and further information about the type, thickness and distribution are hardly available. In addition, reflected radiation is not included, which is important in areas, where a high albedo prevails on ground surfaces, such as snow-covered surfaces. In Jotunheimen, depending on the season, snow can be detected on the surface. Furthermore, there are several glaciers which also have a higher albedo than the ground surface. According to Fu et al. (1994), the algorithm estimates on a simple level reflected radiation by the viewshed from which direct and diffuse radiation originates, whereas reflection from the
ground arise from directions that are blocked. Another limitation of the PISWR algorithm is that ground features such as vegetation and infrastructure are not included. In Jotunheimen hardly any vegetation and human infrastructures exists.

The ALRTs generated through the regression analysis in Jotunheimen showed for winter, spring and autumn a characteristic pattern. In spring and autumn a steeper ALRT than for winter was compiled. This might result of unstable weather conditions in this mountainous area during these two seasons. In winter the ALRT is shallower compared to spring and autumn since the weather is more stable. During winter no inversion was modeled, since the loggers are neither located on valley bottoms, sinks or at high-mountain plateaus (Tveito and Førland, 1999). For summer the adjusted \( R^2 \) was low (0.2) and the p-values insignificant. Therefore, the factors elevation and PISWR can not fully explain rock wall temperatures during summer. Still, a realistic pattern of temperature distribution was found and the regression equation used. It has to be searched for another factor that influences the rock wall temperatures during summer. Different studies in high-mountain areas show during summer, compared to other seasons a steeper ALRT.

The results of the regression analysis might be influenced by the two loggers RW2 and RW3, because of (1) the prolonged season was included the warm summer 2014, and (2) the loggers were installed on sun-exposed rock walls, respectively. These cardinal directions receive more solar radiation than the others.

The created *map of steep rock walls potentially underlain by permafrost* did not include solar radiation (Figure 34). Therefore, the map shows a too low lower limit of permafrost in most of the aspects. The map indicates permafrost well in north-westerly directed rock walls. A reason for the higher lower limit of permafrost for the *seNorge* in north and northeast exposed walls (Figure 34), could be that the cells in the the regression analysis were located in areas which received less solar radiation due to shadowing effects. In northern Norway the conditions remain unknown, since no temperature data loggers in rock walls are installed at this latitude. Therefore, installation of rock wall loggers in steep rock walls, with a large
range of different aspects and elevation is of high importance.

The surface offsets was the same for the prolonged study period for sun-exposed rock walls as in Hipp et al. (2014), which could indicated that rock wall temperatures react immediately to temperature increase. To determine air temperature by extrapolating air temperature of a reference altitude (climate station at Juvassho) using a ALRT is a simple approach, and may include uncertainties. Locally the air temperatures may vary due to wind, shadowing and micro-scale effects along the rock wall (fractures, water, ice presence). The mean surface offset between the interpolated seNorge data and rock wall temperature were 1°C (sun-averted) - 4°C (sun-exposed). This is lower than in studies in the Alps (Hasler et al., 2011) and in previous studies in this region Hipp2014. A dependance of the 0°isotherm on aspect was found. South exposed rock walls were 1°C - 8°C warmer than air temperature (Hasler et al., 2011). Probably the influence of solar radiation is higher in the Alps than in southern Norway. In October the Swiss Alps get twice as much solar radiation than southern Norway (Hartmann, 1994). Possible reasons for the difference with the previous study in this region conducted by (Hipp et al., 2014) might be (1) that the used MAAT is from a colder period (1961-1990) than the investigated period (2010-2014); (2) due to the steeper lapse rate of -0.73 °C (100 m)^{-1} instead of -0.45 °C (100 m)^{-1}.

On sun-averted walls in winter and spring and in all cardinal directions in autumn a negative surface offset was found. An explanation for this ground cooling could be an existing thin snow layer, where high long-wave emissivity (albedo of 0.99) and low short-wave absorption leads to low ground temperatures. This is called the autumn-snow effect (Keller and Tamas, 2003). The hierarchical partitioning showed that in winter most of the variance of rock wall temperatures is explained by elevation. The same has been found in the Canadian Arctic during winter season (Lewkowicz, 2001), due to the lack of radiation during the polar night. In this thesis highest explanations of PISWR variance was found in spring. Possibly, due to cloud cover or/and the existence of a radiation-reflecting snowpack (Isaksen et al., 2002; Lewkowicz, 2001).
The lower limit of permafrost in Jotunheimen calculated through the regression analysis for the period 2010 - 2014 is similar compared to the results of Hipp et al. (2014) in north facing slopes (1200 - 1400 m asl). On south facing slopes, the lower limit of permafrost of this study is higher (1750 - 2000 m asl). Leading to a larger difference in south and north facing slopes (580 m) than the one of Hipp et al. (2014) (400 m). A possible reason is, as earlier mentioned, the influence of the warm spring and summer 2014 and the rock wall logger position. By using temperature data from 14 loggers installed in the Alps at elevations between 2500 and 4500 m asl, Gruber et al. (2004b) developed an energy-balance model. A lower limit of permafrost at 2700 m asl for north-facing and 4000 m asl for south-facing slopes was found (Fig. 47). This is a difference in aspect of more than 1000 m. Compared to the Alps, the aspect dependency of the lower limit of permafrost calculated through the regression analysis in the Jotunheimen area is much smaller (580 m), but still higher than in the study by Hipp et al. (2014), where a difference of 400 m was calculated. Etzelmüller et al. (2003) found a lower limit of mountain permafrost in Jotunheimen at 1600 m asl. In this thesis a lower lower limit of permafrost is suggested, both for the regression analysis and the interpolated seNorge data set. Since both studies use the seNorge data, this difference originated because of different chosen cut-off values. Etzelmüller et al. (2003) had chosen a MAAT of -4 °C, to account for snow.

Figure 47: Modelled mean annual rock wall surface temperature on a 70° steep slope at Corvatsch (left) and Jungfraujoch (right) for the period from 1982-2002. The mean 0 °isotherm for this period, is marked by the thick dashed line and and the highest and lowest mean 0 °isotherm by the thin dashed lines (Gruber et al., 2004b).
Uncertainties can also arise from the interpolation method, e.g. the interpolation from 1 km to 10 m, leading to a smoothening of the raster layers.

### 6.1.3 Hazard assessment

The applied method of Sætre (2014) is based on topographical elevation. A more detailed investigation of the geology, triggering factors and historical rock slide events should be included to get a more actual state of hazard. Many other factors were not taken into account. According to Luckmann (1975), rockfall is controlled by the morphological and geological character of a cliff and rock surface temperature fluctuations. Further, vegetation can also be taken into account, even if for many mountainous regions the influence of a forest on the rock fall path is not clear (Dorren and Seijmonsbergen, 2003). Another important aspect is the integration of the energy conservation approach by Scheidegger (1975), where a friction coefficient is responsible for the energy loss at a rockfall. The dynamics of tumbling and bouncing rocks are included. Moreover, many studies include the volume and shape of the falling rocks (Okura et al., 2000). A kinematic analysis can then be performed to detect future failure mechanics (planar sliding, wedge failure, toppling) (Loye et al., 2009). Azzoni et al. (1995) experimentally gained parameters such as a restitution coefficient, rolling friction coefficient, dispersion of trajectories and analyzed the effect of block geometry on its fall. To compare the results a historical data analysis, field studies and analysis of orthophotos can be conducted. The created map using the alpha-beta method is only a first indication.

### 6.2 Spatial analysis of permafrost in steep rock walls

A comparison with aerial images by NorgeiBilder (2015) revealed that with the simple used approach, based solely on MAAT, permafrost on steep rock walls was quite well determined. Permafrost was regularly modeled to be present in glacier cirques. This agrees well with Etzelmuller and Hagen (2005) and Lilleøren et al. (2013), where a close relationship between permafrost and glaciers are found.
The generated map of permafrost in steep rock walls was compared to results of Gisnás et al. (2013). Comparing both maps is not simple, since the TTOP map is based on forced data (daily air temperature and snow cover) and on factors that influence ground thermal properties, such as different bedrock types, sediment covers and blockfields. For the map in this thesis, no thermal offset was included. The differences emerged in regions where only minor permafrost occurrence in steep rock walls was found.

The rock glacier inventory in the study by Lilleøren (2011) is an independent verification of permafrost occurrence. Since both, the rock glacier in the inventory and the steep permafrost rock walls in the produced maps were shown as dots. These dots are quite large in comparison with the features they depict. Therefore the co-occurrence of rock-glaciers and permafrost rock walls has to be investigated in more detail.

A decrease of the lower limit of permafrost in steep rock walls from west to east was found (section 5.4). Etzelmüller et al. (2003) described the same pattern. Similar results were obtained, since both studies use the seNorge data. In this thesis the lower limit of steep permafrost that were calculated to be below the ones of Etzelmüller et al. (2003). The main reason for this difference is that Etzelmüller et al. (2003) used a lower MAAT to account for snow.

Figure 48: Altitude distribution of the lower limit of mountain permafrost (MPA) and ELA in southern Norway (Etzelmüller et al., 2003).

Figure 21 (section 5.4) gives only a rough estimation of the surface area, the aspect and elevation frequency, since steep rock walls are not well represented in the DEM. However,
the results can be used for a relative measure between the counties. An improvement would be using a DEM of a higher resolution (e.g. LiDAR).

A future mean annual warming in Scandinavia of 0.3-0.4°C is assumed (Benestad, 2005). This would mean that most areas that were depicted as having "warm" permafrost in the map (-2 - -3°C), would possibly disappear. This especially in the counties Telemark, Hordaland, Møre og Romsdal, Nordland and Finnmark, were most of the permafrost in the rock walls was defined as being "warm" (Figure 3). However, studies at the Konkodiaplatz of Wegmann et al. (1998) and the Mittlerer Burgstall in Austria Kellerer-Pirklbauer et al. (2012) demonstrated a local build-up of permafrost once glaciers disappeared. This is dependent on local aspect and shading. This could occur in areas in Norway, where glaciers and permafrost co-exist. Such as in regions with warm permafrost along glaciers or ice caps, e.g. on Hardangerjøkulen or Jostedalsbreen.

6.3 Relative Hazard Assessment

Thermal changes in permafrost affected rock walls influence the stability of a slope and therefore, increase the hazard of rock falls. To predict the exact location and timing of future events without a detailed monitoring system, is difficult (Huber et al., 2005). The implemented hazard assessment in this thesis, gives a basic indication for possible areas at risk. Solar radiation was not included in the created map. Therefore, the hazard assessment was conducted with cells lying in detachment zones, where possibly no permafrost occurs. In southern Norway permafrost is found in mountainous areas, without much human activity. This leads to few elements at risk. However, lakes have been affected quite often. Larger lakes such as Vangsmjøse and Gjende (both in the county Oppland) are in the list of the 100 lakes with highest topographic rock slide potential (Romstad et al., 2009). In their study Romstad et al. (2009) evaluated the rock slide tsunami hazards to all Norwegian lakes larger than 0.1 km². As a result, a score indicating the topographic rock slide potential of the relative hazard in each lake was calculated. Possible damming of lakes and tsunamis can
Most of the objects at risk in southern Norway, are below sun-exposed rock walls of low altitude. After the previous analysis of the influence of solar radiation on the distribution of the lower limit of permafrost in Jotunheimen, it can be assumed that these objects at risk are actually not exactly in danger of being hit by a rock fall. Only two sites were found to be below north-facing, high-altitude slopes (Juvvatnet, Galdhøppigen area and Skagastølsvatnet, Hurrengane area). During fieldwork Bergfjellet was visited, a mountain close to Vang (Figure 37). After the analysis of solar radiation (section 5.5) it can be stated that in the upper most parts of this mountain permafrost can potentially be detected. This since the upper part is above the lower limit of permafrost and north-facing. On the other side of the Vangsmjøse rock walls potentially underlain by permafrost were found too, but since these walls are south-facing they most probably do not have permafrost.

In northern Norway, the influence of solar radiation could not be included in the analysis, since no data is available. Still, many permafrost rock walls that were defined as detachment zones for possible rock falls were north-facing and on high altitudes, especially in Kåfjord. A possible warming of this permafrost could increase the risk of rock fall activity. During fieldwork, many rock avalanches originating from rock walls potentially underlain by permafrost were observed. On selected sites (Figure 40) rather warm temperatures were modeled. This could represent a hazard, since a warmer climate in Scandinavia is supposed to exist in the near future (Benestad, 2005). Since both, the created permafrost map and the runout modeling are based on simple assumptions and have their limitations, this statement is insecure.

This is another reason, why in future studies rock wall temperature loggers need to be installed in northern Norway.

Since most of the runout paths were modeled in mountainous areas, the rock avalanche data base (skrednett.no, 2015) could not be used for southern Norway. The data base reports mostly rock falls along main roads. However, in northern Norway, the data base could be of
higher use, since more rock avalanches occur along roads.

In this thesis no dating of the mass movements was conducted. However, it would be interesting if with an increase of temperature, an increasing instability of rock walls would be observed. For this reason, relict rock avalanches have to be dated and combined with information about climate changes. Furthermore, a map depicting glacial history of the regions would support the analysis.
7 Conclusion

- The generated map of steep rock walls potentially underlain by permafrost gives a first-order estimate of permafrost occurrence in steep rock walls. Permafrost presence was confirmed after a comparison with existing permafrost maps, a rock glacier inventory, and by comparing to maps created through a regression analysis based on temperature data of loggers installed in steep rock walls. Factors such as solar radiation, snow and talus occurrence, rock wall fracturization, ice content, geology and 3D effects have not been included in this map and thereby represent the largest uncertainties.

- In southern Norway, steep rock walls potentially underlain by permafrost occur with the largest lateral extent in mountainous regions, such as Halligskavet, Jotunheimen, Rondane and Dovrefjell. Areas of permafrost with minor lateral extent were estimated to occur along mountains on the north-western coast (Rondane, Trollheimen), on high-mountain plateaus (Hardangervidda) and on continental areas close to the Swedish boarder (Femunden, Sylan). In northern Norway most extensive permafrost in steep rock walls appears in Lyngen Alps and Indre Troms. The lower limit of permafrost in steep rock walls decreases in southern Norway from west to east (c. 1500 m asl to c. 1200 m asl). In northern Norway the the lowest limit of permafrost in steep rock walls can be found in Finnmark, which is c. 660 m asl.

- A rough estimate of the surface area of steep permafrost rock walls revealed that for most Norwegian counties, the relative percentage of permafrost occurrence compared to the total county area is 0.001 - 0.16%, which is low. Rock walls with a high fraction of warm permafrost can be found along the west coast of Norway and in Finnmark; cold permafrost rock walls are most prevalent in the continental and mountainous areas of southern Norway, and in the mountainous areas of northern Norway.

- The generation of permafrost maps on steep rock walls for each season by use of a regression analysis revealed that sun-exposed rock walls in Jotunheimen, central southern
Norway are in spring up to 7°C and in summer 6°C warmer than air temperature. In autumn and on sun-averted faces in spring and winter, a negative offset was measured, which indicates a cooling down through a thin snow cover; a so-called autumn-snow effect. In winter no explicit surface offset was measured. A reason for these differences in spring, summer and autumn, can be the influence of solar radiation. In spring, summer and winter solar radiation is the main contributing factor explaining variance and in winter it is elevation.

- The created map shows, if compared to a regression analysis that includes solar radiation, lower temperatures in sun-exposed rock walls by 4°C and in sun-averted rock walls by 1°C.

- An aspect-dependency of the steep rock walls, potentially underlain by permafrost in Jotunheimen, central southern Norway is 580 m between north and south exposed walls. The interpolated seNorge data set for the same region only in north-west facing rock walls show a similar height of the lower limit of permafrost. The map overestimates permafrost occurrence in sun-exposed rock walls in the Jotunheimen region by 380 m.

- Hazards associated with rock walls emerge in mountainous areas of southern Norway where there is low human activity. Most of the rock walls have their detachment zones in south-facing slopes in low altitudes and are therefore only a limited threat. In comparison, hazard risks are higher in northern Norway due to the frequency of runout models inundating most lakes, some roads, however almost no houses. Along Storfjord, rock falls into the fjord were modeled, which could potentially cause a tsunami.

Future research should focus on:

- Improving the measured spatial distribution records of permafrost occurrence in Norway. Additional temperature loggers need to be installed in steep rock walls to refine the link between steep rock wall permafrost with latitude, aspect, and altitude.
• Improving the knowledge of the influencing factors on steep rock walls. The information about precipitation needs to be included. Depending on the season, snow influences the thermal regimes of the wall. To better understand the influence of solar radiation on rock walls diurnal variations of temperature, snow (grain size, timing) and cloud cover (type, timing) have to be analyzed more deeply, e.g. with time lapse cameras or remote sensing approaches.

• Including geological information (conductivity, water saturation, ice content), fracturation, and talus cover under the steep walls in future maps, since these factors can influence the thermal properties of the walls.

• The consequences of collapsing steep permafrost walls above lakes needs to be analyzed more deeply, since they could lead to secondary disaster.
References


URL: [http://www.the-cryosphere-discuss.net/5/1419/2011/](http://www.the-cryosphere-discuss.net/5/1419/2011/)


URL: http://doi.wiley.com/10.1002/ppp.687


URL: http://linkinghub.elsevier.com/retrieve/pii/S0169555X0300045X


eKlima.no (2015), ‘Monthly Air Temperature Values for Station Juvasshøe, Station number 15270’.

URL: http://sharki.oslo.dnmi.no


ESRI (2015b), ‘Spline (Spatial Analyst) ’.


**URL:** [http://doi.wiley.com/10.1002/ppp.1765](http://doi.wiley.com/10.1002/ppp.1765)

Goodrich (1982), ‘The influence of snow cover on the ground thermal regime’, *Geotechnical Section, Division of Building Research, National Research Council of Canada, Ottawa, Ont., Canada K1A 0R6* p. 421432.


High Mountains of Europe: the PACE Project in its Global Context’, 11 (September 2000), 3–11.


URL: http://doi.wiley.com/10.1002/ppp.493


URL: http://www.tandfonline.com/doi/abs/10.1080/00291950510038377


URL: http://doi.wiley.com/10.1002/ppp.1799


Huber, H. K., Bugmann and Reasoner, M., eds (2005), Global Change and Mountain Regions, Springer.

unstable rock slopes in western and northern Norway’, 13, 10942.


URL: http://www.tandfonline.com/doi/abs/10.1080/002919502760056459


URL: http://services.geodataonline.no/arcgis/services


URL: www.jstor.org/stable/521452

King, L., Gorbunov, A. and Evin, M. (1992), ‘Prospecting and Mapping of Mountain Per-


**URL:** [http://doi.wiley.com/10.1002/esp.3374](http://doi.wiley.com/10.1002/esp.3374)


**URL:** [https://snl.no/Norgemenuemtem0](https://snl.no/Norgemenuemtem0)


**URL:** [http://hol.sagepub.com/cgi/doi/10.1177/0959683612471984](http://hol.sagepub.com/cgi/doi/10.1177/0959683612471984)


met.no (2015a), ‘Regionalt klima’.

**URL:** [http://met.no/Klima/Natidsklima/Klima_i_Norge/Regionalt_klima/](http://met.no/Klima/Natidsklima/Klima_i_Norge/Regionalt_klima/)
met.no (2015b), ‘The climate of Norway’.

URL: http://met.no/English/Climate,norway/


URL: http://opac.nebis.ch/F/?local_base=NEBIS&CON_LNG=GER&func=find-b&find_code=SYS&request=008567986


URL: http://linkinghub.elsevier.com/retrieve/pii/S0013795210000748


URL: http://norgeibilder.no

NVE (2015), ‘Nve data base shapefiles for esri arcgis’.


Ødegård, R. and Sollid, J. (1993), ‘Coastal cliff temperatures related to the potential for


Rekacewicz, P. (1998), ‘Circulmpolar active-layer permafrost system (caps) verison 1.0.’.


Romanovsky, V., Burgess, M., Smith, S., Yoshikawa, K. and Brown, J. (2002), ‘Permafrost temperature records: Indicators of climate change’, *Eos, Transactions American Geophys-

URL: [http://doi.wiley.com/10.1002/ppp.689](http://doi.wiley.com/10.1002/ppp.689)


skrednett.no (2015), ‘NVE Skredatlas’.

URL: [www.skrednett.no](http://www.skrednett.no)


URL: [http://doi.wiley.com/10.1017/S1350482705001490](http://doi.wiley.com/10.1017/S1350482705001490)


Tveito, O. E. and Førland, E. J. (1999), ‘Mapping temperatures in Norway applying terrain

**URL:** http://www.tandfonline.com/doi/abs/10.1080/002919599420794


**URL:** http://www.unisdr.org/we/inform/terminology


**URL:** http://www.tandfonline.com/doi/abs/10.1080/10889379909377670
## Appendix

<table>
<thead>
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<th>Average of Temp</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>Average</th>
</tr>
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<tbody>
<tr>
<td>RW3 (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>jan</td>
<td>-12.01</td>
<td>-12.03</td>
<td>-11.25</td>
<td>-11.96</td>
<td>-11.81</td>
<td></td>
</tr>
<tr>
<td>feb</td>
<td>-10.06</td>
<td>-10.32</td>
<td>-8.81</td>
<td>-9.44</td>
<td>-9.66</td>
<td></td>
</tr>
<tr>
<td>mar</td>
<td>-9.22</td>
<td>-5.69</td>
<td>-7.64</td>
<td>-6.53</td>
<td>-7.27</td>
<td></td>
</tr>
<tr>
<td>apr</td>
<td>-0.25</td>
<td>-2.98</td>
<td>-4.75</td>
<td>1.83</td>
<td>-1.54</td>
<td></td>
</tr>
<tr>
<td>mai</td>
<td>2.53</td>
<td>3.05</td>
<td>2.54</td>
<td>3.84</td>
<td>2.99</td>
<td></td>
</tr>
<tr>
<td>jun</td>
<td>4.65</td>
<td>4.81</td>
<td>5.57</td>
<td>6.29</td>
<td>5.33</td>
<td></td>
</tr>
<tr>
<td>jul</td>
<td>8.24</td>
<td>5.35</td>
<td>7.39</td>
<td>10.76</td>
<td>7.93</td>
<td></td>
</tr>
<tr>
<td>aug</td>
<td>6.09</td>
<td>6.41</td>
<td>6.35</td>
<td>5.98</td>
<td>6.21</td>
<td></td>
</tr>
<tr>
<td>sep</td>
<td>6.34</td>
<td>2.07</td>
<td>-1.42</td>
<td>4.10</td>
<td>8.10</td>
<td>3.04</td>
</tr>
<tr>
<td>oct</td>
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<td>-2.85</td>
<td>-5.35</td>
<td>0.01</td>
<td>-2.81</td>
<td></td>
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<td>nov</td>
<td>-12.64</td>
<td>-2.59</td>
<td>-8.10</td>
<td>-8.88</td>
<td>-8.05</td>
<td></td>
</tr>
</tbody>
</table>

*Average Temperature Season 2010/2011: -2.97*
*Average Temperature Season 2011/2012: -2.20*
*Average Temperature Season 2012/2013: -3.39*
*Average Temperature Season 2013/2014: -0.42*

Figure 49: Temperature RW3 monthly averages.
<table>
<thead>
<tr>
<th>Average RW2 (°C)</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>-11.98</td>
<td>-12.36</td>
<td>-12.06</td>
<td>-12.27</td>
<td>-12.17</td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>-11.44</td>
<td>-10.46</td>
<td>-10.47</td>
<td>-10.00</td>
<td>-10.59</td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>1.01</td>
<td>-3.61</td>
<td>-3.81</td>
<td>1.52</td>
<td>-1.22</td>
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</tr>
<tr>
<td>Mai</td>
<td>3.09</td>
<td>4.85</td>
<td>2.68</td>
<td>5.37</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>6.30</td>
<td>5.85</td>
<td>6.65</td>
<td>8.13</td>
<td>6.74</td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>8.69</td>
<td>6.81</td>
<td>9.22</td>
<td>11.48</td>
<td>9.05</td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>5.96</td>
<td>7.11</td>
<td>6.42</td>
<td>4.95</td>
<td>6.11</td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>3.37</td>
<td>1.60</td>
<td>-0.98</td>
<td>2.30</td>
<td>5.70</td>
<td>1.97</td>
</tr>
</tbody>
</table>

**Average Season 2010/2011:** -3.15  
**Average Season 2011/2012:** -2.14  
**Average Season 2012/2013:** -3.24  
**Average Season 2013/2014:** -0.98

Figure 50: Temperature series RW2 monthly averages.
<table>
<thead>
<tr>
<th>Name Mountain</th>
<th>elevation (m asl)</th>
<th>aspect</th>
<th>Geology (in the part where permafrost was modelled: MAAT&lt;-2deg &amp; 60deg steep)</th>
<th>Mass movement</th>
<th>water, vegetation</th>
<th>Type A,B,C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahkavatgaisi</td>
<td>1100</td>
<td>N/NE</td>
<td>Garnetquartzglimmerschist</td>
<td>no recent active rock avalanches</td>
<td>wet (several rivers), vegetation</td>
<td>B</td>
</tr>
<tr>
<td>Bergsfjellet</td>
<td>ca. 1500</td>
<td>N</td>
<td>Granite</td>
<td>recent rock fall</td>
<td>dry (no rivers), no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Bitihorn</td>
<td>1607</td>
<td>E</td>
<td>Monzodioritt</td>
<td>frequent rock fall, creeping lobes on the valley side and in the upper part glaciers and perennial snow patches</td>
<td>several rivers coming down from the snow patches, vegetation in the lower part</td>
<td>A</td>
</tr>
<tr>
<td>Bogen</td>
<td>1146</td>
<td>N</td>
<td>Hornblendeschist and greenschist</td>
<td>no recent active rock avalanches</td>
<td>glacier below a mountain top, no vegetation</td>
<td>A/B/C</td>
</tr>
<tr>
<td>Brøran</td>
<td>1427</td>
<td>W</td>
<td>Amphibolite</td>
<td>no recent active rock avalanches, some on the glacier</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Durmålsfjellet</td>
<td>1408</td>
<td>NE</td>
<td>Granitt</td>
<td>lots of debris, many recent weathering deposits</td>
<td>dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Elnesdalen (North facing)</td>
<td>c. 1200)</td>
<td>N</td>
<td>Garnetquartzglimmerschist</td>
<td>Some funnels where lose material can come down. But mostly ancient.</td>
<td>wet, vegetation</td>
<td>B</td>
</tr>
<tr>
<td>Elnesdalen (South facing)</td>
<td>1100-1400</td>
<td>NE</td>
<td>Garnetquartzglimmerschist</td>
<td>Some funnels where lose material can come down. But mostly ancient.</td>
<td>wet, vegetation</td>
<td>B</td>
</tr>
<tr>
<td>Location</td>
<td>Alt (m)</td>
<td>Direction</td>
<td>Rock Type</td>
<td>Rock Phenomena</td>
<td>Vegetation Status</td>
<td>Acme</td>
</tr>
<tr>
<td>---------------</td>
<td>---------</td>
<td>-----------</td>
<td>-------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>----------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Elvegårdstinden</td>
<td>1448</td>
<td>SW</td>
<td>Granitt</td>
<td>recent large rock avalanche, much debris</td>
<td>dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Erikhumpen</td>
<td>965</td>
<td>W</td>
<td>Glimmerskifre and Glimmergneiss</td>
<td>recent rock avalanche, much debris</td>
<td>dry, vegetation in the debris zone</td>
<td>A</td>
</tr>
<tr>
<td>Fornestinden</td>
<td>1050</td>
<td>N</td>
<td>Gabbro</td>
<td></td>
<td>dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Gammanjuni</td>
<td>1200</td>
<td>SW</td>
<td>Garnet-Qartglimmerschist</td>
<td>recent rock avalanches</td>
<td>dry, no vegetation in the higher mountain parts</td>
<td>A</td>
</tr>
<tr>
<td>Gaskacohkka</td>
<td>1507</td>
<td>S</td>
<td>Gabbro</td>
<td>many recent rock falls</td>
<td>dry, vegetation in the lower parts</td>
<td>A</td>
</tr>
<tr>
<td>Grindane</td>
<td>c. 1600</td>
<td>N</td>
<td>Chlorite-Gneiss</td>
<td>recent rock fall</td>
<td>wet (rivers), vegetation</td>
<td>A/B</td>
</tr>
<tr>
<td>Hattavarri</td>
<td>1408</td>
<td>SW</td>
<td>Garnet-Qartglimmerschist</td>
<td>Stable on the South side, no rock avalanches, seemed to be a paleo surface</td>
<td>dry, no vegetation</td>
<td>B</td>
</tr>
<tr>
<td>Hattefjell East</td>
<td>1431</td>
<td>SE</td>
<td>Garnetquartglimmerschist</td>
<td>glacier surrounded by rock walls</td>
<td>glacier, no vegetation around</td>
<td>C</td>
</tr>
<tr>
<td>Imagaisi</td>
<td>1416</td>
<td>N</td>
<td>Gabbro</td>
<td>glacier surrounded by rock walls, some rock fall activity</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Isfjellet</td>
<td>1206</td>
<td>N</td>
<td>Top: Quartzschist with Distehn and Sturolitt, some Migmatit, Lower part: Garnetquartglimmerschist</td>
<td>some small scale rock avalanches in the lower part of the mountain and more frequent slides in the higher parts</td>
<td>many rivers, vegetation</td>
<td>A/B</td>
</tr>
<tr>
<td>Location</td>
<td>Elevation</td>
<td>Orientation</td>
<td>Rock Type</td>
<td>Features</td>
<td>Vegetation</td>
<td>Class</td>
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<tr>
<td>Isskardtindane</td>
<td>1440</td>
<td>W</td>
<td>Gabbro</td>
<td>many recent rock falls</td>
<td>dry, vegetation in the lower parts</td>
<td>A</td>
</tr>
<tr>
<td>Istinden</td>
<td>1489</td>
<td>W</td>
<td>Tops (&gt;1000m asl): Dioritt, Lower part: Glimmerskifre and Glimmergneiss</td>
<td>recent rock avalanches in funnels, but in debris zone much vegetation growing</td>
<td>dry, vegetation in debris zone growing</td>
<td>A/B</td>
</tr>
<tr>
<td>Istinden</td>
<td>1489</td>
<td>N</td>
<td>Tops (&gt;1000m asl): Dioritt, Lower part: Glimmerskifre and Glimmergneiss</td>
<td>glacier, some rock avalanches that went on the glacier</td>
<td>glacier, no vegetation around</td>
<td>C</td>
</tr>
<tr>
<td>Istinden på Postdalen</td>
<td>1399</td>
<td>N</td>
<td>Granite and pegmatite with Garnet and Turmalin</td>
<td>many rock avalanches, funnels, debris cones</td>
<td>snow patches, vegetation below the debris cones</td>
<td>A</td>
</tr>
<tr>
<td>Kirkesdalen (point)</td>
<td>1270</td>
<td>W</td>
<td>Glimmerschist and Glimmergneiss</td>
<td>no recent active rock avalanches</td>
<td>some single rivers, vegetation growing on mountain and cracks</td>
<td>B</td>
</tr>
<tr>
<td>Bukkehåmåren</td>
<td>1910</td>
<td>N</td>
<td>Pyroxenegranulite</td>
<td>?</td>
<td>?</td>
<td>A/B</td>
</tr>
<tr>
<td>Kyrkja</td>
<td>2032</td>
<td>W</td>
<td>Pyroxene-granulite</td>
<td>recent rock falls, lose mountain top</td>
<td>dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Lakselv, Vuoddovarri</td>
<td>300</td>
<td>E</td>
<td>Quartzite sandstone</td>
<td>Loose rocks, unstable slopes</td>
<td>vegetation</td>
<td>B</td>
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<tr>
<td>Lakselvtinden</td>
<td>1616</td>
<td>W</td>
<td>Gabbro</td>
<td>Debris cones, scree slopes and some small-scale rock avalanches</td>
<td>Vegetation growing in the lower part, dry</td>
<td></td>
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<tr>
<td>Location</td>
<td>Elevation</td>
<td>Aspect</td>
<td>Rock Type</td>
<td>Description</td>
<td>Vegetation</td>
<td>Grade</td>
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<tr>
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<tr>
<td>Lappviktinden</td>
<td>1170</td>
<td>E</td>
<td>Granitt</td>
<td>lots of recently formed debris at the base of the rock walls, a large debris cone, some small-scale rock avalanches</td>
<td>dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Lemetfjellet Tamokdalen</td>
<td>1342</td>
<td>S</td>
<td>Garnet-Quartz-micaschist</td>
<td>some recent rock falls</td>
<td>dry, vegetation in the lower parts</td>
<td>A</td>
</tr>
<tr>
<td>Lemetfjellet</td>
<td>1435</td>
<td>NE</td>
<td>Garnet-Quartz-micaschist</td>
<td>too far away to see rock avalanches</td>
<td>glacier circe</td>
<td>C</td>
</tr>
<tr>
<td>Mannfjellet</td>
<td>1552</td>
<td>S/SW</td>
<td>Top: Garnet-Quartz-Micaschist; Lower part: Garnet-Quartz-Micaschist</td>
<td>many rock avalanches, funnels, debris cones</td>
<td>dry, vegetation in the lower parts</td>
<td>A</td>
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<tr>
<td>Melhuskletten</td>
<td>1437</td>
<td>N</td>
<td>Glimmerschist and Glimmergneiss</td>
<td>Bad visibility. But rather no recent mass movement</td>
<td>wet (snow patch (perrenial?)), vegetation</td>
<td>B</td>
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<tr>
<td>Moskuskaisa</td>
<td>1146</td>
<td>N</td>
<td>Top: Calsparmarmor (with some dolomite), Lower part: hornblendeschist (and greenschist)</td>
<td>one large rock avalanches on the north side, on the Northwest side of the mountain some recent but mostly ancient</td>
<td>?</td>
<td>A/B</td>
</tr>
<tr>
<td>Nallancohka</td>
<td>1328</td>
<td>E</td>
<td>Gabbro</td>
<td>?</td>
<td>?</td>
<td>C</td>
</tr>
<tr>
<td>Location</td>
<td>Altitude</td>
<td>Aspect</td>
<td>Rock Type</td>
<td>Landform Features</td>
<td>Vegetation</td>
<td>Rock Movement</td>
</tr>
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<tr>
<td>Oksfjellet</td>
<td>1143</td>
<td>NE</td>
<td>Garnetquartzglimmerschist, containing Disthen and Staurolitt, with some Amphibolite and Konglomerates</td>
<td>recent rock avalanches</td>
<td>dry, vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Barstinden</td>
<td>1352</td>
<td>NE/S</td>
<td>Top: Granite and pegmatite with garnet and Turmalin, Lower parts: garnet-Quartzmica schist and garnet chalk micaschist</td>
<td>many funnels, rock avalanches, unstable slope parts</td>
<td>mostly dry, some small snow patches, vegetation growing in the lower part</td>
<td>A</td>
</tr>
<tr>
<td>Postdalsfjellet</td>
<td>1363</td>
<td>E</td>
<td>Garnet-Quartzmicaschist</td>
<td>many rock avalanches, large debree cones</td>
<td>snow patches, wet, vegetation growing in the lower part</td>
<td>A</td>
</tr>
<tr>
<td>Raikiskaisa</td>
<td>1369</td>
<td>S</td>
<td>Garnetquartzmicashist, containing Disthen and Staurolitt, Amphibolitt and Konglomerate</td>
<td>no rock avalanches</td>
<td>dry rock wall (some small rivers), vegetation growing on cracks</td>
<td>B</td>
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<tr>
<td>Rankonøse</td>
<td>1750</td>
<td>S/SE</td>
<td>Granite</td>
<td>recent rock fall</td>
<td>?</td>
<td>A/B</td>
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<tr>
<td>Raudberget i Stordalen</td>
<td>1188</td>
<td>E</td>
<td>Amfibolitt and Meta-Gabbro</td>
<td>no recent mass movement</td>
<td>much vegetation, water</td>
<td>B</td>
</tr>
<tr>
<td>Location</td>
<td>Altitude</td>
<td>Aspect</td>
<td>Rock Type</td>
<td>Description</td>
<td>Vegetation/Water</td>
<td>Area</td>
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<tr>
<td>Rombakstøtta</td>
<td>1230</td>
<td>N/NE</td>
<td>Garnetglimmergneis or -schist</td>
<td>no recent active rock avalanches</td>
<td>much vegetation, water</td>
<td>C</td>
</tr>
<tr>
<td>Rostafjellet</td>
<td>1590</td>
<td>W</td>
<td>Garnetglimmer, some quartzband</td>
<td>Many rock avalanches in the upper part of the mountain</td>
<td>dry and no vegetation in the higher parts. In the lower part some vegetation can be found</td>
<td>A/B</td>
</tr>
<tr>
<td>Rostakulen</td>
<td>1240</td>
<td>NW</td>
<td>Garnetglimmer, some quartzband</td>
<td>Lose material on top of the mountain</td>
<td>in funnels rock avalanches came down, probably the debris is located on a terrace and we could not spot it</td>
<td>probably a B</td>
</tr>
<tr>
<td>Ruten</td>
<td>1361</td>
<td>N</td>
<td>Glimmerschist and Glimmergneiss</td>
<td>? Debris lying on a terrace, which was not visible from our point of view</td>
<td>in the rock wall no newly created outcrops</td>
<td>probably a B</td>
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<tr>
<td>Rømesfjellet</td>
<td>1255</td>
<td>N</td>
<td>Greenschist</td>
<td>many recent rock falls</td>
<td>dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Røimestind</td>
<td>1041</td>
<td>N</td>
<td>Greenschist</td>
<td>many recent rock falls</td>
<td>dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Skutshødn (Vang)</td>
<td>1600</td>
<td>S</td>
<td>Granite</td>
<td>recent rock fall</td>
<td>?</td>
<td>A/B</td>
</tr>
<tr>
<td>Skørsnøse (Tyinkryset)</td>
<td>1453</td>
<td>S</td>
<td>Granite</td>
<td>recent rock fall</td>
<td>dry (no rivers), no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Stalofjellet</td>
<td>1246</td>
<td>E</td>
<td>Granodioritt</td>
<td>no recent mass movement</td>
<td>wet, vegetation</td>
<td>B</td>
</tr>
<tr>
<td>Steindalstinden</td>
<td></td>
<td></td>
<td>Gabbro</td>
<td>lots of debris in the lower part of the mountain</td>
<td>wet, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Steitinden</td>
<td>920</td>
<td>W</td>
<td>Granite and granodioritt</td>
<td>no recent rock falls</td>
<td>dry, dense vegetation in the lower part</td>
<td>B</td>
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<tr>
<td>Store Smørstabtinden</td>
<td>2200</td>
<td>E</td>
<td>Pyroxene-granulite</td>
<td>no recent rock falls</td>
<td>glacier below the steep rock wall</td>
<td>C</td>
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<tr>
<td>Location</td>
<td>Elevation</td>
<td>Aspect</td>
<td>Rock Type</td>
<td>Mass Movement</td>
<td>Runout Zone and Vegetation</td>
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<tr>
<td>Storfjellet</td>
<td>1395</td>
<td>SW</td>
<td>Glimmerskifre and Glimmergneiss</td>
<td>no recent</td>
<td>dry, vegetation growing on debris and cracks</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mass movement</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>single detached small sized boulders, and debris unin the runout zone.</td>
<td></td>
<td>B</td>
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<tr>
<td>Sørfjelltinden</td>
<td>1468</td>
<td>E</td>
<td>Garnet-Quartzmicaschist</td>
<td>many rock</td>
<td>snow patches, wet, vegetation growing in the lower part</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>avalanches,</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>large debris cones</td>
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<tr>
<td>Tamokfjellet</td>
<td>1342</td>
<td>W</td>
<td>Garnet-Gartsglimmerschist</td>
<td>no recent</td>
<td>wet (rivers), vegetation</td>
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<td></td>
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<td>mass movements</td>
<td></td>
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<tr>
<td>Tverrbythornet</td>
<td>2102</td>
<td>S</td>
<td>Pyroxene-granulite</td>
<td>recent rock</td>
<td>dry, no vegetation</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>falls especially in funnels</td>
<td></td>
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<tr>
<td>Vesleskardtinden</td>
<td>1385</td>
<td>SW</td>
<td>Glimmerschist and Glimmergneiss</td>
<td>no recent</td>
<td>a little wet, no vegetation in the mountain top but below in the runout zone</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mass movement.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A single large sized rock boulder was discovered.</td>
<td></td>
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<tr>
<td>Veslfjellet (Beseggen)</td>
<td>1700</td>
<td>S</td>
<td>Pyroxene-granulite</td>
<td>recent rock</td>
<td>dry, no vegetation</td>
<td></td>
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<tr>
<td></td>
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<td>falls</td>
<td></td>
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<tr>
<td>Jotunheimen RW3 (Galdhøe)</td>
<td>2226</td>
<td>SE</td>
<td>Pyroxene-granulite</td>
<td>rock walls</td>
<td>mostly dry, no vegetation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>surrounded by glaciers and perennial snow patches</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Jotunheimen RW2 (Galdhøe)</td>
<td>2204</td>
<td>E</td>
<td>Pyroxene-granulite</td>
<td>rock walls</td>
<td>mostly dry, no vegetation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>surrounded by glaciers and perennial snow patches</td>
<td>C</td>
<td></td>
</tr>
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<tr>
<td>Location</td>
<td>Range</td>
<td>Elevation</td>
<td>Geology</td>
<td>Recent Mass Movements</td>
<td>Vegetation</td>
<td>Hazard Level</td>
</tr>
<tr>
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<tr>
<td>Polvartinden</td>
<td>N, S</td>
<td>1280</td>
<td>Top: Garnet-Qtartsglimmerschist, lower part: Garnet-Chalkglimmerschist</td>
<td>recent mass movement (rock slide/debris flow Signalalen 2008)</td>
<td>mostly dry, no vegetation</td>
<td>A</td>
</tr>
<tr>
<td>Hurrungane: Austanbotstindane</td>
<td>N, S, W, E</td>
<td>2200</td>
<td>Pyroksengranulit</td>
<td>no mass movements</td>
<td>glacier on all sides</td>
<td>C</td>
</tr>
<tr>
<td>Store Ringstind</td>
<td>N</td>
<td>2124</td>
<td>Pyroksengranulit</td>
<td>no mass movements</td>
<td>glacier on all sides</td>
<td>C</td>
</tr>
<tr>
<td>Hurrungane: Soleibotntindane</td>
<td>E</td>
<td>2083</td>
<td>Pyroksengranulit</td>
<td>no mass movements</td>
<td>glacier on all sides</td>
<td>C</td>
</tr>
<tr>
<td>Tomefjellet (Stryn)</td>
<td></td>
<td>1841</td>
<td>Granit-Orthogneiss</td>
<td>small-scale rock falls, large-scale debris cones</td>
<td>wet, vegetated in the lower part, glaciers</td>
<td>B</td>
</tr>
<tr>
<td>Kjenndalskruna (Stryn)</td>
<td></td>
<td>1777</td>
<td>Granit-Orthogneiss</td>
<td>no recent mass movements</td>
<td>wet, no vegetation</td>
<td>B/C</td>
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Histograms of elevation Region 1

Histograms of elevation Region 2

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Histograms of elevation Region 3

<table>
<thead>
<tr>
<th>Region</th>
<th>Frequency Distribution</th>
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<tbody>
<tr>
<td>Sor Trøndelag</td>
<td><img src="image1" alt="Histogram of Sor Trøndelag" /></td>
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<tr>
<td>Nord Trøndelag</td>
<td><img src="image2" alt="Histogram of Nord Trøndelag" /></td>
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Histograms of elevation Region 4

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<th>Region</th>
<th>Frequency Distribution</th>
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<tr>
<td>Troms</td>
<td><img src="image3" alt="Histogram of Troms" /></td>
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<tr>
<td>Nordland</td>
<td><img src="image4" alt="Histogram of Nordland" /></td>
</tr>
<tr>
<td>Finnmark</td>
<td><img src="image5" alt="Histogram of Finnmark" /></td>
</tr>
</tbody>
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Histogramms of aspect Region 1

Histogramms of aspect Region 2