Author's response to the reviewers' comments:

We would like to thank Referee #1 for the constructive comments and suggestions that helped improving our manuscript.

We will address the comments point-by-point where **referee comments are in bold**, our answers are without formatting, and *changes to the initial manuscript are in Italics*.

Pg 6662, line 24 – what means in this paper: ground temperatures (MAGT) -> in

which depth please define! MAGT is here defined as the depth at top of the permafrost or at the bottom of the seasonal freezing layer. However, at page 6662 and line 24 we refer to the temperatures at the ground surface. Since this was not clear, the following revision is made for clarification:

Page 6662, line 24: This small-scale pattern of varying snow depths results in highly variable ground *surface* temperatures on the meter scale.

Page 6667, line 17: MAGT (Mean Annual Ground Temperature *at the top of the permafrost or at the bottom of the seasonal freezing layer*)

Page 6662, line 25: Citations: please add 'eg' because there are hundreds of such studies showing this effect.

The reviewer is correct, and we have included *e.g.* before "Gisnås et al., 2014; Gubler et al., 2011", as suggested.

Page 6663, Line 12: The effect of sub-grid variation is not only important in high latitudes but also in high altitudes. Please add.

The sentence is revised as suggested: At high latitudes and altitudes,...

Page 6663, Line 17: I would suggest to write this sentence in a more general sense, because accumulation season can be very different in different latitudes and under different climate conditions (eg tropics).

Following the suggested revision from the reviewer, we have deleted "*during accumulation season*". The sentence is now as follows:

The spatial variation of snow is a result of several mechanisms operating on different scales in different environments.

Page 6666, Line 9: ...seven search vectors. Do the authors not mean eight search vectors?

Seven is here the correct number. The upward slope is calculated along search vectors with 5° increments within a 30° window, giving seven search vectors that are averaged to estimate the exposure for this particular wind direction. Thereafter, this is done for eight wind directions, and then weighted. This was maybe not entirely clear in the manuscript, and to clarify we have added one sentence after the sentence on page 6666, line 7 - 8:

This gives in total seven search vectors for each of the eight 30° wide sectors.

Page 6666, Line 21: accumulation season January to March. Is this justified for whole Norway?

On average more than 60% of the solid precipitation in Norway falls in the months January, February and March, with some variations between the regions. The calculations in this paper, however, aim to estimate the general distribution pattern at snow maximum, under the

assumption that the snow distribution at this point is mainly controlled by the topography and general exposure to main wind directions over the winter season. We realize that the sentence "The accumulation season is here chosen as January to March" is imprecise, and should be reformulated. We have now changed the sentence into: "The period of wind directions influencing the redistribution of snow is here chosen as January to March."

Page 6666, Line 22: What is about wet snow? Insert please a short reasoning why you do not discuss wet snow deposition. Humidity, temperature and radiation conditions can influence the deposition of snow and the possibility of snow transport considerably (eg wet or dry snow deposition or formation of 'firnspiegel' in spring preventing further redistribution of snow).

This is absolutely true. Minor transport will of course occur when the snow is wet, compared to when the snow is dry. However, we do not model the snow transport, but estimate how a given terrain would be filled up by snow during the winter season. Field observations show that in mountainous areas the snow cover reaches an "equilibrium level" over the terrain where irregularities are smoothed out. The snow distribution does therefore highly depend on the topography and main wind the directions while snow was available for transport. In this modelling exercise we assume that the snow distribution at the time of maximum snow depth is still mainly controlled by the terrain and the main wind directions over the winter season.

For clarification we include the following sentence on page 6666, line 22:

We assume that the snow distribution at snow maximum is highly controlled by the terrain and the general wind exposure over the winter season, and we do not account for the variation in snow properties over the season that controls how much snow is available for transport at a given time.

Page 6667, Line 6-13: This approach is not really physically-based and therefore in strong contrast to the other used approaches, where the authors try to be as physically based as possible?

This is true. The authors acknowledge this fact and have tested more physically-based approaches over smaller areas. However, such models have shown not to be applicable over regional scales, both due to the need for calibration and the requirement for fine resolved input data. The aim of this study is to improve the previous implementations of very coarsely resolved distributions of CV used in some hydrological studies (see p. 6663 l. 17 – 30), and assess the effect of implementing this method in permafrost models. To clarify: we include the following sentence at page 6663, line 20:

Physically-based snow distribution models are useful over smaller areas, but are not applicable on a regional scale.

Page 6668, Line 1: What means thermal conductivities if you have also convective transport of water and air? Please specify or better use another expression like 'apparent thermal conductivities', which you have to define beforehand!

For this study looking only at annual averages and equilibrium situations over several years we assume that the energy transfer within the ground is purely controlled by thermal conduction.

We clarify this in the paper with the following revision on page 6668, Line 1:

"..., rk is the ratio of thermal conductivities of the ground in thawed and frozen states (assuming that heat transfer in the ground is entirely governed by heat conduction), while nT

and nF are semiempirical transfer-functions including a variety of processes in one single variable (see Gisnås et al., 2013, Westermann et al., 20(Gisnås et al., 2013; Westermann et al., 2015)15 for details)."

Page 6669, Line 12: MAGT means always the temperature at the top of permafrost?

Yes. The following sentence is corrected for clarification:

Page 6667, line 17: MAGT (Mean Annual Ground Temperature *at the top of the permafrost or at the bottom of the seasonal freezing layer*)

Page 6669, Line 21: à instead of á

á is removed, see comment from referee #2.

Page 6670, line 11: you mean that the logger measures really the surface temperatures? Please be more precise and define depth of temperature sensors.

The following revision is made for clarification:

...data loggers have measured the distribution of ground surface temperatures at 2 cm depth...

Page 6676, line 5-8: A table would be more clear.

The text is now partly revised, and the following table is included:

"The observed and modelled range in MAGST was [-1.8 °C, 1.0 °C] and [-2.6 °C, 0.8 °C] at Juvvasshøe, and at Finse [-1.9 °C, 2.7 °C] and [-1.6 °C, 1.0 °C]. The average MAGSTs are - 0.5/-0.5/0.8 °C (Juvvasshøe) and 0.8/0.2/1.3 °C (Finse) for observations, the sub-grid model and the model without sub-grid temperatures, respectively" is changed into:

"The measured ranges of MAGST within the 1 km x 1 km areas were relatively well reproduced by the model (Table 3). The average MAGST within each field area was also improved compared to a model without a sub-grid representation of snow (Table 3, in parenthesis)."

Table 3: Observed and modelled values for the coefficient of variation for maximum snow depth (CV_{sd}) and spatial distributions of Mean Annual Ground Surface Temperatures (MAGST) at the field sites at Finse and Juvvasshøe. The MAGST modelled without a sub-grid distribution of snow is given in parenthesis.

	Juv	vasshøe	Finse		
	Observed	Modelled	Observed	Modelled	
CV _{sd}	0.85	0.80	0.71	0.77	
MAGST < 0 °C	77 %	64 %	30 %	32 %	
	-1.8 °C	-2.6 °C	-1.9 °C	-1.6 °C	
MAGST _{max}	1.0 °C	0.8 °C	2.7 °C	1.0 °C	
MAGSTavg	-0.5 °C	-0.5 °C (0.8 °C)	0.8 °C	0.2 °C (1.3 °C)	

Page 6678, line 4: This depends strongly from the snow and the surface processes if snow can blown away easily or not (see already comment above)! This approach should then be probably more process-based.

The authors agree with this comment, and we are aware that this snow distribution scheme is a simplification in order to be able to implement sub-grid distribution on a regional scale. However, as we have shown, the snow distribution in wind exposed mountain areas are highly dependent on the topography, and even with differences in the snow pack and weather systems between the winter seasons, the snow distribution at snow maximum is fairly similar. We therefore believe it is valid to assume that wind exposed areas with rough topography also will have bare blown areas with a changing climate.

Page 6679, line 15: ...and of course the roughness of the surface eg coarse material.

This is true. The meaning was a 0.5 - 1 m thick snow cover over the entire ground surface (also including blocks). However, we see that this was not clear, and included the following clarification (in italics):

"depending on the physical properties of the snow pack *and the surface roughness* (e.g. Haeberli)."

Reply to Referee #2's comments.

MAIN COMMENTS

1. Section **3.1**: is the subgrid distribution of snow depth conservative of the original coarse observation?

The sub-grid distribution is derived from the CV and the mean snow depth (which is the original coarse observation). The snow depth is therefore conserved. For clarification we include the following sentence at page 6669, line 6:

The average maximum snow depth corresponds to the coarse scale snow observation, and the original coarse scale snow depth is therefore conserved in the sub-grid snow distribution.

2. I think would be useful to have more information about the boreholes that were used. What depth are these boreholes? which depths are used in the analysis? Time periods? (related to point 6 below).

The output of the model is MAGT and MAGST (page 6667 line 15-18), and it is also validated for the same values (page 6670 l. 6-8). For clarification we revise the following sentences:

Page 6667 line 15-18: MAGT is defined as "Mean Annual Ground Temperature *at the top of the permafrost or at the bottom of the seasonal freezing layer*".

Page 6670, 1-8): *For the evaluation runs the model* is forced with climatic data for the hydrological year corresponding to the observations.

Furthermore we have included full table of boreholes with depth and measurement periods in the supplementary material, and refer to it in the text as follows:

Page 6670, line 21: Tables of ground surface temperature loggers (Table S1) and boreholes used for validation (Table S2), are included in the supplementary material.

3. Section 3.2: Due to the great importance of nF/nT on your results, it would be nice to include a short section critical appraising the various pros/cons of such statistical approach in the context of permafrost modelling. A very first thought is how spatial and temporally consistent are these relationships likely to be? Where were they developed? Over what period of time? You of course mention the variability of snow depth as being a large driver in the variability you see in nF/nT (motivation for this paper) but what else is significant?

We have included the following section at page 6668, line 26:

The relationships between n-factors and snow cover in open areas are shown to be consistent within the two sites in southern Norway (Gisnås et al. 2013 and Gisnås et al. 2014). Due to lack of field observations including all required variables at one site in northern Norway, the relation is not tested for this area. However, it fits very well with a detailed study with 107 loggers recording the variation in ground surface temperature at a lowland site in Svalbard (Gisnås et al. 2014). Other factors, such as solar radiation and soil moisture, have minor effects on the small-scale variation in ground surface temperatures in these areas. Gisnås et al (2014) demonstrated that most of the sub-grid variation in ground temperatures within 1x1 km areas in Norway and Svalbard was reproduced by including only the sub-grid variation of snow depths. In other areas other parameters than snow depth might have a larger effect on the ground surface temperatures, and should be accounted for in the derivation of n-factors.

4. Section 3.2: Following on from the point above, you state that the relationship between n factors and snow depth is based on 13 stations in S.Norway and 80 loggers in Finse and Juvvasshoe. This seems to be quite geographically limited. Can you briefly state if/how you might expect these relationships to vary with space, i.e what might they look like in Lyngen or Finnmark?

Compared to the total model domain we agree that these observations are limited. However, compared to the amount of available datasets including systematic measurements of ground surface and air temperatures together with snow depths in the same point location, these datasets are quite unique on global basis. The relationships for *n*-factors in vegetated areas will vary within different species, and this is not discussed here. However, because permafrost is not present in vegetated areas in Norway, we have not focused on the variation within these surface classes. The variation in the relation between *n*-factors and snow depth is not examined in northern Norway because we lack detailed field observations in this area. However, the dataset from Ny-Ålesund, which includes 107 loggers in a 1x1 km area, shows very similar dependencies as the data from southern Norway, even though this site is a lowland site (20 - 40 m a.s.l.) with higher soil moisture and finer sediments.

We have included some comments on this in the section at page 6668, line 26, described in the previous point:

The relationships between n-factors and snow cover in open areas are shown to be consistent within the two sites in southern Norway (Gisnås et al. 2013 and Gisnås et al. 2014). Due to lack of field observations including all required variables at one site in northern Norway, the relation is not tested for this area. However, it fits very well with a detailed study with 107 loggers recording the variation in ground surface temperature at a lowland site in Svalbard (Gisnås et al. 2014). Other factors, such as solar radiation and soil moisture, have minor effects on the small-scale variation in ground surface temperatures in these areas. Gisnås et al (2014) demonstrated that most of the sub-grid variation in ground temperatures within 1x1 km areas in Norway and Svalbard was reproduced by including only the sub-grid variation of snow depths. In other areas other parameters than snow depth might have a larger effect on the ground surface temperatures, and should be accounted for in the derivation of n-factors.

5. P.6678, l.6-10: You mention the question of equilibrium with surface forcing on climatic scales, but how about seasonal lags ie. its quite typical to see max. Temperatures at 10m or so at around beginning of winter when summer forcing has been conducted to depth. Therefore to compare model and obs (even assuming you describe conductivities perfectly) you need to drive your model with at least 6months previous atmosphere to get the warming/cooling signal of that time slice. This could have an impact on your model performance, especially if there is an extreme season (dry, warm etc) missed in the simulation. Maybe I miss something here, but that brings me to the following point....

The reviewer makes a valid point. However, since we used field data distributed over larger areas and over longer time periods including all kinds of situations, the effect would mainly show in terms of a larger statistical spread, and not a systematic error. Using data from six months before is not good either, since this will vary quite a bit depending on the ground thermal properties of each single site.

This is already partly commented on in the current manuscript p. 6678, line 15 - 20: "For the model evaluation with measured ground temperatures in boreholes (Sect. 5.4), the modelled temperatures are forced with data for the hydrological year corresponding to the observations. Because of the assumption of an equilibrium situation in the model approach, such a comparison can be problematic as many of the boreholes have undergone warming during the past decades. However, with the majority of the boreholes located in bedrock or coarse

moraine material with relatively high conductivity, the lag in the climate signal is relatively small at the depth of the top of permafrost."

We include the following sentence after this section (Page 6678, line 21) to make this point clearer:

The lag will also vary from borehole to borehole, depending on the ground thermal properties. Since we use data distributed over larger areas and longer time periods, including a large range of situations, the effect mainly shows in terms of a larger statistical spread and not a systematic error.

6. In general you use a large amount of data and have a reasonable complex modell setup with multiple simulations and evaluations against various datasets. At times I felt a little lost on what was being computed, when and how. I think the paper would benefit tremendously from 3 additions: (1) a schematic of the model chain to give a very quick overview of the setup (forcing, permafrost model, wind model, subgrid distribution routine, calibrations and evaluations). (2) A table giving all data used together with details such as time period, depths of boreholes etc. (3) A table describing all your simulations with important information such as simulation period(s) - which I am really missing. To illustrate this I dont know what your MAGT and MAGST are based on? I see 2 date ranges 1961-2013 and 1981-2010 but presumably borehole data and surface loggers are a subset of this. Perhaps there is a better way to summarise but my main point is this paper really needs more synoptic figures/tables to guide the reader through the methods and evaluation.

The output of the model is MAGT and MAGST (page 6667 line 15-18), and it is also validated for the same values (page 6670 l. 6-8) (see comments above).

1) We have included the following schematic overview to clarify the modelling routines:

We refer to the figure on page 6669, Line 12: A schematic of the model chain and the evaluation is shown in Figure 4.

Figure 4: Schematic of the model chain, including input data and calibration and evaluation procedures.



2) This is partly answered in point 2 above. We have included the following for clarification: Page 6667 line 15-18: MAGT is defined as "Mean Annual Ground Temperature *at the top of the permafrost or at the bottom of the seasonal freezing layer*".

Page 6670, 1-8: *For the evaluation runs the model* is forced with climatic data for the hydrological year corresponding to the observations.

We have also included a full table of boreholes and ground surface temperature loggers in the supplementary material, giving the location, depth of boreholes, measurement periods, and vegetation type. We refer to this in the text as follows:

Page 6670, line 21: *Tables of ground surface temperature loggers (Table S1) and boreholes used for validation (Table S2), are included in the supplementary material.*

3) The model is forced with annual thawing and freezing degree days calculated over hydrological years. The main permafrost distribution results are given as an average over the 30-year period 1981 - 2010. For validation with ground surface temperature loggers and boreholes temperatures, the degree days forcing the model are calculated over the same hydrological year as the observation. This will therefore vary, but is not defined in the supplementary material (Table S1 and S2). There are no other periods used. The date range 1961 - 2013 is only the years with available climate forcing. We understand from the comments that this was confusing, but we think that some clarification in the text is better than another table. Instead we have included the tables of ground surface loggers and boreholes in the supplementary material (see point above), and made the following changes in the text:

Page 6670, line 8: *For the evaluation runs the model* is forced with climatic data for the hydrological year corresponding to the observations.

Page 6672, line 10-11: The climatic forcing of the permafrost model is daily gridded air temperature and snow depth data, called the seNorge dataset, provided by the Norwegian Meteorological Institute. (deleted: *for the period* 1961 - 2013)

Page 6672, line 13-14: The dataset, *available for the period 1961 - 2015*, is based on air temperature and precipitation data collected at the official meteorological stations in Norway, interpolated to 1 km x 1 km resolution.

P. 6674, line 18: Included the following sentence: *The main results are given as averages over the 30-year period 1981 - 2010.*

7. P.6672, l.16. What is this 'snow algorithm' - is there a reference?

Yes, a detailed description was published in Saloranta et al. (2012), and it is also partly described in Engeset et al 2004. The following references are moved down from the previous sentence for clarification: (*Engeset et al. 2004; Saloranta, 2012*)

8. I think it is important to mention in the discussion that due to statistical nature inherent in core methods there maybe difficulties in inferring conclusions about future development of permafrost. That's not to say this contribution isn't valuable - just to include some discussion of possible limitations.

We have already discussed this on page 6678 l. 6-22: "CryoGRID1 is a simple modelling scheme delivering a mean annual ground temperature at the top of the permanently frozen ground based on near-surface meteorological variables, under the assumption that the ground thermal regime is in equilibrium with the applied surface forcing. This is a simplification, and the model cannot reproduce the transient evolution of ground temperatures. However, it has proven to capture the regional patterns of permafrost reasonably well (Gisnås et al., 2013; Westermann et al., 2013). Because of the simplicity it is computationally efficient, and suitable for doing test-studies like the one presented in this paper and in similar studies (Westermann et al., 2015).

For the model evaluation with measured ground temperatures in boreholes (Sect. 5.4), the modelled temperatures are forced with data for the hydrological year corresponding to the observations. Because of the assumption of an equilibrium situation in the model approach, such a comparison can be problematic as many of the boreholes have undergone warming during the past decades. However, with the majority of the boreholes located in bedrock or coarse moraine material with relatively high conductivity, the lag in the climate signal is relatively small at the depth of the top of permafrost."

To comment it more explicit we have now added the following sentence on p. 6678, l. 10: ", *and is therefore not suitable for future climate predictions.*"

9. Topography isn't mentioned anywhere in the methods - can air temperature and exposure to solar radiation be important predictors for subgrid variability of permafrost within 1km grids? Particularly in the south? Both variables are reasonably easy to distribute based on terrain parameters. Is there a reason not to do this? If so can you provide some references justifying the omission. I did find this reference (also cited by you in another context) which discuss some of these points (and possibly in the end favours ignoring topography) - but I think this deserves a short discussion:

Isaksen, K., Hauck, C., Gudevang, E., ØdegaÊ rd, R. S. & Sollid, J. L. 2002. Mountain permafrost distribution in Dovrefjell and Jotunheimen, southern Norway, based on BTS and DC resistivity tomography data. Norsk GeograÂO["] sk Tidsskrift–Norwegian Journal of Geography Vol. 56, 122–136. Oslo. ISSN 0029-1951.

Topography is absolutely discussed as the main driver for the snow distribution. But, correctly, this paper only accounts for the variation in snow depths as the driver for the variation of ground temperatures within 1x1 km. The relation between snow cover and surface offset in this study shows that more than 60 % of the variation in *nF* and almost 50 % of the variation in nT is explained by snow depths. The same logger sites were also analyzed with respect to aspect, slope, solar radiation, vegetation and sediment type. With the now four years of data we find that maximum snow depth is the main explaining variable for the spatial variation in both nF and nT at all three field sites. The timing of melt out, or length of summer season, has a significantly higher correlation to maximum snow depth than to solar radiation. Gisnås et al. (2014) show that the observed small-scale distribution in MAGST could to a large degree be explained including only the sub-grid variation in maximum snow depths. It was concluded in Gisnås et al. (2014) that maximum snow depth is the main explaining variable for the spatial variation of ground surface temperatures within 1 x 1 km areas at the three field sites in southern Norway and Svalbard. Based on the study by Gisnås et al. (2014) this paper aims to implement sub-grid snow distribution over larger areas.

This is a fundamental point for this study, and as we realize that this was not entirely clear, we include the following sentence in the introduction at page 6663, line 14:

Gisnås et al., (2014) show that the observed variability in ground surface temperatures within 1 km x 1 km areas is large degree reproduced by only accounting for the variation in maximum snow depths.

We also found that the reference (Gisnås et al. 2013) in the previous sentence is wrong, and it is now corrected to (*Gisnås et al. 2014*).

TECHNICAL POINTS

1. P.6666, l.25: "ALS" is mentioned for the first time without explanation of acronym.

"the ALS" is changed into "an Airborne Laser Scanning (ALS) of snow depths (see Sect. 4.1)

2. P.6669, l.21: accent on "a" is not needed in English.

"a" is deleted.

3. P.6669, l.21: ">4000 grid cells in 70% of the areas" - I didn't understand this sentence, can you make it more clear what you mean? Why do the coarse grids of fixed area (0.5x1km) have varying numbers of 10x10m subgrids?

The sentences have been changed into: Each 0.5 km x 1 km area includes 500 to 5000 grid cells a 10m x 10m, *depending on the area masked out due to lakes or measurement errors. There were* > 4000 grid cells in 70% of the areas.

4. P.6670, l.21: I think "Figure 2" is the wrong reference here.

That's correct. It should be Figure 1, and is now changed.

5. P.6670, l.25: Can you specify "10 m above surface" for the wind variables you use - I think that is whats meant.

Included "above surface"

6. P.6671, l.7: Now use just acronym (see point 1).

Airborne Laser Scanning (ALS) is changed into ALS.

7. P.6671, l.9: ALS data instead of ALS scan? As 'S' already stands for 'scanning'.

This is true. However, we find that "*survey*" is more precise than "*data*" in this sentence. "*Scan*" is therefore changed into "*survey*".

8. P.6671, l.13: 'ASL' -> 'ALS'

Changed as suggested

9. P.6671, l.16:'when' -> 'after'

Changed as suggested

10. P.6671, l.5-6: how was the wind speed scaled with elevation? Linearly?

The wind speeds are from a dataset dynamically downscaled from ERA-40 (see page 6670-6671). The bias-correction is simple, and all wind speeds (regardless of altitude) are increased with 60 % (p. 6671 line 5), which is derived from validation with weather stations in mountainous areas. We are aware that this is a rough approximation, and because of the poor quality, the wind speed data is only used to select the wind events accounted for when calculating the fraction of wind directions. For clarification we made the following change:

Page 6671, l. 5-6: For these areas the forcing dataset has been *linearly increased by 60 %*.

11. P.6671, 7-10: What is the resolution of the raw ALS data?

The survey was done with nominal 1.5 m x 1.5 m ground point spacing. The following is included in line 10, p. 6671:

The ALS survey is made along six transects, each covering a 0.5 km x 80 km area, with nominal 1.5 m x 1.5 m ground point spacing.

12. P.6671, l.22: These elevations seem very similar to me, 1300/1450m - is it really significant as a difference between sites?

"elevation (1300/1450 m a.s.l.)" has been removed.

13. P.6672, l.15: How was this interpolation done?

We have also revised the following sentence for clarification:

The dataset, *available for the period 1961 - 2013*, is based on air temperature and precipitation data collected at the official meteorological stations in Norway, interpolated to 1 km x 1 km resolution *applying Optical Interpolation, as described in Lussana (2010)*.

Lussana, C., Uboldi, F., and Salvati, M. R.: A spatial consistency test for surface observations from mesoscale meteorological networks, Quarterly Journal of the Royal Meteorological Society, 136, 1075-1088, 10.1002/qj.622, 2010.

P.6679, l.1 'sensitivity of the model for' -> 'sensitivity of the model to'

Now changed into "The sensitivity of the CV_{sd}-model to"

14. P.6679, l.8 What was the conclusion of Luce and Tarboton?

They conclude in the paper that "Dimensionless depletion curves depend primarily on the CV and to a lesser extent on the shape of the snow distribution function, and are a generalization of previously presented methods for depletion curve estimation." We refer to this saying: "This result contradicts the conclusions by Luce and Tarboton (2004), suggesting that the parameterization of the distribution function is more important than the choice of distribution model.». For clarification we change *«suggesting»* into *«which suggest»*.

16. Figure 6 caption: typo 'poability'

Changed into "probability"

15. Figure 8: over what time period is the data in this correlation from?

For the validation the model is run for the same periods as the years of observations in the boreholes and ground surface temperature loggers, respectively. See page 6678 l. 15-18. To clarify this point we have now provided an overview of the validation data, including the years of observation at each point as a supplementary table (see previous points).

Supplementary material:

Latitude	Longitude	Elevation (m)	Vegetation type	Start Year	End Year	No. Years
62.543	6.303	92	Forest	2005	2008	3
62.575	6.317	796	Non-vegetated	2005	2006	1
62.297	9.338	1505	Non-vegetated	2001	2007	6
62.296	9.354	1467	Non-vegetated	2001	2004	3
62.264	9.467	1094	Non-vegetated	2002	2007	5
62.247	9.499	1039	Non-vegetated	2002	2007	5
61.522	12.504	541	Forest	2005	2008	3
61.542	12.439	1022	Non-vegetated	2005	2008	3
60.593	7.526	1210	Non-vegetated	2006	2007	1
60.651	7.493	1559	Non-vegetated	2006	2007	1
60.632	7.496	1431	Non-vegetated	2006	2007	1
60.647	7.489	1508	Non-vegetated	2006	2007	1
60.948	8.152	1220	Non-vegetated	2005	2007	2
62.429	11.274	1538	Non-vegetated	2004	2007	3
62.480	11.293	676	Forest	2006	2008	2
62.447	11.261	1251	Non-vegetated	2006	2008	2
61.721	8.401	1065	Non-vegetated	2004	2007	3
61.707	8.403	1307	Non-vegetated	1999	2007	8
61.702	8.395	1391	Non-vegetated	1999	2002	3
61.702	8.394	1410	Non-vegetated	1999	2002	3
61.701	8.393	1430	Non-vegetated	1999	2002	3
61.701	8.393	1447	Non-vegetated	1999	2008	9
61.699	8.391	1480	Non-vegetated	1999	2001	2
61.699	8.390	1492	Non-vegetated	1999	2000	1
61.685	8.376	1767	Non-vegetated	2004	2007	3
61.678	8.369	1893	Non-vegetated	1999	2004	5
61.677	8.369	1893	Non-vegetated	1999	2007	8
61.678	8.369	1893	Non-vegetated	1999	2004	5
61.649	9.012	855	Forest	2005	2008	3
61.401	8.831	1525	Non-vegetated	2005	2007	2
61.555	8.193	1522	Non-vegetated	2005	2007	2
61.556	8.207	1389	Non-vegetated	2005	2007	2
61.552	8.182	1460	Non-vegetated	2006	2007	1
61.547	8.163	1354	Non-vegetated	2006	2007	1
61.532	8.230	1448	Non-vegetated	2006	2007	1
61.538	8.180	1696	Non-vegetated	2006	2007	1
62.099	8.931	607	Forest	2005	2008	3
62.027	8.925	1573	Non-vegetated	2004	2008	4
59.989	10.670	528	Forest	2003	2006	3
59.980	10.683	443	Forest	2004	2008	4
59.980	10.684	435	Forest	2004	2008	4

Table S1: Location, vegetation type and period of measurements of ground surface temperature loggersused for validation.Latitude Longitude Elevation (m) Vegetation type Start Year End Year No. Years

60.232	10.428	196	Forest	2006	2008	2
61.934	11.548	805	Non-vegetated	2002	2003	1
61.931	11.543	868	Non-vegetated	2002	2006	4
61.930	11.542	918	Non-vegetated	2002	2006	4
61.927	11.540	1010	Non-vegetated	2002	2006	4
61.925	11.538	1109	Non-vegetated	2002	2006	4
61.922	11.507	987	Non-vegetated	2002	2006	4
61.926	11.511	1051	Non-vegetated	2002	2006	4
61.919	11.536	1211	Non-vegetated	2002	2006	4
61.929	11.527	1043	Non-vegetated	2002	2003	1
61.929	11.527	1043	Non-vegetated	2002	2006	4
61.902	11.500	1069	Non-vegetated	2004	2005	1
61.892	11.504	1078	Non-vegetated	2004	2005	1
61.926	11.535	1071	Non-vegetated	2004	2005	1
61.926	11.535	1071	Non-vegetated	2004	2005	1
61.908	11.537	1418	Non-vegetated	2004	2005	1
61.908	11.537	1418	Non-vegetated	2004	2007	3
61.929	11.527	1043	Non-vegetated	2005	2007	2
62.134	12.020	906	Shrubs	2002	2006	4
62.135	12.055	1196	Non-vegetated	2002	2006	4
62.140	12.060	1316	Non-vegetated	2002	2003	1
62.137	12.053	1207	Non-vegetated	2002	2006	4
62.138	12.051	1192	Non-vegetated	2002	2006	4
62.137	12.030	1052	Non-vegetated	2002	2006	4
62.140	12.060	1316	Non-vegetated	2004	2007	3
62.141	12.061	1335	Non-vegetated	2005	2007	2
69.942	24.862	508	Non-vegetated	2003	2005	2
69.937	24.854	614	Non-vegetated	2003	2005	2
69.913	24.775	1002	Non-vegetated	2003	2005	2
69.910	24.770	1034	Non-vegetated	2003	2005	2
69.909	24.771	982	Non-vegetated	2003	2005	2
69.933	24.789	471	Non-vegetated	2004	2005	1
69.933	24.792	428	Non-vegetated	2004	2005	1
70.075	20.431	839	Non-vegetated	2003	2006	3
70.063	20.451	476	Non-vegetated	2003	2005	2
69.831	21.279	895	Non-vegetated	2002	2008	6
69.838	21.273	700	Non-vegetated	2002	2007	5
69.843	21.259	500	Non-vegetated	2002	2007	5
69.563	20.433	861	Non-vegetated	2002	2007	5
69.576	20.437	685	Non-vegetated	2002	2005	3
69.583	20.435	500	Non-vegetated	2002	2005	3
69.457	20.882	966	Non-vegetated	2006	2007	1
69.354	21.211	786	Non-vegetated	2004	2007	3
69.267	22.481	739	Non-vegetated	2003	2010	7
69.008	23.235	355	Forest	2003	2010	7
69.980	27.269	130	Forest	2003	2009	6

70.542	29.322	502	Non-vegetated	2002	2009	7
70.541	29.342	480	Non-vegetated	2002	2009	7
70.538	29.363	415	Non-vegetated	2002	2009	7
70.537	29.380	355	Non-vegetated	2002	2009	7
70.400	28.200	10	Shrubs	2008	2010	2
70.126	28.593	50	Mire	2008	2010	2
69.376	24.496	284	Non-vegetated	2008	2010	2
69.370	24.082	469	Non-vegetated	2008	2010	2
69.377	24.082	408	Non-vegetated	2008	2010	2
68.996	23.035	308	Shrubs	2008	2010	2
68.755	23.538	380	Shrubs	2008	2010	2
69.580	23.535	380	Shrubs	2008	2010	2
68.749	19.485	1713	Non-vegetated	2008	2010	2
69.292	18.133	1011	Non-vegetated	2007	2011	4
69.638	22.229	923	Non-vegetated	2007	2010	3
61.676	8.365	1861	Non-vegetated	2008	2010	2
61.684	8.372	1771	Non-vegetated	2008	2010	2
61.700	8.385	1559	Non-vegetated	2008	2010	2
61.698	8.401	1561	Non-vegetated	2008	2010	2
61.707	8.403	1314	Non-vegetated	2008	2010	2
61.701	8.393	1450	Non-vegetated	2008	2010	2
62.174	10.702	1630	Non-vegetated	2008	2009	1
62.170	10.703	1589	Non-vegetated	2008	2010	2
62.151	10.715	1290	Shrubs	2008	2010	2
61.903	9.275	1490	Non-vegetated	2008	2010	2
61.898	9.282	1664	Non-vegetated	2008	2010	2
69.291	18.130	990	Non-vegetated	2007	2009	2
69.249	20.445	766	Non-vegetated	2007	2009	2
69.642	22.194	761	Non-vegetated	2007	2010	3
69.681	22.126	570	Non-vegetated	2007	2010	3
62.149	9.378	1047	Non-vegetated	2005	2006	1
69.308	25.341	450	Shrubs	2008	2011	3
69.306	25.340	495	Shrubs	2008	2010	2
69.304	25.338	548	Shrubs	2008	2011	3
69.299	25.330	540	Shrubs	2008	2011	3
69.296	25.326	497	Shrubs	2008	2011	3
69.294	25.318	445	Shrubs	2008	2011	3
69.290	18.131	990	Non-vegetated	2007	2011	4
69.292	18.129	967	Non-vegetated	2007	2011	4
60.700	10.868	264	Forest	1994	2004	10
67.284	14.451	33	Non-vegetated	1994	2004	10

Borehole	Lat	Lon	Elevation	Depth	08/09	09/10	10/11	11/12	Reference
Abojavri BH1	69 642	22 10/	761	66	v	x	×		Farbrot et al
Abojavii bili	05.042	22.134	701	0.0	^	Λ	^		2013
Abojavri BH2	69.681	22.126	570	30.3	x	х			Farbrot et al. 2013
BH31/PACE31	61.676	8.368	1894	20	х	Х	x	x	Isaksen et al. 2011
Guolosjavri BH1	69.354	21.211	786	32.3		Х	x	х	Farbrot et al. 2013
Guolosjavri BH2	69.366	21.168	814	10.5	x				Farbrot et al. 2013
Guolosjavri BH3	69.356	21.061	780	10.5	х				Farbrot et al. 2013
Iskoras BH2	69.300	25.346	600	58.5		х	х	х	Farbrot et al. 2013
Jetta BH1	61.901	9.285	1560	19.5		Х	х		Farbrot et al. 2011
Jetta BH2	61.902	9.234	1450	10		Х	х		Farbrot et al. 2011
Jetta BH3	61.905	9.186	1218	10		х	х	х	Farbrot et al. 2011
Juvvass BH1	61.676	8.365	1861	10		Х	х	х	Farbrot et al. 2011
Juvvass BH2	61.684	8.372	1771	10		х	х		Farbrot et al. 2011
Juvvass BH3	61.697	8.386	1561	10		Х	x		Farbrot et al. 2011
Juvvass BH4	61.700	8.385	1559	10		х	х	х	Farbrot et al. 2011
Juvvass BH5	61.701	8.392	1468	10		Х	x	х	Farbrot et al. 2011
Juvvass BH5	61.707	8.403	1314	10		Х	х	х	Farbrot et al. 2011
Kistefjellet	69.291	18.130	990	24.8	х				Farbrot et al. 2013
Lavkavagge BH1	69.249	20.445	766	14	x	Х	x	x	Farbrot et al. 2013
Lavkavagge BH2	69.239	20.493	600	30.5	х				Farbrot et al. 2013
Lavkavagge BH3	69.224	20.580	492	15.8	x				Farbrot et al. 2013
Tron BH1	62.174	10.702	1640	30		Х	х	х	Farbrot et al. 2011
Tron BH2	62.170	10.703	1589	10		Х	x	x	Farbrot et al. 2011
Tron BH3	62.151	10.715	1290	10		Х	х	х	Farbrot et al. 2011

Table S2: Boreholes used for validation of the permafrost model. x marks years where data is available.

Small-scale variation of snow in a regional permafrost model

3

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- 9

10 Abstract

11 The strong winds prevalent in high altitude and arctic environments heavily redistribute the 12 snow cover, causing a small-scale pattern of highly variable snow depths. This has profound implications for the ground thermal regime, resulting in highly variable near-surface ground 13 14 temperatures on the meter scale. Asymmetric snow distributions combined with the non-linear 15 insulating effect of snow also mean that the spatial average ground temperature in a 1km² area 16 can not necessarily be determined based on the average snow cover for that area. Land surface 17 or permafrost models employing a coarsely classified average snow depth will therefore not 18 yield a realistic representation of ground temperatures. In this study we employ statistically 19 derived snow distributions within 1km² grid cells as input to a regional permafrost model in 20 order to represent sub-grid variability of ground temperatures. This is shown to improve the 21 representation of both the average and the total range of ground temperatures: The model 22 results show that we reproduce observed sub-grid ground temperature variations of up to 6°C, 23 with 98% of borehole observations within the modelled temperature range. Based on this 24 more faithful representation of ground temperatures, we find the total permafrost area of 25 mainland Norway to be nearly twice as large as what is modelled without a sub-grid 26 approach.

1 **1 Introduction**

2 High altitude and arctic environments are exposed to strong winds and drifting snow can 3 create a small-scale pattern of highly variable snow depths. Seasonal snow cover is a crucial 4 factor for the ground thermal regime in these areas (e.g. Goodrich, 1982; Zhang et al., 2001). 5 This small-scale pattern of varying snow depths results in highly variable ground surface temperatures on the meter scale; up to 6 °C within areas of less than 1 km² (e.g. Gubler et al., 6 7 2011; Gisnås et al., 2014). In general, grid-based numerical land surface and permafrost 8 models operate on scales too coarse to resolve the variability of snow depths, and are not 9 capable of representing such small-scale variability. For the Norwegian mainland, permafrost models have been implemented with a spatial grid resolution of 1 km² (Gisnås et al., 2013; 10 Westermann et al., 2013), and do therefore only represent the larger scale patterns of ground 11 12 temperatures. As a consequence, they usually represent the lower limit of permafrost as a sharp boundary, where the average ground temperature of a grid-cell crosses the freezing 13 14 temperature (0°C). In reality, the lower permafrost boundary is a fuzzy transition. Several local parameters, such as snow cover, solar radiation, vegetation, soil moisture and soil type 15 16 cause a pronounced sub-grid variation of ground temperature. Different approaches have been 17 developed to address this mismatch of scales, such as the TopoSub (Fiddes and Gruber, 18 2012), which accounts for the variability of a range of surface parameters using k-means 19 clustering. At high latitudes and altitudes, one of the principal controls on the variability of ground temperature is the effect of sub-grid variation in snow cover (Langer et al., 2013; 20 21 Gisnås et al., 2014). Gisnås et al. (2014) show that the observed variability in ground surface 22 temperatures within 1 km x 1 km areas is to a large degree reproduced by only accounting for 23 the variation in snow depths. Therefore procedures capable of resolving the small scale 24 variability of snow depths will have the potential to considerably improve the representation 25 of the ground thermal regime.

The spatial variation of snow during accumulation season-is a result of several mechanisms operating on different scales in different environments (Liston et al. 2004). In tundra and alpine areas, wind-affected deposition is the dominant control on the snow distribution at distances below 1 km (Clark et al., 2011). Physically-based snow distribution models are useful over smaller areas, but are not applicable on a regional scale. The coefficient of variation (*CV*), defined as the ratio between the standard deviation and the mean, can be used as a measure of the extent of spread in a distribution. Previous studies suggest that the

coefficient of variation of snow depths (CV_{sd}), typically ranging from low spread at 0.2 to 1 2 high spread at 0.8, is well suited to reflect snow distributions in a range of environments (e.g. Liston, 2004; Winstral and Marks, 2014). Liston (2004) assigned individual values of CV_{sd} to 3 different land use classes in order to address sub-grid variability of snow in land surface 4 5 schemes. According to this scheme, non-forested areas in Norway, as well as most of the permafrost areas in northern Europe ("high-latitude alpine areas"), would have been allocated 6 a CV_{sd} of 0.7. A review of observed CV_{sd} from a large number of snow surveys in the northern 7 8 hemisphere shows a large spread of CV_{sd} values, in particular within this land use class, 9 ranging from 0.1 to 0.9 (Clark et al., 2011). This illustrates the need for improved 10 representation of snow distribution within this land use class.

An accurate representation of the small scale snow variation highly influences the timing and magnitude of runoff in hydrological models, and a detailed picture of the sub-grid variability is of great value for the hydropower industry and in flood forecasting. Adequate representations of the snow covered fraction in land surface schemes are important for enhanced realism of simulated near surface air temperatures, ground temperatures and evaporation due to the considerable influence of snow cover on the duration of melt season and the surface albedo.

18 In this study we derive functional dependencies between distributions of snow depth within 19 1x1 km grid cells and CV_{sd} , based on an extensive in-situ data set from Norwegian alpine areas. In a second step, we employ the resulting snow distributions as input to the permafrost 20 21 model CryoGRID1, a spatially distributed, equilibrium permafrost model (Gisnås et al., 22 2013). From the sub-grid representation of ground temperatures, permafrost probabilities are 23 derived, hence enabling a more realistic, fuzzy permafrost boundary instead of a binary, sharp 24 transition. With this approach, we aim to improve permafrost distribution modelling in 25 inhomogeneous terrains.

26

27 2 Setting

The model is implemented for the Norwegian mainland, extending from 58° to 71°N. Both the topography and climate in Norway is dominated by the Scandes, the mountain range stretching south-north through Norway, separating the coastal western part with steep mountains and deep fjords from the eastern part where the mountains gradually decrease in height. The maritime climate of the west coast is dominated by low-pressure systems from the

1 Atlantic Ocean resulting in heavy precipitation, while the eastern parts of the Scandes have a 2 more continental and drier climate. Mountain permafrost is present all the way to the southern 3 parts of the Scandes, with a gradient in the lower limit of permafrost from c. 1400 to 1700 m from east to west in central southern Norway, and from c. 700 to 1200 m from east to west in 4 5 northern Norway (Gisnås et al., 2013). While permafrost is also found in mires at lower 6 elevations both in southern and northern Norway, most of the permafrost is located in exposed 7 terrain above the tree line. This environment is dominated by strong winds resulting in heavy 8 redistribution of snow.

9 In-situ records of snow depth data used to establish the snow distribution scheme were 10 collected at the Hardangervidda mountain plateau in the southern part of the Scandes (Fig. 11 1Fig. 1). It is the largest mountain plateau in northern Europe, located at elevations from 1000 12 to above 1700 meters a.s.l., with occurrences of permafrost in the highest mountain peaks. The terrain is open and slightly undulating in the east, while in the west it is more complex 13 14 with steep mountains divided by valleys and fjords. The mountain range represents a 15 significant orographic barrier for the prevailing westerly winds from the Atlantic Ocean, 16 giving rise to large variations in precipitation and strong winds, two agents promoting a 17 considerably wind-affected snow distribution. Mean annual precipitation varies from 500 to 18 more than 3000 mm over distances of a few tens of kilometres, and maximum snow depths 19 can vary from zero to more than 10 meters over short distances (Melvold and Skaugen, 2013).

20

21 **3 Model description**

22 **3.1** A statistical model for snow depth variation

The Winstral terrain-based approach (Winstral et al., 2002) is applied over the entire Norwegian mainland using the 10-meter national digital terrain model from the Norwegian Mapping Authority (available at Statkart.no), with wind data from the NORA10 dataset (Section 4.1) used to indicate the distribution of prevailing wind directions during accumulation season.

The terrain-based exposure parameter (Sx), described in detail in Winstral et al. (2002), quantifies the extent of shelter or exposure of the grid-cell considered. Sx is determined by the slope between the grid-cell and the cells of greatest upward slope in the upwind terrain. The upwind terrain is defined as a sector towards the prevailing wind direction *d* constrained by the maximum search distance (dmax = 100 m) and a chosen width (A) of 30° with the two azimuths extending 15° to each side of d (see Fig. 2Fig. 2). The cell of the maximum upward slope is identified for each search vector, separated by 5° increments. This gives in total seven search vectors for each of the eight 30° wide sectors. *Sx* for the given grid-cell is finally calculated as the average of the maximum upward slope gradient of all seven search vectors:

6
$$Sx_{d,A,dmax}(x_iy_i) = max \left[tan(\frac{Z(x_v,y_v) - Z(x_i,y_i)}{[(x_v - x_i)^2 + (y_v - y_i)^2]^{0.5}}) \right]$$
 (1)

where *d* is the prevailing wind direction, (x_i, y_i) are the coordinates of the considered grid-cell, and (x_v, y_v) are the sets of all cell coordinates located along the search vector defined by (x_i, y_i) , *A* and *dmax*. This gives the degree of exposure or shelter in the range -1 to 1, where negative values indicate exposure.

11 To estimate a realistic degree of exposure based on the observed wind pattern at a local site, 12 Sx was computed for each of the eight prevailing wind directions $d = [0^{\circ}, 45^{\circ}, 90^{\circ}, 135^{\circ}, 135^{\circ}$ 180°, 225°, 270°, 315°], and weighted based on the wind fraction (wf_d). wf_d accounts for the 13 14 amount of different exposures in the terrain at various wind directions, and represents the 15 fraction of hourly wind direction observations over the accumulation season for the eight 16 wind directions. The period of wind directions influencing the redistribution of snow is here chosen as January to March. The accumulation season is here chosen as January to March. 17 Wind speeds below a threshold of 7 ms^{-1} are excluded, as this threshold is considered a lower 18 19 limit required for wind drifting of dry snow (Li and Pomeroy, 1997; Lehning and Fierz, 2008). We assume that the snow distribution at snow maximum is highly controlled by the 20 21 terrain and the general wind exposure over the winter season, and we do not account for the 22 variation in snow properties over the season that controls how much snow is available for 23 transport at a given time.

The calculated *Sx* parameter values are used as predictors in different regression analyses to describe the CV_{sd} within 1 x 1 km derived from the an Airborne Laser Scanning (ALS) of snow depths (see Sect. 4.1)ALS. The coefficient of variation of exposure degrees (CV_{Sx}) within each 1x1 km grid cell is computed by aggregating the *Sx* map from 10 meter to 1 km resolution according to:

29
$$cV_{Sx} = \operatorname{std}(e^{Sx})/\operatorname{mean}(e^{Sx})$$
 (2)

30 *Sx*-values below the 2.5th and above 97.5th percentiles of the *Sx*-distributions are excluded, 31 giving $Sx \approx [-0.2, 0.2]$. Three regression analyses were performed to reduce the RMS between

1 CV_{Sx} and observed CV_{sd} , where additional predictors such as elevation above treeline (z) and 2 maximum snow depth (μ) successively have been included (<u>Table 1</u>). Elevation above 3 treeline is chosen as predictor to account for the increased wind exposure with elevation. Ideally, wind speed should be included as predictor. However, the NORA10 dataset (Section 4 5 4.1) does not sufficiently reproduce the local variations in wind speeds over land, especially 6 not at higher elevations and for terrain with increased roughness. Because of the strong 7 gradient in treeline and general elevation of mountain peaks from high mountains in the south 8 to lower topography in the north of Norway, applying only elevation as predictor would result 9 in an underestimation of redistribution in the north.

10 **3.2** CryoGRID 1 with an integrated sub-grid scheme for snow variation

The equilibrium permafrost model CryoGRID 1 (Gisnås et al., 2013; Westermann et al., 2015) provides an estimate for the *MAGST* (Mean annual ground surface temperature) and MAGT (Mean Annual Ground Temperature at the top of the permafrost or at the bottom of the seasonal freezing layer) from freezing (*FDD_a*) and thawing (*TDD_a*) degree days in the air according to

$$16 \quad MAGST = \frac{TDD_a \times nT - FDD_a \times nF}{P}$$
(3)

17 and

18
$$MAGT = \begin{cases} \frac{(TDD_a * nT * r_k - FDD_a * nF)}{P} \text{ for } K_t TDD_s \leq K_f FDD_s \\ \frac{(TDD_a * nT - \frac{1}{r_k} * FDD_a * nF)}{P} \text{ for } K_t TDD_s \geq K_f FDD_s \end{cases}$$
(4)

where *P* is the period that FDD_a and TDD_a are integrated over, *rk* is the ratio of thermal conductivities of the ground in thawed and frozen states (assuming that heat transfer in the ground is entirely governed by heat conduction), while *nT* and *nF* are semi-empirical transferfunctions including a variety of processes in one single variable_(see Gisnås et al., 2013; Westermann et al., 2015 for details).

The winter *nF*-factor relates the freezing degree days at the surface to the air and thus accounts for the effect of the winter snow cover, and likewise the *nT*-factor relates the thawing degree days at the surface to the air and accounts for the surface vegetation cover:

27
$$FDD_s = nF * FDD_a$$
 and $TDD_s = nT * TDD_a$ (5)

Variation in observed *n*-factors for forests and shrubs are relatively small, with *nT*-factors
 typically in the range 0.85 to 1.1, and *nF*-factors in the range 0.3 to 0.5 (Gisnås et al., 2013).
 Following Gisnås et al. (2013) forest, shrubs and mires are assigned *nT*-factors 0.9/1.0/0.85
 and *nF*-factors 0.4/0.3/0.6, respectively.

Observed variations in nT and nF within the open non-vegetated areas are comparably large, 5 with values typically in the range 0.4 - 1.2 for *nT* and 0.1 - 1.0 for *nF*. The variability is 6 7 related to the high impact and high spatial variability of snow depths (Gisnås et al., 2014). 8 While nF accounts for the insulation from snow due to low thermal conductivity, nT9 indirectly compensates for the shorter season of thawing degree days at the ground surface in 10 areas with a thick snow cover. Relationships between *n*-factors for open areas and maximum 11 snow depths are established based on air and ground temperature observations together with 12 snow depth observations at the end of accumulation season at the 13 stations in southern Norway, presented in Hipp (2012) and at arrays of nearly 80 loggers at Finse and Juvvasshøe 13 14 (Gisnås et al., 2014) (Fig. 3Fig. 3):

15
$$nF = -0.17 * \ln(\mu) + 0.25$$
 (6)

$$16 \quad nT = -0.13 * \mu + 1.1 \tag{7}$$

17 The relationships between *n*-factors and snow cover in open areas are shown to be consistent 18 within the two sites in southern Norway (Gisnås et al. 2013 and Gisnås et al. 2014). Due to 19 lack of field observations including all required variables at one site in northern Norway, the 20 relation is not tested for this area. However, it fits very well with a detailed study with 107 loggers recording the variation in ground surface temperature at a lowland site in Svalbard 21 (Gisnås et al. 2014). Other factors, such as solar radiation and soil moisture, have minor 22 effects on the small-scale variation in ground surface temperatures in these areas. Gisnås et al 23 24 (2014) demonstrated that most of the sub-grid variation in ground temperatures within 1 km x 25 1 km areas in Norway and Svalbard was reproduced by including only the sub-grid variation of snow depths. In other areas other parameters than snow depth might have a larger effect on 26 the ground surface temperatures, and should be accounted for in the derivation of *n*-factors. 27

We assume that the distribution of maximum snow depths within a grid cell with a given CV_{sd} and average maximum snow depth (μ) follows a *gamma* distribution with a probability density function (PDF) given by:

1
$$f(x; \alpha, \beta) = \frac{1}{\beta^{\alpha} \Gamma(\alpha)} x^{\alpha - 1} e^{-\frac{x}{\beta}}$$
 (8)

with a *shape* parameter $\alpha = CV_{sd}^{-2}$ and a *rate* parameter $\beta = \mu * CV_{sd}^{-2}$ (e.g. Skaugen et al., 2 3 2004; Kolberg and Gottschalk, 2006). The average maximum snow depth corresponds to the 4 coarse scale snow observation, and the original coarse scale snow depth is therefore conserved in the sub-grid snow distribution. Corresponding *n*-factors are computed for all 5 6 snow depths (x) based on Eq. 6 and 7, and related to the PDF (Eq. 8). The model is run for 7 each nF from 0 to 1 with 0.01 spacing, giving 100 model realizations. Each realization 8 corresponds to a unique snow depth, represented with a set of nF and nT factors. Based on the 9 100 realizations a distribution of MAGST and MAGT are calculated for each grid cell, where 10 the potential permafrost fraction is derived as the percentage of sub-zero MAGT. A schematic overview of the model chain and the evaluation is shown in Fig. 4. To assess the sensitivity 11 12 of the choice of the theoretical distribution function, the model was also run with PDFs 13 following a *lognormal* distribution, given by (e.g. Liston, 2004):

14
$$f(x;\lambda,\zeta) = \frac{1}{x\zeta\sqrt{2}}e^{\left\{-\frac{1}{2}\left[\frac{\ln(x)-\lambda}{\zeta}\right]^2\right\}}$$
(9)

15 where

16
$$\lambda = \ln(\mu) - \frac{1}{2}\zeta^2, \quad \zeta^2 = \ln(1 + CV_{sd})$$
 (10)

17 **3.3 Model evaluation**

The CV_{sd} was derived for 0.5 km x 1 km areas based on the ALS snow depth data (Section 18 4.1) resampled to 10 x 10 meter resolution. Each 0.5 x 1 km area includes 500 to 5000 grid 19 20 cells-á 10 x 10 m, depending on the area masked out due to lakes or measurement errors. 21 There were (> 4000 grid cells in 70% of the areas). Goodness of fit evaluations for the theoretical lognormal and gamma distributions applying the Anderson-Darling test in 22 23 MATLB [adtest.m (Stephens, 1974)] were conducted for each distribution. Parameters for 24 gamma (shape and rate) and lognormal (mu, sigma) distributions were estimated by maximum likelihood as implemented in the MATLAB functions gamfit.m and lognfit.m. 25

The results of the permafrost model are evaluated with respect to the average *MAGST* and *MAGT* within each grid cell, as well as the fraction of sub-zero *MAGST*. For the evaluation <u>runs the model is The model runs are</u> forced with climatic data for the hydrological year corresponding to the observations. The performance in representing fractional permafrost

1 distribution is evaluated at two field sites where arrays of 26 (Juvvasshøe) and 41 (Finse) data 2 loggers have measured the distribution of ground surface temperatures at 2 cm depth within 3 500 x 500 meter areas for the hydrological year 2013 (Gisnås et al., 2014). The general lower 4 limits of permafrost are compared to permafrost probabilities derived from BTS (basal 5 temperature of snow) - surveys (Haeberli, 1973; Lewkowicz and Ednie, 2004), conducted at Juvvasshøe and Dovrefjell (Isaksen et al., 2002). The model performance of MAGST is 6 7 evaluated with data from 128 temperature data loggers located a few cm below the ground 8 surface in the period 1999 - 2009 (Farbrot et al., 2008; Isaksen et al., 2008; Ødegaard et al., 9 2008; Farbrot et al., 2011; Isaksen et al., 2011; Farbrot et al., 2013). The loggers represent all 10 vegetation classes used in the model, and spatially large parts of Norway (Fig. 2Fig. 2). Four years of data from 25 boreholes (Isaksen et al., 2007; Farbrot et al., 2011; Isaksen et al., 2011; 11 12 Farbrot et al., 2013) are used to evaluate modelled MAGT (Fig. 1Fig. 2). Tables of ground 13 surface temperature loggers (Table S1) and boreholes used for validation (Table S2) are included in the supplementary material. 14

15

16 **4 Data**

17 **4.1** Forcing and evaluation of the snow distribution scheme

Wind speeds and directions during the snow accumulation season are calculated from the 18 19 boundary layer wind speed and direction at 10 meter above surface in the Norwegian 20 Reanalysis Archive (NORA10) wind dataset. NORA10 is a dynamically downscaled dataset 21 of ERA -40 to a spatial resolution of 10-11 km, with hourly resolution of wind speed and 22 direction (Reistad et al., 2011). The dataset is originally produced for wind fields over sea, 23 and underestimates the wind speeds at higher elevation over land (Haakenstad et al., 2012). 24 Comparison with weather station data revealed that wind speeds above the tree line are 25 underestimated by about 60% (Haakenstad et al., 2012). For these areas the forcing dataset 26 has been scaled accordingly linearly increased by 60 %.

The snow distribution scheme is derived from an Airborne Laser Scanning (ALS) snow depth
over the Hardangervidda mountain plateau in southern Norway (Melvold and Skaugen, 2013).
The ALS scan-survey is made along six transects, each covering a 0.5 x 80 km area with
nominal 1.5 x 1.5 m ground point spacing. The survey was first conducted between 3rd and
21st of April 2008, and repeated in the period 21st-24th April 2009. The snow cover was at a

1 maximum during both surveys. A baseline scan was performed 21^{st} of September 2008 to 2 obtain the elevation at minimum snow cover. The <u>ASL-ALS</u> data are presented in detail in 3 Melvold and Skaugen (2013). Distributions of snow depth, represented as CV_{sd} , are calculated 4 for each 0.5 x 1 km area, based on the snow depth data resampled to 10 x 10 meter resolution. 5 About 400 cells of 0.5 x 1 km exist for each year, when after lakes and areas below treeline 6 are excluded.

7 The snow distribution scheme is validated with snow depth data obtained by ground penetrating radar (GPR) at Finse (60°34'N, 7°32'E, 1250-1332 m a.s.l.) and Juvvasshøe 8 9 (61°41'N, 8°23'E, 1374-1497 m a.s.l.). The two field sites are both located in open, non-10 vegetated alpine landscapes with major wind re-distribution of snow. However, they differ with respect to elevation (1300/1450 m a.s.l.), mean maximum snow depth (~2 m / ~1 m), 11 12 average winter wind speeds (7-8/10-14 m/s) and topography (very rugged at Finse, while steep, but less rugged at Juvvasshøe). The timing of the snow surveys were late March to 13 April (2009, 2012-2014) around maximum snow depth, but when the snow pack was still dry. 14 The GPR surveys at Finse are constrained to an area of 1x1 km, while at Juvvasshøe they 15 16 cover several square kilometres, but with lower observation density. The GPR data from the 17 end of the accumulation season in 2013 are presented in Gisnås et al. (2014), and the data 18 series from the other years are obtained and processed following the same procedures, 19 described in detail in Dunse et al. (2009). The propagation speed of the radar signal in dry snow was derived from the permittivity and the speed of light in vacuum, with the 20 permittivity obtained from snow density using an empirical relation (Kovacs et al., 1995). The 21 22 snow depths were determined from the two-way travel time of the reflection from the ground 23 surface and the wave-speed. Observations were averaged over 10 x 10 meter grid cells, where 24 grid cells containing less than three samples were excluded. The CV_{sd} for 1x1 km areas are 25 computed based on the 10-meter resolution data.

26 4.2 Permafrost model setup

The climatic forcing of the permafrost model is daily gridded air temperature and snow depth data for the period 1961 2013, called the *seNorge* dataset, provided by the Norwegian Meteorological Institute (Mohr and Tveito, 2008; Mohr, 2009) and the Norwegian Water and Energy Directorate (Engeset et al., 2004; Saloranta, 2012). The dataset, available for the period 1961 – 2015, is based on air temperature and precipitation data collected at the official

1 meteorological stations in Norway, interpolated to 1 x 1 km resolution applying Optimal 2 Interpolation as described in Lussana et al. (2010). Snow depths are derived from the air 3 temperature and precipitation data, using a snow algorithm accounting for snow accumulation 4 and melt, temperature during snow fall and compaction (Engeset et al., 2004; Saloranta, 5 2012). Freezing- (FDD_a) and thawing (TDD_a) degree days in the air are calculated as annual accumulated negative (FDD) and positive (TDD) daily mean air temperatures, and maximum 6 7 annual snow depths (μ) are derived directly from the daily gridded snow depth data. The 8 CryoGRID 1 model is implemented at 1 x 1 km resolution over the same grid as the seNorge 9 dataset.

10 Soil properties and surface cover is kept as in Gisnås et al. (2013), with five land cover 11 classes; *forest, shrubs, open non-vegetated areas, mires* and *no data*, based on CLC level 2 in 12 the Norwegian Corine Land Cover map 2012 (Aune-Lundberg and Strand, 2010). Sub-grid 13 distributions of snow are only implemented for *open non-vegetated areas*.

14

15 **5 Results**

16 **5.1** Observed snow distributions in mountain areas of Norway

 CV_{sd} within 1 x 1 km areas in the ALS snow survey at Hardangervidda ranged from 0.15 to 17 18 1.14, with mean and median of respectively 0.58 and 0.59. According to the Anderson-Darling goodness of fit evaluations 70 out of 932 areas had a snow distribution within the 5% 19 20 significance interval of a gamma distribution, while only 1 area was within the 5% 21 significance interval of a *lognormal* distribution. Although the null hypothesis rejected more 22 than 90% of the sample distributions, the Anderson-Darling Test Score was all over lower for 23 the gamma distribution, indicating that the observed snow distributions are closer to a gamma 24 than to a lognormal theoretical distribution (Fig. 5Fig. 4). For lower lying areas with less 25 varying topography and shallower snow depths, in particular in the eastern parts of 26 Hardangervidda, the observed snow distributions were similarly close to a *lognormal* as to a 27 gamma distribution. In higher elevated parts with more snow to the west of the plateau the 28 snow distributions were much closer to a gamma distribution. Based on these findings a 29 gamma distribution was used in the main model runs, while a model run with lognormal 30 distributions of snow was made to evaluate the sensitivity towards the choice of the 31 distribution function (Section 3.2).

5.2 Evaluation of the snow distribution scheme

2 Three regression models for CV_{sd} as a function of the terrain-based parameter Sx, elevation (z) 3 and mean maximum snow depth (μ) were calibrated with the snow distribution data from the 4 ALS snow survey over the Hardangervidda mountain plateau (Table 1 Table 1). Model 1 results in a root mean square error (RMSE) of only 0.14, however, the correlations of the 5 distributions are significantly improved by including *elevation* as predictor (*Model 2*; R^2 = 6 7 0.52). By including maximum snow depth as additional predictor (Model 3) the model improves slightly to $R^2 = 0.55$ (Fig. 6Fig. 5). The distribution of CV_{sd} (example of *Model 3* in 8 Fig. 8Fig. 7, left) shows increased values in areas of rougher topography (western side of 9 Norway) and higher elevations (central part following the Scandes), with maximum CV_{sd} up 10 to 1.2 in the Lyngen Alps and at peaks around Juvvasshøe (Fig. 1Fig. 1, site 2 and 4). The 11 12 lowest values of 0.2-0.3 are modelled in larger valleys in south eastern Norway, where 13 elevations are lower and topography gentler.

The regression models for CV_{sd} are validated with data from GPR snow surveys at Juvvasshøe 14 and Finse (<u>Table 1</u>). The correlation for *Model 1* is poor, with $R^2 = 0.04$ and Nash-15 Sutcliff model efficiency (*ME*) = -0.7 (Table 1 Table 1). *Model* 2 improves the correlation 16 significantly, while the best fit is obtained with *Model 3* (Fig. 6Fig. 5, RMSE = 0.094, R^2 = 17 0.62 and ME = 0.61). The improvement in *Model 3* compared to *Model 2* is more pronounced 18 19 in the validation than in the fit of the regression models, and is mainly a result of better representation of the highest CV_{sd} -values. The validation area at Juvvasshøe is located at 20 21 higher elevations than what is represented in the ALS snow survey data set and undergoes 22 extreme redistribution by wind. The representation of extreme values therefore has a high 23 impact in the validation run.

24 **5.3** Modelled ground temperatures for mainland Norway

The main results presented in this section are based on the model run with 100 realizations per grid cell, applying *gamma* distributions over the CV_{sd} from *Model 3*. The main results are given as averages over the 30-year period 1981 – 2010. According to the model run, in total 25 400 km² (7.8 %) of the Norwegian mainland is underlain by permafrost in an equilibrium situation with the climate over the 30-years period 1981-2010 (Fig. 1Fig. 1). 12 % of the land area features sub-zero ground temperatures in more than 10% of a 1 km grid cell, and is classified as sporadic (4.4 %), discontinuous (3.2 %) or continuous (4.3 %) permafrost (Fig.

1 <u>1Fig. 1</u>). In comparison, the model run without a sub-grid variation results in a permafrost 2 area of only 13460 km², corresponding to 4.1% of the model domain (Table 2Table 2). The difference is illustrated for Juvvasshøe (Fig. 7Fig. 6, a) and Dovrefjell (c), where the sub-grid 3 4 model very well reproduces the observed lower limit of permafrost based on borehole 5 temperatures and BTS-surveys. In contrast, the model without sub-grid variability indicates a 6 hard line for the permafrost limit at much higher elevations (Fig. 7Fig. 6, b and d). At 7 Juvvasshøe, the model without sub-grid distribution still reproduces the permafrost limit to some extent because of the large elevation gradient. At Dovrefjell, where the topography is 8 9 much gentler, the difference between the models is much larger and the approach without subgrid distribution is not capable of reproducing the observed permafrost distribution. The 10 11 modelled permafrost area for model runs applying the other models for CV_{sd} and theoretical distribution functions are summarized in Table 2Table 2. 12

The standard deviations of the modelled sub-grid distribution of MAGT range from 0 °C to 14 2.5 °C (Fig. 8Fig. 7, right). The highest *standard deviation* values are found in the 15 Jotunheimen area, where modelled sub-grid variability of MAGT is up to 5 °C. Also at lower 16 elevations in south eastern parts of Finnmark *standard deviations* exceed 1.5 °C. Here, the 17 CV_{sd} values are below 0.4, but because of cold (FDD_a < -2450 °C) and dry (max SD < 0.5 18 meters) winters even small variations in the snow cover result in large effects on the ground 19 temperatures.

20 Close to 70% of the modelled permafrost is situated within open, non-vegetated areas above 21 treeline, classified as mountain permafrost according to Gruber and Haeberli (2009). This is 22 the major part of the permafrost extent both in northern and southern Norway. In northern 23 Norway the model results indicate that the lower limit of continuous / sporadic mountain 24 permafrost decreases eastwards from 1200/700 meters a.s.l., respectively, in the west to 25 500/200 meters in the east. In southern Norway, the southernmost location of continuous 26 mountain permafrost is in the mountain massif of Gaustatoppen at 59.8°N, with continuous 27 permafrost above 1700 meters a.s.l. and discontinuous permafrost down to 1200 m a.s.l. In 28 more central southern Norway the continuous mountain permafrost reaches down to 1600 29 meters a.s.l in the western Jotunheimen and Hallingskarvet, and down to 1200 meters a.s.l. in 30 the east at the Swedish border. The sporadic mountain permafrost extends around 200 meters 31 further down both in the western and eastern parts.

5.4 Evaluation of CryoGRID 1 with sub-grid snow distribution scheme

2 The observed and modelled CV_{sd} values at the field sites were 0.85 and 0.80 at Juvvasshøe, 3 and 0.71 and 0.77 at Finse. At Juvvasshøe the observed fraction of loggers with MAGST 4 below 0°C was 77 %, while the model result indicates an aerial fraction of 64 %. Similarly, at Finse the observed negative MAGST fraction was 30 %, while the model indicates 32 %. The 5 6 measured ranges of MAGST within the 1 km x 1 km areas were relatively well reproduced by 7 the model (Table 3). The average MAGST within each field area was also improved 8 compared to a model without a sub-grid representation of snow (Table 3, in parenthesis). The 9 observed and modelled range in MAGST was [-1.8°C, 1.0°C] and [-2.6°C, 0.8°C] at Juvvasshøe, and at Finse [-1.9°C, 2.7°C] and [-1.6°C, 1.0°C]. The average MAGSTs are -0.5/-10 11 0.5/0.8°C (Juvvasshøe) and 0.8/0.2/1.3°C (Finse) for observations, the sub-grid model and the 12 model without sub-grid temperatures, respectively.

13 58% of the observed MAGSTs are captured by the modelled range of MAGST for the 14 corresponding grid cell, and 87% within 1°C outside the range given by the distribution. The 15 overall correlation between observed MAGST and average modelled MAGST for a grid cell is fairly good with *RMSE*, R^2 and *ME* of 1.3°C, 0.65 and 0.37, respectively (Fig. 9Fig. 8, left). 16 17 The measured MAGT was within the range of modelled MAGT in all boreholes except of one, 18 this being 0.2°C outside the range. All the average modelled MAGT are within ± 1.6 °C of 19 observations, while 90 % are within 1°C. The RMSE between the observed and modelled 20 average *MAGT* is 0.6°C (Fig. 9Fig. 8, right).

21 The evaluation of the model runs with all three CV_{sd} -models, as well as *lognormal* instead of 22 gamma distribution functions are summarized in Table 2Table 2. The highest correlation 23 between observed and mean MAGST and MAGT was obtained by Model 3, but Model 2 yielded similar correlations. All three model runs capture 58 % of the observed MAGST and 24 25 more than 98 % of the observed MAGT within the temperature range of the corresponding grid cell. The total area of modelled permafrost is 9% less when applying the simplest snow 26 27 distribution model (Model 1) compared to the reference model (Model 3), while the same 28 model without any sub-grid distribution results in 47 % less permafrost area. With a 29 lognormal distribution the modelled permafrost area is 18 % less (Model 3) than with a 30 gamma distribution.

1 6 Discussion

6.1 The effect of a statistical representation of sub-grid variability in a regional permafrost model

4 The total distribution of modelled permafrost with the sub-grid snow scheme corresponds to 5 7.8% of the Norwegian land area, while the modelled permafrost area without a sub-grid 6 representation of snow c. 4%. This large difference in total modelled permafrost area stems 7 exclusively from differences in the amount of modelled permafrost in mountains above the 8 treeline. In these areas the snow distribution is highly asymmetric with a majority of the area 9 having below average snow depths. Because of the non-linearity in the insulating effect of 10 snow cover the mean ground temperature of a grid cell is not, and is often far from, the same 11 as the ground temperature below the average snow depth. Often, the majority of the area in high, wind exposed mountains is nearly bare blown with most of the snow blown into terrain 12 hollows. Consequently, most of the area experiences significantly lower average ground 13 14 temperatures than with an evenly distributed, average depth snow cover. In mountain areas 15 with a more gentle topography and relatively small spatial temperature variations, an evenly 16 distributed snow depth will result in large biases in modelled permafrost area, as illustrated at 17 Dovrefiell in Fig. 7Fig. 6. This study is clear evidence that the sub-grid variability of snow 18 depths should be accounted for in model approaches targeting the ground thermal regime and 19 permafrost distribution.

20 The model reproduces the large range of variation in sub-grid ground temperatures, with 21 standard deviations up to 2.5 °C. This is in accordance with the observed small-scale 22 variability of up to 6 °C within a single grid cell (Gubler et al., 2011; Gisnås et al., 2014). 23 Inclusion of sub-grid variability of snow depths in model approaches allows for a more 24 adequate representation of the gradual transition from permafrost to permafrost-free areas in 25 alpine environments, and thus a better estimation of permafrost area. With a warming of the climate, a model without such a sub-grid representation would respond with an abrupt 26 27 decrease in permafrost extent. In reality, bare blown areas with mean annual ground 28 temperatures of -6 °C need a large temperature increase to thaw. Increased precipitation as 29 snow would also warm the ground; however, bare blown areas may still be bare blown with 30 increased snow accumulation during winter. A statistical snow distribution reproduces this 31 effect, also with an increase in mean snow depth.

1 CryoGRID1 is a simple modelling scheme delivering a mean annual ground temperature at 2 the top of the permanently frozen ground based on near-surface meteorological variables, 3 under the assumption that the ground thermal regime is in equilibrium with the applied surface forcing. This is a simplification, and the model cannot reproduce the transient 4 5 evolution of ground temperatures, and is therefore not suitable for future climate predictions. However, it has proven to capture the regional patterns of permafrost reasonably well (Gisnås 6 et al., 2013; Westermann et al., 2013). Because of the simplicity it is computationally 7 efficient, and suitable for doing test-studies like the one presented in this paper and in similar 8 9 studies (Westermann et al., 2015).

10 For the model evaluation with measured ground temperatures in boreholes (Section 5.4), the 11 modelled temperatures are forced with data for the hydrological year corresponding to the 12 observations. Because of the assumption of an equilibrium situation in the model approach, such a comparison can be problematic as many of the boreholes have undergone warming 13 14 during the past decades. However, with the majority of the boreholes located in bedrock or 15 coarse moraine material with relatively high conductivity, the lag in the climate signal is 16 relatively small at the depth of the top of permafrost. The lag will also vary from borehole to 17 borehole, depending on the ground thermal properties. Since we use data distributed over 18 larger areas and longer time periods, including a large range of situations, the effect mainly 19 shows in terms of a larger statistical spread and not a systematic error.

The large amount of field observations used for calibration and evaluation in this study is mainly conducted in alpine mountain areas. The large spatial variation in winter snow depths is a major controlling factor also of the ground temperatures in peat plateaus and palsa mires, and is a driving factor in palsa formation (e.g. Seppälä, 2011). The sub-grid effect of snow should therefore also be implemented for mire areas, where comparable data sets are lacking.

25 6.2 Model sensitivity

The sensitivity of the model for CV_{sd} -model to the modelled ground temperatures is relatively low, with only 9 % variation in permafrost area, although the performance of the snow distribution scheme varies significantly between the models when evaluated with GPR snow surveys (<u>Table 1</u><u>Table 1</u>). In comparison, a *lognormal* instead of a *gamma* distribution function reduces the permafrost area by 18% (<u>Table 2</u><u>Table 2</u>). The choice of distribution function therefore seems to be of greater importance than the fine tuning of a model for CV_{sd} .

This result contradicts the conclusions by Luce and Tarboton (2004), suggesting which 1 2 suggest that the parameterization of the distribution function is more important than the 3 choice of distribution model. With a focus on hydrology and snow cover depletion curves, 4 equal importance was given to both the deeper and shallower snow depths in the mentioned 5 study. In contrast, an accurate representation of the shallowest snow depths is crucial for 6 modelling the ground thermal regime. The low thermal conductivity of snow results in a 7 disconnection of ground surface and air temperatures at snow packs thicker than 0.5 - 1 m, 8 depending on the physical properties of the snow pack and the surface roughtness (e.g. 9 Haeberli, 1973). In wind exposed areas prone to heavy redistribution, large fractions of the area will be entirely bare blown (Gisnås et al., 2014). These are the areas of greatest 10 11 importance for permafrost modelling. In order to reproduce the gradual transition in the 12 discontinuous permafrost zone, where permafrost is often only present at bare blown ridges, 13 shallow snow covers must be satisfactorily represented. Compared to a gamma function, a 14 *lognormal* distribution function to a larger degree underestimates the fraction of shallow snow 15 depths, resulting in a less accurate representation of this transition.

16 Several studies include statistical representations of the sub-grid variability of snow in 17 hydrological models, most commonly applying a two- or three-parameter lognormal 18 distribution (e.g. Donald et al., 1995; Liston, 2004; Pomeroy et al., 2004; Nitta et al., 2014). 19 Observed snow distributions within 1x1 km in the ALS snow survey presented in this paper 20 are closer to a *gamma* than to a *lognormal* distribution, supporting the findings by Skaugen 21 (2007) and Winstral and Marks (2014) which were conducted in non-forested alpine 22 environments. However, the difference is not substantial in all areas; the two distributions can 23 provide near-equal fit in eastern parts of the mountain plateau where the terrain is gentler and 24 the wind speeds lower. We suggest that the choice of distribution function of snow is 25 important in model applications for the ground thermal regime, and recommend the use of 26 gamma distribution for non-vegetated high alpine areas prone to heavy redistribution of snow.

While a *gamma* distribution offers improvements over a *lognormal* distribution, the bare blown areas are still not sufficiently represented. One attempt to solve this is to include a third parameter for the "snow free fraction" (e.g. Kolberg et al., 2006; Kolberg and Gottschalk, 2010). We made an attempt to calibrate such a parameter for this study, however, no correlations to any of the predictors were found. It is also difficult to determine a threshold depth for "snow free" areas in ALS data resampled to 10 meter resolution, where the uncertainty of the snow depth observations are in the order of ten centimetres (Melvold and
 Skaugen, 2013).

In this study a high number of realizations could be run per grid cell because of the low computational cost of the model. To evaluate the sensitivity of sampling density, the number of realizations was reduced from 100 to 10 per grid cell. This resulted is a 2.6 % increase in total modelled permafrost area relative to the reference model run. This demonstrates that a statistical downscaling of ground temperatures as demonstrated in this study is robust and highly improves the model results with only a few additional model realizations per grid cell.

9

10 7 Conclusions

11 We present a modelling approach to reproduce the variability of ground temperatures within the scale of 1 km² grid cells based on probability distribution functions over corresponding 12 13 seasonal maximum snow depths. The snow distributions are derived from climatic parameters 14 and terrain parameterizations at 10 meter resolution, and are calibrated with a large scale data set of snow depths obtained from laser scanning. The model results are evaluated with 15 independent observations of snow depth distributions, ground surface temperature 16 17 distributions and ground temperatures. From this study the following conclusions can be 18 drawn:

The model results indicate a total permafrost area of 25 400 km², corresponding to 7.8 %
of the Norwegian mainland, in an equilibrium situation with the average climate over
1981-2010. 4 % of the model domain features permafrost for all snow depths.

The same permafrost model without a sub-grid representation of snow produces almost 50
 % less permafrost. Because of the non-linearity in the insulating effect of snow cover in
 combination with the highly asymmetric snow distribution within each grid cell, sub-grid
 variability of snow depths must be accounted for in models representing the ground
 thermal regime.

Observed variations in ground surface temperatures from two logger arrays with 26 and
 41 loggers, respectively, are very well reproduced, with estimated fractions of sub-zero
 MAGST within ±10%. 94 % of the observed mean annual temperature at top of permafrost
 in the boreholes are within the modelled ground temperature range for the corresponding

grid cell, and mean modelled temperature of the grid cell reproduces the observations with
 an accuracy of 1.5°C or better.

The sensitivity of the model to the coefficient of variation of snow (*CV_{sd}*) is relatively
 low, compared to the choice of theoretical snow distribution function. However, both are
 minor effects compared to the effect of running the model without a sub-grid distribution.

• The observed CV_{sd} of snow within 1 km² grid cells in the Hardangervidda mountain plateau varies from 0.15 to 1.15, with an average CV_{sd} of 0.6. The distributions are generally closer to a theoretical gamma distribution than to a *lognormal* distribution, in particular in areas of very rough topography, thicker snow cover and higher average winter wind speeds. The observed CV_{sd} values are nearly identical at the end of the accumulation seasons in 2008 and 2009.

In areas subject to snow redistribution, the average ground temperature of a 1 km² grid cell must be determined based on the distribution, and not the overall average of snow depths within the grid cell. Furthermore, modelling the full range of ground temperatures present over small distances enables representation of the gradual transition from permafrost to nonpermafrost areas and most likely a more accurate response to climate warming. This study is clear evidence that the sub-grid variability of snow depths should be accounted for in model approaches targeting the ground thermal regime and permafrost distribution.

19

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1 References

- Aune-Lundberg, L., and Strand, G.-H.: CORINE Land Cover 2006. The Norwegian CLC2006
 project, Report from the Norwegian Forest and Landscape Institute: 11/10, 14p, 2010.
- 4 Clark, M. P., Hendrikx, J., Slater, A. G., Kavetski, D., Anderson, B., Cullen, N. J., Kerr, T.,
- 5 Hreinsson, E. Ö., and Woods, R. A.: Representing spatial variability of snow water equivalent
- 6 in hydrologic and land-surface models: A review, Water Resources Research, 47,
- 7 10.1029/2011WR010745, 2011.
- 8 Donald, J. R., Soulis, E. D., Kouwen, N., and Pietroniro, A.: A Land Cover-Based Snow
 9 Cover Representation for Distributed Hydrologic Models, Water Resources Research, 31,
 10 995-1009, 10.1029/94WR02973, 1995.
- 11 Dunse, T., Schuler, T. V., Hagen, J. O., Eiken, T., Brandt, O., and Høgda, K. A.: Recent 12 fluctuations in the extent of the firm area of Austfonna, Svalbard, inferred from GPR, Annals
- 13 of Glaciology, 50, 155-162, 10.3189/172756409787769780, 2009.
- 14 Engeset, R., Tveito, O. E., Alfnes, E., Mengistu, Z., Udnæs, C., Isaksen, K., and Førland, E.
- 15 J.: Snow map System for Norway., XXIII Nordic Hydrological Conference, 8-12 Aug., Tallin,
- 16 Estonia. NHP Report: 48(1), 2004,
- Farbrot, H., Isaksen, K., and Etzelmüller, B.: Present and past distribution of mountain
 permafrost in Gaissane Mountains, Northern Norway, In: Proceeding of the Ninth
 International Conference on Permafrost, Fairbanks, Alaska, 2008, 427–432,
- 20 Farbrot, H., Hipp, T. F., Etzelmüller, B., Isaksen, K., Ødegård, R. S., Schuler, T. V., and
- 21 Humlum, O.: Air and Ground Temperature Variations Observed along Elevation and
- Continentality Gradients in Southern Norway, Permafrost and Periglacial Processes, 22, 343 360, 10.1002/ppp.733, 2011.
- Farbrot, H., Isaksen, K., Etzelmüller, B., and Gisnås, K.: Ground Thermal Regime and
 Permafrost Distribution under a Changing Climate in Northern Norway, Permafrost and
 Periglacial Processes, 24, 20-38, 10.1002/ppp.1763, 2013.
- Fiddes, J., and Gruber, S.: TopoSUB: a tool for efficient large area numerical modelling in
 complex topography at sub-grid scales, Geosci. Model Dev., 5, 1245-1257, 10.5194/gmd-51245-2012, 2012.
- 30 Gisnås, K., Etzelmuller, B., Farbrot, H., Schuler, T. V., and Westermann, S.: CryoGRID 1.0:
- Permafrost Distribution in Norway estimated by a Spatial Numerical Model, Permafrost and
 Periglacial Processes, 24, 2-19, 10.1002/ppp.1765, 2013.
- Gisnås, K., Westermann, S., Schuler, T. V., Litherland, T., Isaksen, K., Boike, J., and Etzelmüller, B.: A statistical approach to represent small-scale variability of permafrost temperatures due to snow cover, The Cryosphere, 8, 2063-2074, 10.5194/tc-8-2063-2014, 2014.
- Goodrich, L. E.: The influence of snow cover on the ground thermal regime, Can. Geotech. J.,
 19, 421-432, 1982.
- Gruber, S., and Haeberli, W.: Mountain permafrost, in: Permafrost Soils, edited by: Margesin,
 R., Springer, 33-44, 2009.

- 1 Gubler, H., Fiddes, J., Gruber, S., and Keller, M.: Scale-dependent measurement and analysis
- of ground surface temperature variability in alpine terrain, The Cryosphere, 5, 307-338, 2
- 3 10.5194/tcd-5-307-2011, 2011.
- 4 Haakenstad, H., Reistad, M., Haugen, J. E., and Breivik, Ø.: Update of the NORA10 hindcast 5 archive for 2011 and study of polar low cases with the WRF model, met.no report 17/2012,
- 6 Oslo, 2012.
- 7 Haeberli, W.: Die Basis-Temperatur der winterlichen Schneedecke als möglicher Indikator für
- 8 die Verbreitung von Permafrost in den Alpen, Zeitschrift für Gletscherkunde und
- 9 Glazialgeologie, 9, 221-227, 1973.
- 10 Hipp, T.: Mountain Permafrost in Southern Norway. Distribution, Spatial Variability and
- Impacts of Climate Change., PhD, Faculty of Mathematics and Natural Sciences, Department 11
- 12 of Geosciences, University of Oslo, 166 pp., 2012.
- 13 Isaksen, K., Hauck, C., Gudevang, E., Ødegård, R. S., and Sollid, J. L.: Mountain permafrost
- distribution in Dovrefjell and Jotunheimen, southern Norway, based on BTS and DC 14
- resistivity tomography data, Norsk Geografisk Tidsskrift-Norwegian Journal of Geography, 15
 - 16 56, 122-136, 10.1080/002919502760056459, 2002.
 - Isaksen, K., Sollid, J. L., Holmlund, P., and Harris, C.: Recent warming of mountain 17 18 permafrost in Svalbard and Scandinavia, Journal of Geophysical Research., 112, F02S04, 19 10.1029/2006jf000522, 2007.
 - 20 Isaksen, K., Farbrot, H., Blikra, L., Johansen, B., Sollid, J., and Eiken, T.: Five year ground 21 surface temperature measurements in Finnmark, Northern Norway., Ninth International 22 Conference on Permafrost, Fairbanks, Alaska, 2008, 789–794,
 - 23 Isaksen, K., Ødegård, R. S., Etzelmüller, B., Hilbich, C., Hauck, C., Farbrot, H., Eiken, T.,
- Hygen, H. O., and Hipp, T. F.: Degrading Mountain Permafrost in Southern Norway: Spatial 24 and Temporal Variability of Mean Ground Temperatures, 1999-2009, Permafrost and 25 Periglacial Processes, 22, 361-377, 10.1002/ppp.728, 2011. 26
- 27 Kolberg, S., Rue, H., and Gottschalk, L.: A Bayesian spatial assimilation scheme for snow 28 coverage observations in a gridded snow model, Hydrol. Earth Syst. Sci., 10, 369-381, 29 10.5194/hess-10-369-2006, 2006.
- 30 Kolberg, S., and Gottschalk, L.: Interannual stability of grid cell snow depletion curves as 31 estimated from MODIS images, Water Resources Research, 46. n/a-n/a, 32 10.1029/2008WR007617, 2010.
- Kolberg, S. A., and Gottschalk, L.: Updating of snow depletion curve with remote sensing 33 34 data, Hydrological Processes, 20, 2363-2380, 2006.
- Kovacs, A., Gow, A. J., and Morey, R. M.: The in-situ dielectric constant of polar firn 35 36 revisited, Cold Regions Science and Technology, 23, 245-256, 10.1016/0165-37 232X(94)00016-O, 1995.
- 38 Langer, M., Westermann, S., Heikenfeld, M., Dorn, W., and Boike, J.: Satellite-based 39 modeling of permafrost temperatures in a tundra lowland landscape, Remote Sensing of 40 Environment, 135, 12-24, 10.1016/j.rse.2013.03.011, 2013.
- 41 Lehning, M., and Fierz, C.: Assessment of snow transport in avalanche terrain, Cold Regions 42 Science and Technology, 51, 240-252, 10.1016/j.coldregions.2007.05.012, 2008.

- 1 Lewkowicz, A. G., and Ednie, M.: Probability mapping of mountain permafrost using the
- 2 BTS method, Wolf Creek, Yukon Territory, Canada, Permafrost and Periglacial Processes,
- 3 15, 67-80, 10.1002/ppp.480, 2004.

Li, L., and Pomeroy, J. W.: Estimates of Threshold Wind Speeds for Snow Transport Using
Meteorological Data, Journal of Applied Meteorology, 36, 205-213, 10.1175/15200450(1997)036<0205:EOTWSF>2.0.CO;2, 1997.

- Liston, G. E.: Representing Subgrid Snow Cover Heterogeneities in Regional and Global
 Models, Journal of Climate, 17, 1381-1397, 10.1175/15200442(2004)017<1381:RSSCHI>2.0.CO;2, 2004.
- Luce, C. H., and Tarboton, D. G.: The application of depletion curves for parameterization of subgrid variability of snow, Hydrological Processes, 18, 1409-1422, 10.1002/hyp.1420, 2004.
- Lussana, C., Uboldi, F., and Salvati, M. R.: A spatial consistency test for surface observations
 from mesoscale meteorological networks, Quarterly Journal of the Royal Meteorological
 Society, 136, 1075-1088, 10.1002/qi.622, 2010.

Melvold, K., and Skaugen, T.: Multiscale spatial variability of lidar-derived and modeled
snow depth on Hardangervidda, Norway, Annals of Glaciology, 54, 273-281,
10.3189/2013AoG62A161, 2013.

- Mohr, M., and Tveito, O.: Daily temperature and precipitation maps with 1 km resolution
 derived from Norwegian weather observations, 13th Conference on Mountain
 Meteorology/17th Conference on Applied Climatology, Whistler, BC, Canada, 2008,
- Mohr, M.: Comparison of Versions 1.1 and 1.0 of Gridded Temperature and Precipitation
 Data for Norway, Norwegian Meteorological Institute, Oslo, pp. 46, 2009.
- 23 Nitta, T., Yoshimura, K., Takata, K., O'ishi, R., Sueyoshi, T., Kanae, S., Oki, T., Abe-Ouchi,
- A., and Liston, G. E.: Representing Variability in Subgrid Snow Cover and Snow Depth in a
- 25 Global Land Model: Offline Validation, Journal of Climate, 27, 3318-3330, 10.1175/JCLI-D-
- 26 13-00310.1, 2014.
- Pomeroy, J., Essery, R., and Toth, B.: Implications of spatial distributions of snow mass and
 melt rate for snow-cover depletion: observations in a subarctic mountain catchment, Annals of
 Glaciology, 38, 195-201, 10.3189/172756404781814744, 2004.
- 30 Reistad, M., Breivik, Ø., Haakenstad, H., Aarnes, O. J., Furevik, B. R., and Bidlot, J.-R.: A
- high-resolution hindcast of wind and waves for the North Sea, the Norwegian Sea, and the
 Barents Sea, Journal of Geophysical Research: Oceans, 116, C05019,
 10.1029/2010JC006402, 2011.
- Saloranta, T. M.: Simulating snow maps for Norway: description and statistical evaluation of
 the seNorge snow model, The Cryosphere, 6, 1323-1337, 10.5194/tc-6-1323-2012, 2012.
- Seppälä, M.: Synthesis of studies of palsa formation underlining the importance of local
 environmental and physical characteristics, Quaternary Research, 75, 366-370,
 http://dx.doi.org/10.1016/j.yqres.2010.09.007, 2011.
- 39 Skaugen, T., Alfnes, E., Langsholt, E. G., and Udnæs, H.-C.: Time-variant snow distribution
- 40 for use in hydrological models, Annals of Glaciology, 38, 180-186, 41 10.3189/172756404781815013, 2004.
- 42 Skaugen, T.: Modelling the spatial variability of snow water equivalent at the catchment 43 scale, Hydrol. Earth Syst. Sci., 11, 1543-1550, 10.5194/hess-11-1543-2007, 2007.

- 1 Stephens, M. A.: EDF Statistics for Goodness of Fit and Some Comparisons, Journal of the 2 American Statistical Association, 69, 730-737, 10.1080/01621459.1974.10480196, 1974.
- Westermann, S., Schuler, T. V., Gisnås, K., and Etzelmüller, B.: Transient thermal modeling
 of permafrost conditions in Southern Norway, The Cryosphere, 7, 719-739, 10.5194/tc-7-7192013, 2013.
- 6 Westermann, S., Østby, T., Gisnås, K., Schuler, T. V., and Etzelmüller, B.: A ground 7 temperature map of the North Atlantic permafrost region based on remote sensing and 8 reanalysis data, The Cryosphere Discuss., 9, 753-790, 10.5194/tcd-9-753-2015, 2015.
- 9 Winstral, A., Elder, K., and Davis, R. E.: Spatial snow modeling of wind-redistributed snow
 10 using terrain-based parameters, Journal of Hydrometeorology, 3, 524-538,
 11 <u>http://dx.doi.org/10.1175/1525-7541(2002)003<0524:SSMOWR>2.0.CO;2, 2002.</u>
- Winstral, A., and Marks, D.: Long-term snow distribution observations in a mountain
 catchment: Assessing variability, time stability, and the representativeness of an index site,
 Water Resources Research, 50, 293-305, 10.1002/2012WR013038, 2014.
- 15 Zhang, T., Barry, R. G., and Haeberli, W.: Numerical simulations of the influence of the
- seasonal snow cover on the occurrence of permafrost at high latitudes, Norsk Geografisk
- 17 Tidsskrift Norwegian Journal of Geography, 55, 261-266, 10.1080/00291950152746621,
- 18 2001.
- 19 Ødegaard, R. S., Isaksen, K., Eiken, T., and Sollid, J. L.: MAGST in Mountain Permafrost,
- 20 Dovrefjell, Southern Nroway, 2001-2006, Ninth International Conference on Permafrost 21 (NICOP) 2008, Egirbanka, Alaska, June 20, July 2, 2008
- 21 (NICOP) 2008, Fairbanks, Alaska, June 29 July 3, 2008.
- 22

Figures:



Fig. 1: Modelled distribution of permafrost in Norway. Sites mentioned in the text: 1) Finse,
south of Hallingskarvet, 2) Juvvasshøe in Jotunheimen, 3) Dovrefjell, 4) The Lyngen Alps
and 5) Finnmark.



Fig. 2: The figure illustrates the area accounted for in each of the 8 runs of the Winstral terrain-based parameter, each of them with a prevailing wind direction d_n . The area accounted for when calculating the exposure of a grid cell is constrained by the search window (*A*) and the search distance *dmax* being 100 meters upwind.





9 Fig. 3: *nF* and *nT* related to maximum snow depth observed at more than 90 sites located
10 above 1000 m a.s.l. in southern Norway.





Fig. 4: Schematic of the model chain, including input data and calibration and evaluation









Fig. <u>54</u>: Scores from the Anderson-Darling Test Statistics for Goodness-of-Fit between
theoretical *gamma* and *lognormal* distributions and the observed distribution within each 1x1
km area in the ALS snow survey. Lower scores indicate better fit.



2 Fig. <u>65</u>: Left: Fit for the regression *Model 3* for CV_{sd} , calibrated with CV_{sd} derived from the 3 ALS snow survey. Right: The model performance is evaluated with independent ground 4 penetrating radar (GPR) snow surveys from at Finse and Juvvasshøe.





Fig. <u>76</u>: Distribution of permafrost at Juvvasshøe in Jotunheimen (a and b), and at Dovrefjell (c and d) modelled as permafrost zones applying the sub-grid approach (left) compared to the modelled mean annual ground temperature (*MAGT*) without a sub-grid approach (right).

Lower limit of 50 % and 80 % probability of permafrost derived from BTS-surveys are shown
 as black and red contour lines, respectively. Borehole locations with permafrost (red) and
 seasonal frost (green) are shown as dots in the map at Juvvasshøe.



6 Fig. <u>87</u>: Left: Distribution of modelled CV_{sd} in non-vegetated areas of Norway with *Model 3*. 7 CV_{sd} increases in areas of rougher topography (western side of Norway) and higher elevations 8 (central part following the Scandes). Right: Standard deviation of modelled *MAGT* for areas 9 of modelled permafrost. Sites mentioned in the text: 1) Finse, south of Hallingskarvet, 2) 10 Juvvasshøe in Jotunheimen, 3) Dovrefjell, 4) The Lyngen Alps and 5) Finnmark.

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Fig. <u>98</u>: The figure shows the correlation between modelled and observed *MAGST* (left) and *MAGT* at the top of permafrost (right). The dotted line indicates ± 2 °C of the 1:1 line (black line). The vertical bars indicate the variation of modelled temperatures within the grid cell, and the red dots indicates the mean temperature.

1 Tables:

Table 1: The three regression models for CV_{sd} with in increasing number of predictors are calibrated with observed snow distributions from the ALS snow survey (left columns). Pvalues are $< 10^{-6}$. The isolated snow distribution scheme is validated with independent snow distribution data collected with GPR snow surveys (right columns). Root mean square error (*RMSE*), coefficient of determination (R^2) and Nash-Sutcliffe model efficiency (*ME*) are given for each model evaluation.

8		CV _{sd =}	Fit of	regres	sion	CV _{sd} , GPR survey		
			RMSE	R ²	ME	RMSE	R ²	ME
Mode	el 1	$0.39 + 3.4 * CV_{Sx}$	0.14	0.36	0.36	0.20	0.04	-0.71
Mode	el 2	$0.31 + 3.1^* CV_{Sx} + 4.05 e^{-4*z}$	0.12	0.52	0.52	0.12	0.59	0.36
Mode	el 3	$0.40 + 3.1^* CV_{Sx} + 4.95 e - 04^* z - 0.0713^* \mu$	0.12	0.55	0.55	0.09	0.62	0.61

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9 Table 2: The model performance is evaluated with respect to the mean annual ground surface 10 temperatures (*MAGST*) and the mean annual temperature at the depth of the active layer or 11 seasonal freezing layer (*MAGT*). Modelled average *MAGST* or *MAGT* over a grid cell is 12 compared to more than 100 GST logger locations and 25 boreholes. The location of the GST 13 loggers and boreholes are shown in Fig. 1Fig. 1. Modelled permafrost distribution is given in 14 total areas, and as percentage of the model domain, corresponding to the Norwegian mainland 15 area.

			Permafrost model evaluation					Modelled per	mafrost area
		MAGST, GST loggers			MAGT, boreholes				
		RMSE	R^2	ME	RMSE	R^2	ME	[km ²]	[%]
No sub-grid variation		1.57	0.65	-0.56	1.19	0.62	-1.90	13 462	4.1
IMA	<i>CV_{sd}</i> = 0.6	1.37	0.64	0.06	0.77	0.66	0.22	23 571	7.3
	Model 1	1.36	0.63	0.12	0.77	0.66	0.11	23 147	7.1
BAN	Model 2	1.29	0.65	0.31	0.65	0.71	0.62	23 674	7.3
	Model 3 [*]	1.29	0.65	0.38	0.67	0.71	0.68	25 407	7.8
	Model 1	1.40	0.64	-0.06	0.87	0.67	-0.25	19 975	6.2
OGN	Model 2	1.38	0.65	0.01	0.82	0.69	0.09	20 067	6.2
ΓC	Model 3	1.36	0.65	0.06	0.78	0.69	0.22	20 889	6.2

16 *Reference model run.

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1 Table 3: Observed and modelled values for the coefficient of variation for maximum snow 2 depth (CV_{sd}) and spatial distributions of Mean Annual Ground Surface Temperatures 3 (MAGST) at the field sites at Finse and Juvvasshøe. The MAGST modelled without a sub-

4 grid distribution of snow is given in parenthesis.

	Juv	vasshøe	Finse			
	Observed	Modelled	Observed	Modelled		
CV _{sd}	0.85	0.80	0.71	0.77		
MAGST < 0 °C	77 %	64 %	30 %	32 %		
	-1.8 °C	-2.6 °C	-1.9 °C	-1.6 °C		
MAGST _{max}	1.0 °C	0.8 °C	2.7 °C	1.0 °C		
MAGST _{avg}	-0.5 °C	-0.5 °C (0.8 °C)	0.8 °C	0.2 °C (1.3 °C)		

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7 Supplementary material

Table S1: Location, vegetation type and period of measurements of ground surface

temperature loggers used for validation.

<u>Latitude</u>	<u>Longitude</u>	Elevation (m)	Vegetation type	<u>Start Year</u>	End Year	<u>No. Years</u>
<u>62.543</u>	<u>6.303</u>	<u>92</u>	<u>Forest</u>	<u>2005</u>	<u>2008</u>	<u>3</u>
<u>62.575</u>	<u>6.317</u>	<u>796</u>	Non-vegetated	<u>2005</u>	<u>2006</u>	<u>1</u>
<u>62.297</u>	<u>9.338</u>	<u>1505</u>	Non-vegetated	<u>2001</u>	<u>2007</u>	<u>6</u>
<u>62.296</u>	<u>9.354</u>	<u>1467</u>	Non-vegetated	<u>2001</u>	<u>2004</u>	<u>3</u>
<u>62.264</u>	<u>9.467</u>	<u>1094</u>	Non-vegetated	<u>2002</u>	<u>2007</u>	<u>5</u>
<u>62.247</u>	<u>9.499</u>	<u>1039</u>	Non-vegetated	<u>2002</u>	<u>2007</u>	<u>5</u>
<u>61.522</u>	<u>12.504</u>	<u>541</u>	<u>Forest</u>	<u>2005</u>	<u>2008</u>	<u>3</u>
<u>61.542</u>	<u>12.439</u>	<u>1022</u>	Non-vegetated	<u>2005</u>	<u>2008</u>	<u>3</u>
<u>60.593</u>	<u>7.526</u>	<u>1210</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>60.651</u>	<u>7.493</u>	<u>1559</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>60.632</u>	<u>7.496</u>	<u>1431</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>60.647</u>	<u>7.489</u>	<u>1508</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>60.948</u>	<u>8.152</u>	<u>1220</u>	Non-vegetated	<u>2005</u>	<u>2007</u>	<u>2</u>
<u>62.429</u>	<u>11.274</u>	<u>1538</u>	Non-vegetated	2004	2007	<u>3</u>
<u>62.480</u>	<u>11.293</u>	<u>676</u>	<u>Forest</u>	<u>2006</u>	<u>2008</u>	<u>2</u>

<u>62.447</u>	<u>11.261</u>	<u>1251</u>	Non-vegetated	<u>2006</u>	<u>2008</u>	<u>2</u>
<u>61.721</u>	<u>8.401</u>	<u>1065</u>	Non-vegetated	<u>2004</u>	<u>2007</u>	<u>3</u>
<u>61.707</u>	<u>8.403</u>	<u>1307</u>	Non-vegetated	<u>1999</u>	<u>2007</u>	<u>8</u>
<u>61.702</u>	<u>8.395</u>	<u>1391</u>	Non-vegetated	<u>1999</u>	<u>2002</u>	<u>3</u>
<u>61.702</u>	<u>8.394</u>	<u>1410</u>	Non-vegetated	<u>1999</u>	<u>2002</u>	<u>3</u>
<u>61.701</u>	<u>8.393</u>	<u>1430</u>	Non-vegetated	<u>1999</u>	<u>2002</u>	<u>3</u>
<u>61.701</u>	<u>8.393</u>	<u>1447</u>	Non-vegetated	<u>1999</u>	<u>2008</u>	<u>9</u>
<u>61.699</u>	<u>8.391</u>	<u>1480</u>	Non-vegetated	<u>1999</u>	<u>2001</u>	<u>2</u>
<u>61.699</u>	<u>8.390</u>	<u>1492</u>	Non-vegetated	<u>1999</u>	<u>2000</u>	<u>1</u>
<u>61.685</u>	<u>8.376</u>	<u>1767</u>	Non-vegetated	<u>2004</u>	<u>2007</u>	<u>3</u>
<u>61.678</u>	<u>8.369</u>	<u>1893</u>	Non-vegetated	<u>1999</u>	<u>2004</u>	<u>5</u>
<u>61.677</u>	<u>8.369</u>	<u>1893</u>	Non-vegetated	<u>1999</u>	<u>2007</u>	<u>8</u>
<u>61.678</u>	<u>8.369</u>	<u>1893</u>	Non-vegetated	<u>1999</u>	<u>2004</u>	<u>5</u>
<u>61.649</u>	<u>9.012</u>	<u>855</u>	Forest	<u>2005</u>	<u>2008</u>	<u>3</u>
<u>61.401</u>	<u>8.831</u>	<u>1525</u>	Non-vegetated	<u>2005</u>	<u>2007</u>	<u>2</u>
<u>61.555</u>	<u>8.193</u>	<u>1522</u>	Non-vegetated	<u>2005</u>	<u>2007</u>	<u>2</u>
<u>61.556</u>	<u>8.207</u>	<u>1389</u>	Non-vegetated	<u>2005</u>	<u>2007</u>	<u>2</u>
<u>61.552</u>	<u>8.182</u>	<u>1460</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>61.547</u>	<u>8.163</u>	<u>1354</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>61.532</u>	<u>8.230</u>	<u>1448</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>61.538</u>	<u>8.180</u>	<u>1696</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>62.099</u>	<u>8.931</u>	<u>607</u>	<u>Forest</u>	<u>2005</u>	<u>2008</u>	<u>3</u>
<u>62.027</u>	<u>8.925</u>	<u>1573</u>	Non-vegetated	<u>2004</u>	<u>2008</u>	<u>4</u>
<u>59.989</u>	<u>10.670</u>	<u>528</u>	<u>Forest</u>	<u>2003</u>	<u>2006</u>	<u>3</u>
<u>59.980</u>	<u>10.683</u>	<u>443</u>	<u>Forest</u>	<u>2004</u>	<u>2008</u>	<u>4</u>
<u>59.980</u>	<u>10.684</u>	<u>435</u>	<u>Forest</u>	<u>2004</u>	<u>2008</u>	<u>4</u>
<u>60.232</u>	<u>10.428</u>	<u>196</u>	<u>Forest</u>	<u>2006</u>	<u>2008</u>	<u>2</u>
<u>61.934</u>	<u>11.548</u>	<u>805</u>	Non-vegetated	<u>2002</u>	<u>2003</u>	<u>1</u>
<u>61.931</u>	<u>11.543</u>	<u>868</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>61.930</u>	<u>11.542</u>	<u>918</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>61.927</u>	11.540	1010	Non-vegetated	2002	2006	<u>4</u>
<u>61.925</u>	<u>11.538</u>	<u>1109</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>61.922</u>	11.507	<u>987</u>	Non-vegetated	2002	2006	4

<u>61.926</u>	<u>11.511</u>	<u>1051</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>61.919</u>	<u>11.536</u>	<u>1211</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>61.929</u>	<u>11.527</u>	<u>1043</u>	Non-vegetated	<u>2002</u>	<u>2003</u>	<u>1</u>
<u>61.929</u>	<u>11.527</u>	<u>1043</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>61.902</u>	<u>11.500</u>	<u>1069</u>	Non-vegetated	<u>2004</u>	<u>2005</u>	<u>1</u>
<u>61.892</u>	<u>11.504</u>	<u>1078</u>	Non-vegetated	<u>2004</u>	<u>2005</u>	<u>1</u>
<u>61.926</u>	<u>11.535</u>	<u>1071</u>	Non-vegetated	<u>2004</u>	<u>2005</u>	<u>1</u>
<u>61.926</u>	<u>11.535</u>	<u>1071</u>	Non-vegetated	<u>2004</u>	<u>2005</u>	<u>1</u>
<u>61.908</u>	<u>11.537</u>	<u>1418</u>	Non-vegetated	<u>2004</u>	<u>2005</u>	<u>1</u>
<u>61.908</u>	<u>11.537</u>	<u>1418</u>	Non-vegetated	<u>2004</u>	<u>2007</u>	<u>3</u>
<u>61.929</u>	<u>11.527</u>	<u>1043</u>	Non-vegetated	<u>2005</u>	<u>2007</u>	<u>2</u>
<u>62.134</u>	<u>12.020</u>	<u>906</u>	<u>Shrubs</u>	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>62.135</u>	<u>12.055</u>	<u>1196</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>62.140</u>	<u>12.060</u>	<u>1316</u>	Non-vegetated	<u>2002</u>	<u>2003</u>	<u>1</u>
<u>62.137</u>	<u>12.053</u>	<u>1207</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>62.138</u>	<u>12.051</u>	<u>1192</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>62.137</u>	<u>12.030</u>	<u>1052</u>	Non-vegetated	<u>2002</u>	<u>2006</u>	<u>4</u>
<u>62.140</u>	<u>12.060</u>	<u>1316</u>	Non-vegetated	<u>2004</u>	<u>2007</u>	<u>3</u>
<u>62.141</u>	<u>12.061</u>	<u>1335</u>	Non-vegetated	<u>2005</u>	<u>2007</u>	<u>2</u>
<u>69.942</u>	<u>24.862</u>	<u>508</u>	Non-vegetated	<u>2003</u>	<u>2005</u>	<u>2</u>
<u>69.937</u>	<u>24.854</u>	<u>614</u>	Non-vegetated	<u>2003</u>	<u>2005</u>	<u>2</u>
<u>69.913</u>	<u>24.775</u>	<u>1002</u>	Non-vegetated	<u>2003</u>	<u>2005</u>	<u>2</u>
<u>69.910</u>	<u>24.770</u>	<u>1034</u>	Non-vegetated	<u>2003</u>	<u>2005</u>	<u>2</u>
<u>69.909</u>	<u>24.771</u>	<u>982</u>	Non-vegetated	<u>2003</u>	<u>2005</u>	<u>2</u>
<u>69.933</u>	<u>24.789</u>	<u>471</u>	Non-vegetated	<u>2004</u>	<u>2005</u>	<u>1</u>
<u>69.933</u>	<u>24.792</u>	<u>428</u>	Non-vegetated	<u>2004</u>	<u>2005</u>	<u>1</u>
<u>70.075</u>	<u>20.431</u>	<u>839</u>	Non-vegetated	<u>2003</u>	<u>2006</u>	<u>3</u>
<u>70.063</u>	<u>20.451</u>	<u>476</u>	Non-vegetated	<u>2003</u>	<u>2005</u>	<u>2</u>
<u>69.831</u>	<u>21.279</u>	<u>895</u>	Non-vegetated	<u>2002</u>	<u>2008</u>	<u>6</u>
<u>69.838</u>	21.273	700	Non-vegetated	2002	2007	<u>5</u>
<u>69.843</u>	<u>21.259</u>	<u>500</u>	Non-vegetated	<u>2002</u>	<u>2007</u>	<u>5</u>
<u>69.563</u>	20.433	861	Non-vegetated	2002	2007	<u>5</u>
<u>69.576</u>	<u>20.437</u>	<u>685</u>	Non-vegetated	<u>2002</u>	<u>2005</u>	<u>3</u>

<u>69.583</u>	<u>20.435</u>	<u>500</u>	Non-vegetated	<u>2002</u>	<u>2005</u>	<u>3</u>
<u>69.457</u>	<u>20.882</u>	<u>966</u>	Non-vegetated	<u>2006</u>	<u>2007</u>	<u>1</u>
<u>69.354</u>	<u>21.211</u>	<u>786</u>	Non-vegetated	<u>2004</u>	<u>2007</u>	<u>3</u>
<u>69.267</u>	<u>22.481</u>	<u>739</u>	Non-vegetated	<u>2003</u>	<u>2010</u>	<u>7</u>
<u>69.008</u>	<u>23.235</u>	<u>355</u>	<u>Forest</u>	<u>2003</u>	<u>2010</u>	<u>Z</u>
<u>69.980</u>	<u>27.269</u>	<u>130</u>	<u>Forest</u>	<u>2003</u>	<u>2009</u>	<u>6</u>
<u>70.542</u>	<u>29.322</u>	<u>502</u>	Non-vegetated	<u>2002</u>	<u>2009</u>	<u>7</u>
<u>70.541</u>	<u>29.342</u>	<u>480</u>	Non-vegetated	<u>2002</u>	<u>2009</u>	<u>7</u>
<u>70.538</u>	<u>29.363</u>	<u>415</u>	Non-vegetated	<u>2002</u>	<u>2009</u>	<u>7</u>
<u>70.537</u>	<u>29.380</u>	<u>355</u>	Non-vegetated	<u>2002</u>	<u>2009</u>	<u>7</u>
<u>70.400</u>	<u>28.200</u>	<u>10</u>	<u>Shrubs</u>	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>70.126</u>	<u>28.593</u>	<u>50</u>	Mire	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>69.376</u>	<u>24.496</u>	<u>284</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>69.370</u>	<u>24.082</u>	<u>469</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>69.377</u>	<u>24.082</u>	<u>408</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>68.996</u>	<u>23.035</u>	<u>308</u>	<u>Shrubs</u>	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>68.755</u>	<u>23.538</u>	<u>380</u>	<u>Shrubs</u>	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>69.580</u>	<u>23.535</u>	<u>380</u>	<u>Shrubs</u>	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>68.749</u>	<u>19.485</u>	<u>1713</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>69.292</u>	<u>18.133</u>	<u>1011</u>	Non-vegetated	<u>2007</u>	<u>2011</u>	<u>4</u>
<u>69.638</u>	<u>22.229</u>	<u>923</u>	Non-vegetated	<u>2007</u>	<u>2010</u>	<u>3</u>
<u>61.676</u>	<u>8.365</u>	<u>1861</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>61.684</u>	<u>8.372</u>	<u>1771</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>61.700</u>	<u>8.385</u>	<u>1559</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>61.698</u>	<u>8.401</u>	<u>1561</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>61.707</u>	<u>8.403</u>	<u>1314</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>61.701</u>	<u>8.393</u>	<u>1450</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>62.174</u>	<u>10.702</u>	<u>1630</u>	Non-vegetated	<u>2008</u>	<u>2009</u>	<u>1</u>
<u>62.170</u>	<u>10.703</u>	<u>1589</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>62.151</u>	<u>10.715</u>	<u>1290</u>	<u>Shrubs</u>	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>61.903</u>	9.275	1490	Non-vegetated	2008	2010	2
<u>61.898</u>	<u>9.282</u>	<u>1664</u>	Non-vegetated	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>69.291</u>	<u>18.130</u>	<u>990</u>	Non-vegetated	2007	2009	2

<u>69.249</u>	<u>20.445</u>	<u>766</u>	Non-vegetated	<u>2007</u>	<u>2009</u>	<u>2</u>
<u>69.642</u>	<u>22.194</u>	<u>761</u>	Non-vegetated	<u>2007</u>	<u>2010</u>	<u>3</u>
<u>69.681</u>	<u>22.126</u>	<u>570</u>	Non-vegetated	<u>2007</u>	<u>2010</u>	<u>3</u>
<u>62.149</u>	<u>9.378</u>	<u>1047</u>	Non-vegetated	<u>2005</u>	<u>2006</u>	<u>1</u>
<u>69.308</u>	<u>25.341</u>	<u>450</u>	<u>Shrubs</u>	<u>2008</u>	<u>2011</u>	<u>3</u>
<u>69.306</u>	<u>25.340</u>	<u>495</u>	<u>Shrubs</u>	<u>2008</u>	<u>2010</u>	<u>2</u>
<u>69.304</u>	<u>25.338</u>	<u>548</u>	<u>Shrubs</u>	<u>2008</u>	<u>2011</u>	<u>3</u>
<u>69.299</u>	<u>25.330</u>	<u>540</u>	<u>Shrubs</u>	<u>2008</u>	<u>2011</u>	<u>3</u>
<u>69.296</u>	<u>25.326</u>	<u>497</u>	<u>Shrubs</u>	<u>2008</u>	<u>2011</u>	<u>3</u>
<u>69.294</u>	<u>25.318</u>	<u>445</u>	<u>Shrubs</u>	<u>2008</u>	<u>2011</u>	<u>3</u>
<u>69.290</u>	<u>18.131</u>	<u>990</u>	Non-vegetated	<u>2007</u>	<u>2011</u>	<u>4</u>
<u>69.292</u>	<u>18.129</u>	<u>967</u>	Non-vegetated	<u>2007</u>	<u>2011</u>	<u>4</u>
<u>60.700</u>	<u>10.868</u>	<u>264</u>	Forest	<u>1994</u>	2004	<u>10</u>
<u>67.284</u>	<u>14.451</u>	33	Non-vegetated	<u>1994</u>	2004	<u>10</u>

Table S2: Boreholes used for validation of the permafrost model. x marks years where data is

2 <u>available.</u>

Barahala	Lat	Lon	Flouration	Douth	09/00	00/10	10/11	11/12	Deference
Borenole	<u>Lat</u>	<u>Lon</u>	<u>Elevation</u> (m)	<u>Depth</u> (m)	<u>08/09</u>	<u>09/10</u>	<u>10/11</u>	11/12	Reference
<u>Abojavri BH1</u>	<u>69.642</u>	<u>22.194</u>	<u>761</u>	<u>6.6</u>	x	X	X		<u>Farbrot et al.</u> 2013
<u>Abojavri BH2</u>	<u>69.681</u>	<u>22.126</u>	<u>570</u>	<u>30.3</u>	<u>×</u>	X			Farbrot et al.
<u>BH31/PACE31</u>	<u>61.676</u>	<u>8.368</u>	<u>1894</u>	<u>20</u>	X	X	X	X	<u>Isaksen et al.</u> 2011
<u>Guolosjavri</u> BH1	<u>69.354</u>	<u>21.211</u>	<u>786</u>	<u>32.3</u>		X	X	<u>×</u>	<u>Farbrot et al.</u> 2013
<u>Guolosjavri</u> BH2	<u>69.366</u>	<u>21.168</u>	<u>814</u>	<u>10.5</u>	X				Farbrot et al. 2013
<u>Guolosjavri</u> BH3	<u>69.356</u>	<u>21.061</u>	<u>780</u>	<u>10.5</u>	×				Farbrot et al. 2013
Iskoras BH2	<u>69.300</u>	<u>25.346</u>	<u>600</u>	<u>58.5</u>		X	×	×	Farbrot et al. 2013
<u>Jetta BH1</u>	<u>61.901</u>	<u>9.285</u>	<u>1560</u>	<u>19.5</u>		X	×		Farbrot et al. 2011
<u>Jetta BH2</u>	<u>61.902</u>	<u>9.234</u>	<u>1450</u>	<u>10</u>		X	×		Farbrot et al. 2011
<u>Jetta BH3</u>	<u>61.905</u>	<u>9.186</u>	<u>1218</u>	<u>10</u>		X	×	<u>×</u>	Farbrot et al. 2011
<u>Juvvass BH1</u>	<u>61.676</u>	<u>8.365</u>	<u>1861</u>	<u>10</u>		X	X	X	Farbrot et al. 2011
<u>Juvvass BH2</u>	<u>61.684</u>	<u>8.372</u>	<u>1771</u>	<u>10</u>		X	×		<u>Farbrot et al.</u> 2011
<u>Juvvass BH3</u>	<u>61.697</u>	<u>8.386</u>	<u>1561</u>	<u>10</u>		X	X		<u>Farbrot et al.</u> 2011
Juvvass BH4	<u>61.700</u>	<u>8.385</u>	<u>1559</u>	<u>10</u>		X	X	X	Farbrot et al. 2011
Juvvass BH5	<u>61.701</u>	<u>8.392</u>	<u>1468</u>	<u>10</u>		X	X	<u>×</u>	<u>Farbrot et al.</u> 2011
Juvvass BH5	<u>61.707</u>	<u>8.403</u>	<u>1314</u>	<u>10</u>		X	<u>×</u>	<u>×</u>	Farbrot et al. 2011
<u>Kistefjellet</u>	<u>69.291</u>	<u>18.130</u>	<u>990</u>	<u>24.8</u>	x				Farbrot et al. 2013
<u>Lavkavagge</u> BH1	<u>69.249</u>	<u>20.445</u>	<u>766</u>	<u>14</u>	x	X	×	×	Farbrot et al. 2013
<u>Lavkavagge</u> BH2	<u>69.239</u>	<u>20.493</u>	<u>600</u>	<u>30.5</u>	X				<u>Farbrot et al.</u> 2013
Lavkavagge <u>B</u> H3	<u>69.224</u>	<u>20.580</u>	<u>492</u>	<u>15.8</u>	X				<u>Farbrot et al.</u> 2013
Tron BH1	<u>62.174</u>	<u>10.702</u>	<u>1640</u>	<u>30</u>		X	X	×	<u>Farbrot et al.</u> 2011
Tron BH2	<u>62.170</u>	<u>10.703</u>	<u>1589</u>	<u>10</u>		X	X	×	Farbrot et al. 2011
Tron BH3	<u>62.151</u>	<u>10.715</u>	<u>1290</u>	<u>10</u>		X	X	X	<u>Farbrot et al.</u> <u>2011</u>