Permafrost in Iceland: Thermal State and Climate Change Impact

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Abstract

This paper provides an overview of distribution and thermal characteristics of mountain permafrost in Iceland. Borehole temperature monitoring since summer 2004 and simple distribution modeling suggest widespread mountain permafrost in Iceland above 800 to 900 m a.s.l. The permafrost temperatures are close to 0ºC and some tens of meters thick in the elevation range of 800 to 1000 m a.s.l. At that elevation, the permafrost distribution is mainly governed by the distribution of snow, while above 1200 m a.s.l. smaller areas of continuous permafrost do exist. This presentation presents new borehole temperature data that have been collected until the summer 2007 and associated numerical modeling of snow influence on ground temperatures.

Keywords: ground temperatures; Iceland; modeling; permafrost.

Introduction

Within the context of climate-permafrost relationships in the North Atlantic region, Iceland represents a link between Scandinavia and Greenland. The regional distribution of permafrost in Iceland has been addressed by means of gridded mean annual air temperatures (MAAT) for the 1961–1990 period interpolated from point meteorological data (Etzelmüller et al. 2007) (Fig. 1). Etzelmüller et al. (2007) showed that MAAT~-3ºC gives an indication of the lower limit of widespread permafrost in Iceland, not regarding snow conditions or topographic aspect variability. Figure 1 suggests the presence of widespread mountain permafrost outside the already known sporadic permafrost zone in central Iceland. The lower limit increases in elevation towards the southeast, with elevations between 800 m a.s.l. in the north and more than 1000 a.s.l. in the southern part of Iceland. Permafrost is also predicted on the highest mountain peak areas along the southeastern coast above c. 900 m a.s.l. This paper presents new data series and modeling exercises to elaborate the influence of surface temperature and snow variation on permafrost temperatures in Iceland.

Setting

Iceland is located where the asthenospheric flow under the Mid-Atlantic Ridge interacts and mixes with a deep-seated mantle plume (Shen et al. 1998, Wolfe et al. 1997). This implies generally high geothermal heat fluxes due to heat conduction from the partly molten layer at approximately 10°-km depth (Flóvenz & Sæmundsson 1993). Iceland is characterized by maritime conditions with cool summers and mild winters. In the lowland areas, the MAAT for the 1961–1990 period was 4°–5°C in southern parts, 3°–4°C in the eastern and western parts, and 2°–3°C in northern, coastal parts of the country (Tveito et al. 2000). A large part of the precipitation falls with winds prevailing from eastern and southern directions (Einarsson 1984). Thus, mean annual precipitation increases from above 500 mm in the central and northern parts of the country to more than 3000 mm in the southeast.

In four boreholes, ground temperatures were monitored since 2004 (Farbrot et al. 2007) (Fig. 1). They are located in central and northeastern Iceland at ~890–930 m a.s.l. All boreholes are relatively shallow (12–22 m deep), penetrating through a shallow sediment cover into basaltic bedrock. All sites are on elevated plateaus, and significant slopes are more than 100 m away from the boreholes. The sites are not vegetated and are exposed to wind drift of snow.

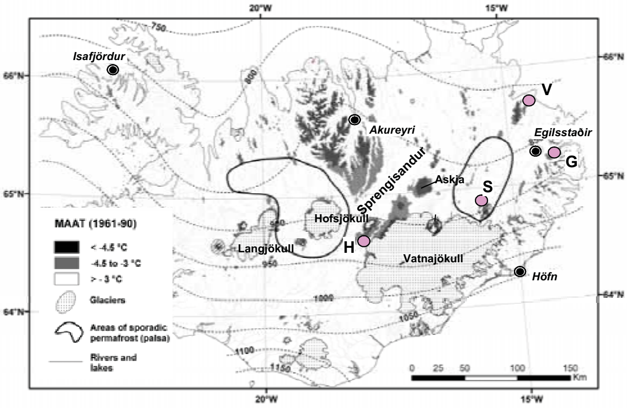

Figure 1: Key map and permafrost map of Iceland (based on Etzelmüller et al. 2007). G=Gagnheiði; S=Snæfell; V=Vopnafjörður; H=Hágöngur. The dotted contour lines indicate the lower limit of permafrost based on the distribution of MAAT~-3ºC.

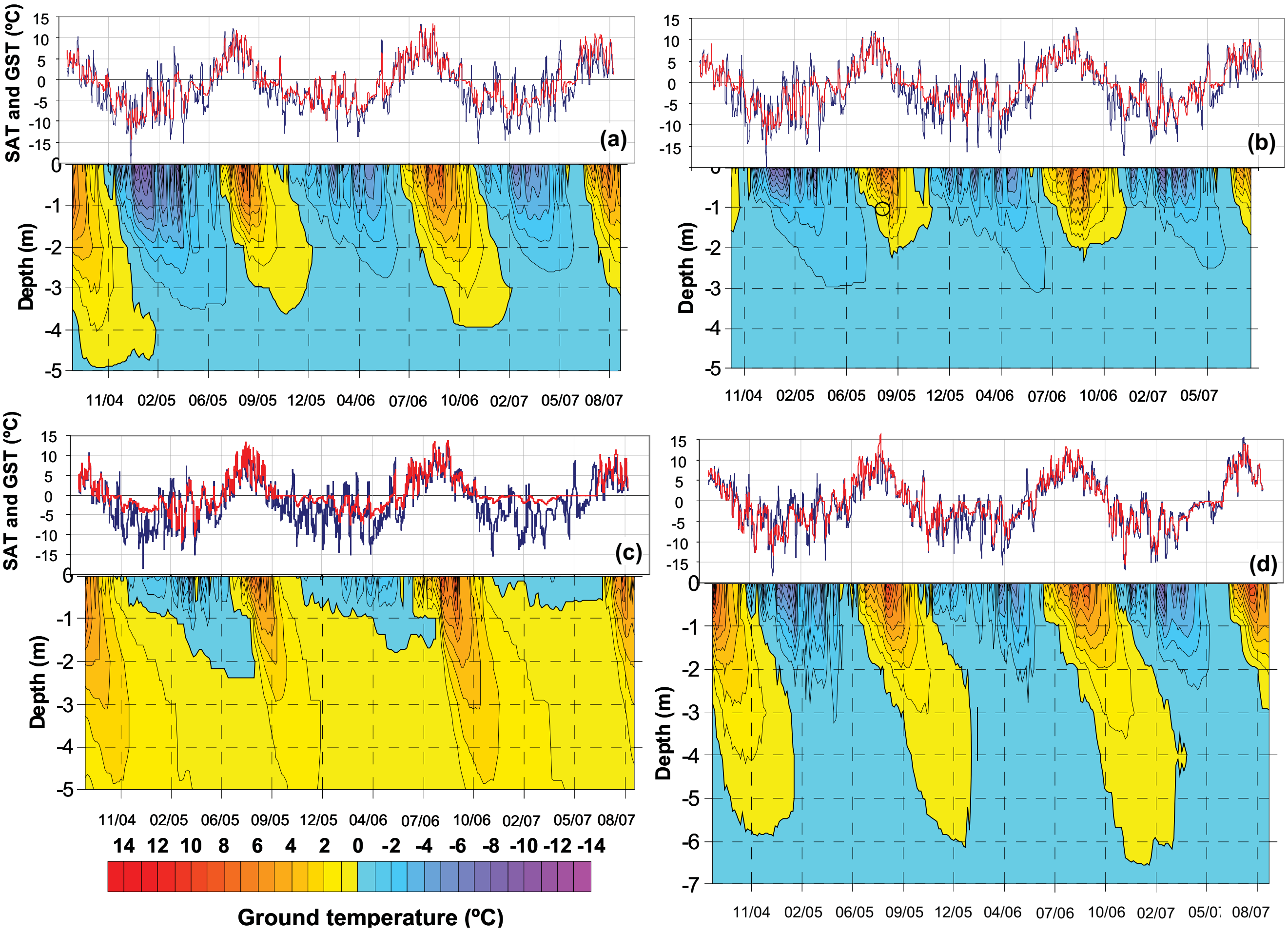

Figure 2: Depth-time series for air, surface, and ground temperatures at the four monitoring stations. The upper graph show SAT (surface air temperature) (blue) and GST (ground surface temperature) (Red) during the measurement period (August 2004 to August 2007). The lower diagram shows an interpolated depth-time series of ground temperatures. The contour interval is 1ºC, (**a**) Gagnheiði, (**b**) Snæfell, (**c**) Vopnafjörður, and (**d**) Hágöngur.

Methods and Results

Temperature monitoring and analysis

Instrumentation: All boreholes were initially equipped with UTL-1 miniature temperature dataloggers (MTDs) having an accuracy of ±0.27°C or better (cf., Hoelzle et al. 1999). In August 2005, the boreholes at Snæfell and Gagnheiði were equipped with thermistor chains consisting of 26 and 15 YSI S40006 thermistors, respectively. These thermistors have an absolute accuracy of ±0.05°C (Vonder Mühll 1992). Close to each borehole, single MTDs, measuring at intervals of 2 hours, were installed near the ground surface (i.e., at 1–5-cm depth) to record ground surface temperature (GST) and in radiation shields 1.5 m above ground to measure surface air temperatures (SAT). At Gagnheiði, the SAT from the meteorological station was used. Minor data gaps existed for air temperature measurements, which were filled in using linear regression to one of the other stations, usually with a $R^2>0.95$. More details of borehole location and characteristics are given in Farbrot et al. (2007).

Calculations: A set of parameters is calculated, representing an average over the three seasons reaching from September 1 to August 31 (Table 1). The frost number for air (F) and ground surface ($F+$) are calculated following Nelson and Outcalt (1987):

$$F = \sqrt{DDF_a} / \left(\sqrt{DDF_a} + \sqrt{DDT_a}\right) \quad (1)$$

and

$$F_+ = \sqrt{DDF_s} / \left(\sqrt{DDF_s} + \sqrt{DDT_s}\right) \quad (2)$$

where DDF are freezing degree days, DDT are thawing degree days and the indexes a and s refer to air and surface, respectively. The n-factors simply follow the equation

$$n_T = DDT_s / DDT_a \text{ and } n_F = DDF_s / DDF_a$$

for the freezing factor n_F and the thawing factor n_T, respectively, $TTOP$ (top of permafrost) temperatures are estimated following, for example, Smith & Riseborough (2002):

$$TTOP = (r_K * n_T * DDT_a - n_F * DDF_a) / P \qquad (3)$$

where P is the period (365 days) and r_K is the quotient between thermal conductivity of soil in thawed and frozen state, respectively. Values of thermal conductivity are taken from literature, with values varying between 1.7 and 1.9 $Wm^{-2}K^{-1}$ (Flóvenz & Sæmundsson 1993).

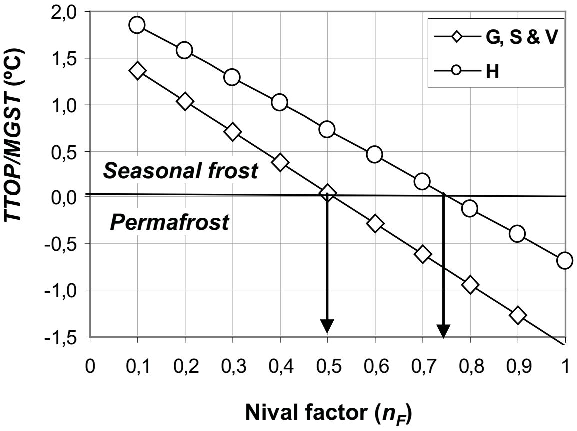

Figure 3: Modeled *TTOP* as a function of n_F, *G, S,* and *V* stands for Gagnheiði, Snæfell, and Vopnafjörður, respectively. For the three stations, it is assumed *DDF=1200* and *DDT=620* according to the last three seasons average (*MAT=-1.6ºC*), *H* stands for Hágöngur, assuming *DDF=1030* and *DD=780* (*MAT=-0.7ºC*), $r_K=1$ and $n_T=1$, as calculated from temperature measurements at the permafrost stations.

Results: The three records from Gagnheiði, Snæfell, and Vopnafjörður are highly correlated with respect to air temperatures with similar annual pattern, and have corresponding DDF_a and DDT_a values. Snæfell is slightly warmer than the two other stations (Table 1). However, ground temperatures are dissimilar (Fig. 2). The Vopnafjörður borehole has no permafrost and only shallow seasonal frost. The two others have permafrost, with *TTOP* temperatures above -0.5ºC. The active layer thickness was higher at Gagnheiði (3.5–4.5 m) than on Snæfell (~2 m), despite higher GST and SAT at the Snæfell station. This is due to higher water content at Snæfell, as discussed in Farbrot et al. (2007). The SAT at the Hágöngur station was slightly higher than the three others (0.7° to 0.8ºC); however, marginal permafrost is present, with an active layer thickness of ~5 m.

It is obvious that permafrost existence and temperatures are highly related to the snow cover at the stations. At the Vopnafjörður station the n_F-factor was at 0.5 or below, while all other stations showed n_F-values >0.7, up to >0.9 (Hágöngur station). We have no recordings of snow cover thickness. All sites are wind-exposed, and thick snow accumulations are unlikely. According to Smith & Riseborough (2002) the obtained nival factors correspond to average snow depths of below 0.2 m, which is in accordance to winter observations at the field stations. No stations show persistent <0ºC winter temperatures, but numerous events of melting episodes throughout the season (Fig. 2). This has two effects: First, snow cover becomes isothermal even with low thicknesses because of latent heat release during refreezing, leading to lower n_F-factors. Second, snow cover decreases and occasionally disappears during these episodes, allowing

Table 1: Summary of temperature recordings at the four measurement stations calculated over three seasons. *SAT*= Mean surface air temperature. *GST* = mean ground surface temperature. *DDF* = freezing degree days. *DDT* = thawing degree days for air and surface (index *a* and *s*). n_T = thawing n-factor. n_F = freezing (nival) n-factor. *F* and *F+* are the frost number for air and surface. respectively. *TTOP* is *measured* mean temperature at the top of permafrost or the bottom of seasonal freezing.

Location	Period	SAT	GST	DDF_a	DDT_a	DDF_s	DDT_s	n_T	n_F	F	F+	TTOP
Vopna	2004/05	-1.7	0.1	1261.2	627.7	629.7	663.2	1.06	0.50	0.59	0.50	1.0
Vopna	2005/06	-1.6	0.4	1225.9	638.6	500.2	648.1	1.01	0.41	0.58	0.47	0.8
Vopna	2006/07	-1.4	1.1	1099.6	601.4	153.7	545.0	0.91	0.14	0.57	0.34	1.1
3-years average		***-1.6***	***0.5***	***1195.6***	***622.6***	***427.9***	***618.8***	***0.99***	***0.35***	***0.58***	***0.44***	***1.0***
Hágöng	2004/05	-0.6	-0.3	941.0	727.4	927.0	834.0	1.15	0.99	0.53	0.53	-0.2
Hágöng	2005/06	-1.1	-0.1	1109.5	706.4	784.0	751.9	1.06	0.71	0.56	0.51	-0.2
Hágöng	2006/07	-0.3	-0.1	1018.7	894.2	890.6	841.4	0.94	0.87	0.52	0.50	-0.1
3-years average		***-0.7***	***-0.2***	***1023.0***	***776.0***	***867.2***	***809.1***	***1.05***	***0.86***	***0.53***	***0.51***	***-0.2***
Gagn	2004/05	-1.6	-1.4	1164.9	601.8	1060.2	549.3	0.91	0.91	0.58	0.57	-0.15
Gagn	2005/06	-1.9	-0.9	1238.9	620.0	933.0	593.1	0.96	0.75	0.59	0.55	-0.15
Gagn	2006/07	-1.5	-0.5	1135.4	599.3	829.9	659.0	1.10	0.73	0.58	0.54	-0.1
3-years average		***-1.6***	***-0.9***	***1179.7***	***607.0***	***941.0***	***600.5***	***0.99***	***0.80***	***0.58***	***0.55***	***-0.1***
Snæfell	2004/05	-1.5	-0.9	1232.1	690.9	952.1	622.3	0.90	0.77	0.57	0.54	
Snæfell	2005/06	-1.6	-0.8	1252.9	655.9	870.7	570.5	0.87	0.69	0.58	0.54	-0.55
Snæfell	2006/07	-1.4	-0.5	1112.9	591.8	826.9	628.1	1.06	0.74	0.58	0.54	-0.55
3-years average		***-1.5***	***-0.8***	***1199.3***	***646.2***	***883.2***	***607.0***	***0.94***	***0.74***	***0.58***	***0.54***	***-0.55***

subsequent cold penetration, resulting in higher n_F-factors. This is especially obvious at the Vopnafjörður station, where deep seasonal frost could develop late in the 2004/05 season after a strong melting episode. The Hágöngur station showed less strong melting episodes. At the Vopnafjörður station, temperature decreases with depth with values <0.4ºC at -20 m. This indicates possibly relic permafrost below 25 m or so (cf. Etzelmüller et al. 2007, Farbrot et al. 2007).

Simple TTOP modeling following Equations (1) and (2) indicate that at the three stations of Vopnafjörður, Gagnheiði, and Snæfell, permafrost persists above a nival factor of n_F >0.5, while the Hágöngur station would produce positive "TTOP" with n_F-factors <0.75 (Fig. 3), showing virtually no snow during the winter season. Etzelmüller et al. (2007) proposed a limit of *MAAT=-3ºC* (normal period 1961–1990) for the lower limit of widespread permafrost in Iceland and Scandinavia. Theoretical considerations based on the TTOP model indicate a minimum n_F-factor of ~0.3 for TTOP <0 and MAAT=-3ºC. Since temperatures during the normal period 1961–1990 were about 1º to 2ºC lower than during our study (Farbrot et al. 2007), the Vopnafjörður station possibly had permafrost during at least the major part of the last century. Measured TTOP temperatures were lowest on Snæfell, which seems to have the most stable permafrost (Table 1). The two other permafrost stations show TTOP-temperatures very close to 0ºC, and seem to be in a stage of degrading. When modeling TTOP temperatures according to Equation (3), the r_K values are close to unity, indicating mostly similar TTOP than GST. This is possibly because of water advection and the influence of unfrozen water content close to 0ºC.

Modeling of ground temperatures

To investigate the sensitivity of ground temperatures to changes in snow coverage, we employ a numerical 1-D heat conduction model. We use an n-factor approach to derive GST from SAT and change the values of n to represent situations of different snow coverage. Based on the results, we discuss possible changes that may have led to the recent deterioration of permafrost at Vopnafjörður

Heat-conduction modeling principles: A numerical 1-D model of heat conduction is used, which accounts for latent heat and is forced by annual, monthly or daily GST input values (cf. Farbrot et al. 2007). The model solves the heat conduction equations following:

$$r\ c\frac{\partial T}{\partial t} = -k\frac{\partial^2 T}{\partial z^2} \tag{4}$$

(e.g., Williams & Smith 1989). As boundary conditions, we prescribe time series of GST and the geothermal heat flux

$$Q_{geo} = -k \cdot {}^{\partial T}\!/_{\partial z} \tag{5}$$

at depth, Q_{geo} was sat to 0 for shallow modeling domains below 30 m. Values for Q_{geo} were obtained from Flóvenz & Sæmundsson (1993), and must be regarded as regionally applicable values rather than local estimates. The thermal properties of the ground are described in terms of density ρ, thermal conductivity *k* and heat capacity *c*. Typical values for Icelandic basalt were derived from the literature (Flóvenz & Sæmundsson, 1993). In our model, we consider the change of latent heat *L* due to phase changes of the pore water by describing a temperature-dependent heat capacity $c_{(T).}$ In a small temperature interval between T_1 (-0.1ºC) and T_2 (0ºC) around the freezing temperature, we add the effect of latent heat release to the heat capacity of the substrate c_0 (e.g., Wegmann et al. 1998).

$$c_{(T)} = c_0 + \frac{L}{(T_2 - T_1)} \tag{6}$$

Any effects of heat advection related to groundwater flow are neglected in this study. The heat conduction equation (Equation [4]) was discretized along the borehole depth using finite differences, and subsequently solved by applying the method of lines (Schiesser 1991).

Calibration run: For this study, the study sites of Vopnafjörður (no permfrost) and Gagnheiði (warm and shallow permafrost) were selected. The model was calibrated using measured ground temperatures, and the values of *w* (volumetric water content) and *k* were adjusted to match modeled and measured temperature distributions, annual amplitudes at a given depth, and modeled and measured thicknesses of the active layer (Fig. 4). Generally, the fit revealed R^2-values of >0.9. The model performance was lower during spring and fall, most probably due to advective processes which are not accounted for, or deficits of the modeling approach because of lacking prescription of important processes. Values for material properties are taken from literature. The calibration indicates relatively dry

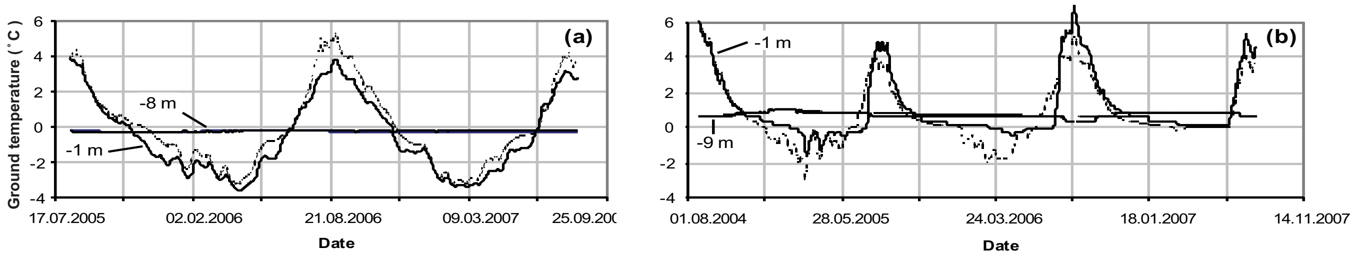

Figure 4: Examples of fit for modeled and measured ground temperatures in depth (8 and 9 m) and close to the surface (1 m). (a) Gagnheiði, (b) Vopnafjörður. Solid line is "modeled"; dashed line is "measured."

conditions at both sites, with volumetric water contents of below 5% (Farbrot et al. 2007).

Simulation run: To investigate the sensitivity of ground temperatures to changes in snow coverage, we use an n-factor linking GST to SAT and change the values of n_F to represent different situations. We prescribe SAT as a sinusoidal variation of specified amplitude around a specified annual mean temperature. Winter temperatures (defined as <0ºC) were damped using the n_F-factor.

Snow cover effect was simulated by changing n_F-factors, and SAT varies around a mean of *-1.6ºC* with amplitude of *9ºC* (Table 2). The n_F-factor was kept constant throughout the winter. For the Gagnheiði station, stable snow cover corresponding to n_F-factors <0.5 will lead to an almost instantaneous development of taliks. A smaller influence of snow coverage ($n_F>0.5$) is conserving the permafrost situation at Gagnheiði. This corresponds well with the TTOP analysis described previously, even if the TTOP approach produces errors especially close to 0ºC (Riseborough 2007). The same is valid for the Vopnafjörður station. Here, further warming of the ground is continued with $n_F<0.3$, while $n_F=0.4$ *to 0.6* results in a situation with no or very limited ground temperature trends, even after *40 years* of model run. This indicates that the measured n_F-factor (0.14) for the 2006/07 season at Vopnafjörður (Table 1) was exceptionally low. With $n_F=0.7$ permafrost aggregates after 7 years of model run. This is also in rough correspondence to Figure 3

In a second simulation, we evaluated the impact of changing SAT on ground temperatures, assuming a constant snow cover like that observed during the three years of recent monitoring. We introduced a step change of ~1ºC warming for Gagnheiði ($n_F=0.7$, *MAT=-0.6ºC)* and cooling for Vopnafjörður station ($n_F=0.45$, *-2.8ºC)*. For the Gagnheiði station, a talik appears after c. 8 years, and permafrost is degraded within 50 years. This is roughly in accordance to the analysis shown in Farbrot et al. (2007). For the Vopnafjörður station the model produces permafrost after c. *15 a* with instant cooling to *-2.8 ºC* and a $n_F=0.45$. The air temperature value corresponds roughly to MAAT during the last normal period 1961–1990 in eastern Iceland close to 900 m a.s.l. After 50 years, permafrost is modeled to be approximately 10 m thick. This clearly demonstrates that permafrost at Vopnafjörður most probably has been degrading during the last decades, and that there might still be relic permafrost. It seems certain that the site had permafrost conditions during the Little Ice Age, since there is plenty of geomorphological evidence, such as rock-glaciers and well-developed patterned ground features.

Table 2: Simulation for varying snow conditions. The model was forced with a sinusoidal curve, with MAT of -1.6ºC and air temperature amplitude of 9ºC. AL=active layer depth; SF=seasonal frost depth after 20 years; GT=ground temperature; T=Tallilk, PF=permafrost. The initial ground temperatures were sat to the measured temperatures from 1.6.2007.

	Gagnheiði		**Vopnafjörður**			
n_F	GT response	AL (m)	GT response	SF (m)	AL (m)	PF thick after 20 a
0.1	T > 1 a		Warming	< 1.5		
0.2	T > 1 a		Warming	< 2		
0.3	T > 2 a		Warming	< 2.5		
0.4	T > 3 a		Stable (no PF)	< 3		
0.5	T > 12 a		Stable (no PF)	< 3.5		
0.6	Stable	> 5	Stable (no PF after 40 a)	< 4		
0.7	Stable	> 3.8	PF > 7 a		4.5	7 m
0.8	Stable	> 3.6	PF > 4 a		4	8 m
0.9	Stable	> 3.4	PF > 3 a		3.5	10 m

Summary and Conclusions

A three-year monitoring series of air and ground temperatures is presented for four permafrost stations in Iceland. Permafrost is warm, and in a degrading stage at two stations. At one, permafrost is absent, and this study indicates that permafrost may have existed at this station during some part of the last century. Snow is the decisive factor for permafrost distribution in elevation ranges between 800 m and 1000 m a.s.l. in Iceland, which corresponds to MAAT during the last normal (1961–1990) period of around *-3ºC*. A $n_F>0.6$ seems necessary to keep permafrost stable in the elevation ranges below 1000 m a.s.l. in Iceland. The study demonstrates the sensitivity of ground temperatures to small changes in air temperatures and snow cover in the maritime mountains of Iceland. As ground temperatures are major decisive factors for understanding a suite of geomorphological processes, the understanding of the impact of expected climate warming on this environment is crucial.

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