Response to Anonymous Referee 1

Referee comments shown as "RC:", author replies as "AR:".

RC: The work presents a very simple endpoint sensitivity analysis of van Genuchten parameters and therefore soil water retention affect subsurface thermal hydrology, with specific attention paid to ice re-distribution due to cryosuction and unsaturated hydrology. The work is very specific to a dry site, and therefore has limited broad application to other sites within the pan-Arctic region. Similar and more extensive studies of subsurface hydro thermal parameters have been conducted previously, but to my knowledge few if any have been done in 'dry sites' and which compare results to more than just observed subsurface temperature, namely the inclusion of soil moisture, which is absolutely necessary when assessing the sensitivity of van Genuchten parameters.

RC: I believe this inclusion of field data with the in depth modeling exercise produced some valuable insight into unsaturated thermal hydrology, which may prove valuable to the cryosphere community if the authors are able to focus both in the introduction and discussion of the need to quantify water retentions properties. The work is generally sound and free of technical errors and the authors do a fairly good job of making appropriate conclusions given the constraints of the modeling approach. Furthermore, the writing is clear and grammatically correct though not very concise or focused.

RC #1: While I believe that this work will eventually achieve full publication I recommend that authors consider revising the manuscript to clearly state assumptions made in the modeling application, which have implications with regards to the interpretation of the results, though not necessarily problematic implications in my view. Furthermore, given the simplicity of the modeling exercise and the narrow scope of only perturbing two parameters within the van Genuchten equation, I believe it is vitally important to clearly motivate within the introduction why understanding water retentions regimes in permafrost systems is necessary. In this version of the manuscript, the introduction is unfocused and instead reads like a history of what research has been done regarding permafrost without much attempt to link it to soil moisture redistribution.

AR #1: *We thank Anonymous Referee 1 for the valuable suggestions to improve and strengthen our paper; the text has been thoroughly revised and all comments have been addressed in our responses below. We acted on your suggestion and condensed the introduction section to better carve out the particular aim of this study. Also, we now stress the importance of soil water retention properties and the resulting moisture distribution more clearly when discussing thaw progression and active layer thickness variations over time.*

Major comments:

RC #2 MAJOR COMMENT-1: I therefore assume that there is no prescribed or simulated water fluxes in and out of the model domain, though it is not explicitly stated. While I see no huge reason why this would affect the validity of most of the results presented here, it should be remembered that any interpolation of the seasonality of the results should be taken with a grain of salt. In the results section the authors do an admirable job of pointing out when the model set-up without water fluxes in or out of the domain is responsible for deviations from observations. However, it maybe good in be supper clear about this set-up and state that what the boundary conditions of the model is. Particularly, that there is a no (water) flow in and out of the domain. In some documented cases water fluxes in and out as well as the shifted water retention location can have big consequences on the thermal regime of the subsurface i.e. [Atchley et al., 2016; Helbig et al., 2013; McKenzie and Voss, 2013; Sjöberg et al., 2016].

Atchley, A. L., E. T. Coon, S. L. Painter, D. R. Harp, and C. J. Wilson (2016), Influences and interactions of inundation, peat, and snow on active layer thickness, Geophysical Research Letters. doi: 10.1002/2016GL068550.

Helbig, M., J. Boike, M. Langer, P. Schreiber, B. R. Runkle, and L. Kutzbach (2013), Spatial and seasonal variability of polygonal tundra water balance: Lena River Delta, northern Siberia (Russia), Hydrogeology Journal, 21(1), 133-147. doi: 10.1007/s10040-012-0933-4.

McKenzie, J. M., and C. I. Voss (2013), Permafrost thaw in a nested groundwater-flow system, Hydrogeology Journal, 21(1), 299-316. doi: 10.1007/s10040-012-0942-3.

Sjöberg, Y., E. Coon, K. Sannel, A. Britta, R. Pannetier, D. Harp, A. Frampton, S. L. Painter, and S. W. Lyon (2016), Thermal effects of groundwater flow through subarctic fens: A case study based on field observations and numerical modeling, Water Resources Research. doi: 10.1002/2015WR017571.

***AR #2 MAJOR COMMENT-1:** It is correct that we assume no water fluxes in and out of the system and therefore assign no-flow boundaries to the model domain. Advective heat transport by lateral water flow is likely to be important for many active layer systems and we now more clearly highlight this and refer to the relevant literature in our revised introduction section. However, at the very dry UNISCALM site, there is strong evidence that the system is largely unaffected by lateral water fluxes and very little infiltration occurs (see page 4, lines 19-24 of the revised text). This has been investigated in detail in previous studies [cited as Schuh, 2015], where summer rainfall and snowmelt infiltration derived from hydro-meteorological field site data was applied to the surface. In that study it was shown that the small amount of infiltration in comparison to the existing amount of ground/pore ice did not have a notable effect on the inter-annual ALT variation at that site. Section 3.3 of our manuscript has been revised to more clearly state the assigned boundary conditions (page 7 line 30 – page 8, line 2) as well as the motivation for deliberately neglecting water fluxes at this particular study site (page 8, lines 15-21): "Lateral water fluxes through and infiltration into the system were neglected and no flow boundaries assigned to all faces of the model domain. While recognizing that flowing water can have considerable thermal effects on active layer processes, its exclusion is considered an appropriate assumption for the dry UNISCALM site (cf. Sect. 2)."*

RC #3 MAJOR COMMENT-2: The work presents mainly endpoint and mid point evaluations of parameter space. While this type of exercise provides some insight into how parameters effect model output, there is no information about the middle parameter space and any non-linearity raising from combinations of van Genuchten parameters is hidden or lost. I would suggest that the authors attempt to simulate or at the very least discuss how combinations of van Genuchten parameters between those that are tested might behave. Could there be non-linarites as a result of untested combinations of van Genuchten parameters that lie within the range of parameters tested?

***AR #3 MAJOR COMMENT-2:** This study is laid out as a scenario analysis which is why we used a combination of average parameter values as reference case, varied both parameters α and m independently by ±50%, and defined two more cases as the higher and lower end of this parameter space. This is a careful selection of parameters corresponding to a systematic range of values for the soil texture type observed at the UNISCALM site (silt loam) and consistent with information obtained from the UNSODA unsaturated soil hydraulic database as well as with the range of retention parameters reported in literature for that soil class. It is correct that by testing these seven cases, any other parameter combination within this range or potentially outside this range remains unconsidered. While this choice of representative scenarios should be sufficient for our study, we acknowledge the necessity to point out the general value of systematic parameter investigations due to the nonlinear nature of the retention curve. This is now highlighted in our revised text (section 3.3 of the revised manuscript; page 7, lines 27-30, as follows: "Given that each combination of van Genuchten parameters will result in different soil moisture profiles, each simulation test case was set-up to attain unique ice-liquid-gas states. Still, despite the systematic approach of testing relevant parameter combinations, note that any potential nonlinearities arising from untested combinations within the parameter space remain unconsidered in this analysis.")*

RC #4 MAJOR COMMENT-3: It seems the central focus of the paper is how does unsaturated soil moisture distribution in the ALT and near surface permafrost layer affect the subsurface thermal regime at this relatively dry site. The introduction on the other hand reads like a history or what has been done, but it is my preference to use that history to highlight why answering the unsaturated soil moisture distribution effect is important. This usually helps focus the paper and reader to why the results matter and produce a more precise manuscript.

AR #4 MAJOR COMMENT-3: We acted on your suggestion and revised the introduction accordingly. We removed those parts that did not contribute directly to the main objective of this study, i.e. the more general review of permafrost-hydrological modeling studies and instead, we placed more focus on the relevance of soil moisture for active layer processes and its importance for climate change *investigations, especially in cold regions: "Both soil moisture and the thickness of the active layer have been identified as Essential Climate Variables (GCOS, 2015). Soil moisture is an important variable for energy exchange and governs the processes occurring at the land-atmosphere interface by partitioning incoming solar radiation into fluxes of latent and sensible heat (GCOS, 2015). Soil moisture controls subsurface physical properties such as thermal conductivity and heat capacity, so that the movement of moisture within the subsurface is essential for understanding the water and heat balance of the ground, particularly in cold climates (Wu et al., 2016). Still, most studies on permafrost thaw projections mainly investigate the structural uncertainty in climate models, whereas the parametric uncertainty in soil properties is barely accounted for (Harp et al., 2016)." (page 2, lines 12-18 of the revised manuscript).*

Minor comments:

RC #5: Page 3 L 14-15: "Soil water retention is a critical, but highly uncertain parameter" I agree with this statement, and I believe the available literature also has evidence that supports this statement. Unfortunately, and despite the extensive literature cited in the introduction, the case that soil water retentions is critical, has not been made within the introduction of this paper, and therefore this statement and the purpose of the paper seems out to come out of no where. I suggest reshaping the introduction to be less of a history of what has been done to how the existing literature suggests that soil water retention may be important.

AR #5: *This section has been revised substantially. Please refer to our response to MAJOR COMMENT-3 (AR #4).*

RC #6: Page 5 Line: 12-13: "Active layer thickness was considered both for the grid centre, which is the point nearest the location of the ground temperature measurements, as well as for the average of all grid points" This is an awkward sentence. Do you mean ALT was measured at the grid center points and then averaged across an array of grid center points? I only see one observed time series in the figures, is this the average across the site?

AR #6: *ALT was measured annually at all 121 nodes of the 100 m x 100 m UNISCALM grid (see page 5, lines 12-14). First, we consider the ALT measurements exclusively from the node in the grid center because it coincides with the location of the utilized subsurface temperature dataset (obtained from the Tinytag loggers, see page 5, lines 14-17). Second, we use the annual ALT average of all 121 grid nodes to reduce measurement uncertainty and obtain a more robust dataset. In our analysis, we refer to the ALT measurements as "grid average" and "grid center" (see Fig. 6a-b, Tab. 5 of the revised manuscript). In the manuscript, we clarified this paragraph by minor adjustments to section 3.1.*

RC #7: Page 5 Line: 30: The unsaturated version of Darcy's law is Richard's equation.

AR #7: *Yes, the model (ATS) couples RE with an equation for heat transport which accounts for latent heat transfer, where several constitutive relationships are used to close the system of equations, including Darcy's law and thermodynamic constraints. This is further clarified in the revised manuscript (page 6, lines 14-16).*

RC #8: Page 6 Line 31: Omit 'Then' in "Then different. . .."

AR #8: *Deleted: "Then".*

RC #9: Page 7 Line 2: It should be noted that setting residual saturation to zero in all cases 1) may produce the largest change in soil water content as all the water can drain out in dry cases, and 2) this formulation will allow all the pore water to go to ice during the winter, which will increase the winter thermal conductivity compared to systems where some pore water remains in a liquid state. Even thought the authors rightly point out that this assumption is often made it may still be worthwhile discussing these result in comparison to other more complete subsurface sensitivity studies such as [Harp et al., 2015], which includes residual saturation.

Harp, D., A. L. Atchley, S. L. Painter, E. Coon, C. Wilson, V. Romanovsky, and J. Rowland (2015), Effect of soil property uncertainties on permafrost thaw projections: a calibration-constrained analysis, The Cryosphere 10(3), 1-18. doi: 10.5194/tc-10-1- 2016.

***AR #9:** We have updated the text and now include a highlight of our results in the context of the highly relevant study by Harp et al. (2016), as follows: "The missing sensitivity of soil water retention parameters to inter-annual ALT variation is not surprising. Also Harp et al. (2016) found the van Genuchten parameters not to affect subsurface temperatures in a long-term thaw projection study. This might be explained by the fact that in areas subject to a seasonal freeze/thaw cycle, the water retention parameters mainly control the seasonal soil moisture (re-)distribution during freezing and thaw (cf. 5.1). While we found the different retention curves to affect the rate of thaw progression and thus the respective annual thaw depth, the total period of active layer development from thaw to freeze-back was similar in all cases (cf. Sec. 5.2). Water retention characteristics therefore seem to be relevant mainly on a short time scale during thaw and freeze-up." (page 15, from line 30 onwards of the revised version).*

RC #10: Page 7 Line 5: Omit 'Then' in "Then, both alpha . . ."

***AR #10:** The manuscript text has been clarified (page 7, lines 21-23).*

RC #11: Page 7 Lines 5-10: I think this can be rephrased to be more clear and concise. Also, why were only 7 parameter combinations explored? Even though endpoint combinations can provide a lot of information about the behavior and sensitivity of parameters, there is little information about the model response to multiple combinations of parameters. Specifically any nonlinearities within the parameters space remain unknown.

***AR #11:** This part of the manuscript text has been re-written to make the presentation more concise (page 7, lines 21-26). For the choice of seven parameter combinations and potential nonlinearities of the parameter space please refer to our response to MAJOR COMMENT-2 (AR # 3)*

RC #12: Page 7 Lines 11-14: I think this needs rephrasing to be clearer, I would suggest something like, "Given that each combination of van Genuchten paramters will result in different soil moisture profiles under frozen conditions, each simulation test case with unique van Genuchten parameter combinations was spun-up and froze to attain unique ice liquid- gas states"

***AR #12:** The section has been rephrased accordingly. We also included a clearer statement of the applied boundary conditions (page 7, line 27 ff).*

RC #13: Page 7 Lines 23-27: This provides reasoning in this modeling experiment to neglect water fluxes in and out of the domain. However the approach to neglect water fluxes is not clearly stated. While this is a huge simplification of the system I am ok with the approach, as long as it is clearly stated that a no water flux boundary is assigned. Please clearly state this boundary condition. Second, without the model able to represent transient water flows during the spin-up how can it be assured that the model is correctly representing the approximate amount of water in the system? Could this approach cause the mismatch between the observed and simulated water content in Figure 4? The reason I am ok with this approach here is that later the authors point out in the results when the model is unable to match observations. Which in my opinion highlights when representing a flux of water in and out of the system is necessary and when it is not, even for relatively dry sites, and thus becomes somewhat of a high-lighted result in my opinion. This then begs the question, how much more important would representing surface and subsurface water flows in wet or highly transient sites be? Furthermore, given that van genuchten parameters were somewhat insensitive to subsurface temperatures in this study, would they be in sights the experience more transient hydrology?

***AR #13:** This section was reformulated and is now more precise in stating the applied boundary conditions. For the assumptions made on water fluxes through the system please refer to our response to MAJOR COMMENT-1 (AR #2). Regarding the correct amount of water in the closed* *system, we generally represent field site conditions by saturating the unfrozen model domain below about 2 m depth. Assigning a pressure of -200 hPa as the top boundary condition before model freezing and spin-up resulted in a water content in the top cell of 0.11-0.32 (depending on scenario) and a linear increase up to full saturation (0.4) in the model domain below about 2 m depth. This is consistent with the water content both in the permafrost (0.4) and in the active layer (0.1-0.25) recorded at the field site. Please note that after freezing the model domain, each simulation test case was subject to a transient spin-up (allowing water to redistribute in the subsurface) until a periodic steady state was achieved (page 8, lines 6-9). Furthermore, previous modeling studies by Schuh [2015] (already cited) showed that infiltration estimated from meteorological field site data only accounted for an insignificant fraction of the existing water content in the system. Therefore, it seems unlikely that the mismatch in water content seen between field site data and some of the model cases is solely caused by the assumption of no water fluxes in to the system.*

RC #14: Page 11 Lines 14-26: Though somewhat addressed in the next section (5.2), it maybe beneficial to discuss why the vertical movement or spreading of the ice thermal mass is important. I can invasion scenarios that create sharp or diffuse thermal gradients in the subsurface due to where and how concentrated the ice is.

AR #14: *The manuscript was substantially revised with regard to the particular effect of ice striation on thermo-hydrological subsurface processes e.g. for the progression of the thawing front (please see our response AR#15 to comment RC #15 below). We also included a short general discussion on the relevance of the vertical spreading of the ice in section 5.3 (page 15, lines 30ff).*

RC #15: Page 12 Lines 21-25: It would be interesting to extend the effective thermal conductivity evaluation to include differences in the location of ice mass in the subsurface, specifically compare the striated ice distribution (Fig 3, b) to the diffuse distribution (Fig 3. C). Does the striation of ice change effective thermal conductivity?

AR #15: *We extended our analysis on thaw progression in section 5.2 insofar as we now also consider the local rate of thaw within the soil profile in addition to the integrated consideration of the 1 m soil column (Tab. 7). We use the scenarios shown in Fig. 3 with different striation to illustrate the different rates of thaw in systems characterized by different soil moisture contents and distribution, ranging from diffuse to highly striated ice distribution. Please see the revised manuscript and the new Fig. 5 (relevant excerpts of the text reproduced in the following).*

"Furthermore, model simulations show that not only the amount of soil moisture, but also the distribution of ice within the active layer impacts the progression of the thawing front. Fig. 5 compares the ice content profile before the onset of thaw in 2011 to the respective thaw rate when the ground surface temperatures become positive. As shown previously (cf. Fig. 3), model scenarios 'ref case' (black), 'high m' (green) and 'max case' (orange) resulted in a distinct stratification of ice, whereas 'low m' (blue) shows almost a linear increase in ice content towards the permafrost table (Fig. 5a). In all scenarios, thawing the upper 10 cm of the ground occurs at a relatively low rate between 1.3-1.4 cm/d (Fig. 5b) mainly because air temperatures are still low, but also because of latent heat consumption due to the increased ice content in the thin layer just beneath the surface. Once the thawing front passes the ice layer at 5 cm depth, the thaw rate increases to its maximum of 5 cm/d, fuelled by markedly increasing air temperatures (not shown) and regardless of the respective soil moisture content. Below 20 cm depth, all scenarios show a generally decreasing thaw rate, but with notably case-specific differences only between 40 cm and 60 cm depth. Here, discrepancies originate from the particular ice-liquid-gas composition in the thawing ground and its effect on heat propagation, as discussed above. Furthermore, enhanced thaw due to advective heat transport through previously frozen water is likely to occur in more saturated systems such as 'ref case' (e.g. at 50 cm depth). Scenarios 'high m' and 'low m' show discrepancies in their thaw rate, while having comparable ice contents. In 'high m', the thaw rate drops to 1.4 cm/d when reaching the clearly defined ice-rich zone at 60 cm depth, whereas the thaw rate at that depth is much higher (2.5 cm/d) in the 'low m' case, characterized by a more stable ice content profile." (page 14, lines 7-23)

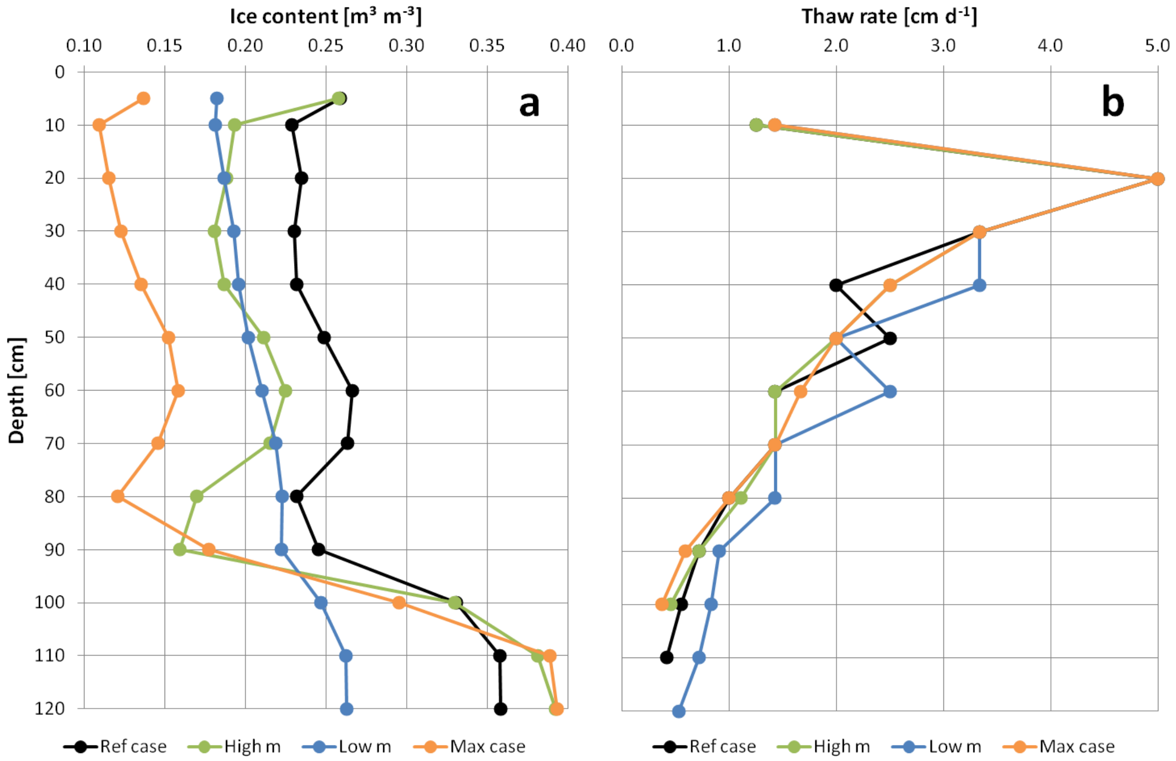

Figure 5: Comparison of (a) simulated ice content distribution with depth at the end of winter 2011 (01.05.2011) and (b) the corresponding modelled rate of active layer thaw starting after the first day of positive ground surface temperatures (25.05.2011), exemplified by four selected model scenarios.

RC #16: Page 13 Section 5.3: I appreciate this discussion that addresses ALT characteristics beyond the scope of soil moisture distribution and how seasonal differences i.e. winter versus summer, have been shown in literature and the present study to act differently on ALT. However, I think it too should be discussed within the context of soil moisture distribution. While in general it may be counter intuitive that ALT is more responsive to winter conditions then summer, but for those of us working on permafrost it makes since. In the Arctic winters are long, summers are short and the ground is mostly in a frozen state. Furthermore, ice is more thermally conductive than water and therefore a cold signal or lack thereof in the winter will propagate further into the subsurface. Given that winter conditions are important, this work should then address how does soil moisture distribution and therefore ice distribution in the winter moderate the winter time signal. Does it at all? If so, how does it? Given that this experiment is in a dry site with little water moving through the subsurface, can the conclusions be applied to wet sites with lots of subsurface flow? What further research would be necessary to answer these issues?

AR #16: *We appreciate your suggestion. Section 5.3 has now been extended by a more detailed paragraph about the role of the particular water retention curve for inter-annual ALT variation. This was an important step also to synthesize our findings and conclusions from the previous sections regarding the sensitivity of retention parameters to seasonal vs. inter-annual active layer dynamics. This way we believe to have polished the manuscript further to make in more focused on the importance of soil moisture (re-)distribution. Nonetheless, this comment certainly highlights a need for further research, in particular considering how sites with different hydro-climatic conditions may yield different active layer moisture/wetness conditions and ice dynamics.*

"The missing sensitivity of soil water retention parameters to inter-annual ALT variation is not surprising. Also Harp et al. (2016) found the van Genuchten parameters not to affect subsurface temperatures in a long-term thaw projection study. This might be explained by the fact that in areas

subject to a seasonal freeze/thaw cycle, the water retention parameters mainly control the seasonal soil moisture (re-)distribution during freezing and thaw (cf. 5.1). While we found the different retention curves to affect the rate of thaw progression and thus the respective annual thaw depth, the total period of active layer development from thaw to freeze-back was similar in all cases (cf. Sec. 5.2). Water retention characteristics therefore seem to be relevant mainly on a short time scale during thaw and freeze-up." (page 16, lines 30ff).

Response to Anonymous Referee 2

Referee comments shown as "RC:", author replies as "AR:".

General comments:

RC #1 GENERAL COMMENT: This manuscript investigates freeze/thaw dynamics in a soil profile for a 14-years time series of measured data from the UNISCALM-site on Svalbard with the aid of a numerical model. Specifically, for a homogeneous silt profile, the van Genuchten parameters α and n are varied in a reasonable range. Differences in thaw depth, water and ice content are interpreted i) for a quasi-synthetic test case using upper and lower boundary conditions measured in the field and ii) compared to field observations. The paper is very well written and fits well into the scope of The Cryosphere. I have one major concern which is the fit between measured and modeled data which – in my opinion - needs major revision or restructuring of the paper before the manuscript can be recommended for publication.

AR # 1 GENERAL COMMENT: *We thank Anonymous Referee 2 for valuable suggestions to improve and strengthen our paper; all comments have been thoroughly addressed in our responses below. With regard to the major concern regarding the comparability of model results and field site data, we revised the manuscript insofar as we removed text/paragraphs focusing on detailed quantitative comparison. Also, we rephrased the introduction and study aim to distinguish more clearly the character and claims of our work from that of a calibration study.*

Major comments:

RC #2 MAJOR COMMENT: Run in a quasi-synthetic mode, the model is very helpful for exploring the effects of variations in van Genuchten α and n on thaw depth as well as water and ice distribution throughout a silty soil profile (cf. Fig. 3). In this case, a rather simple test case is generated where modelled data depend only on the chosen parameterizations of the soil profile and the imposed upper and lower boundary conditions. With these simulations, processes can be interpreted based on the assumed conceptual model without real linkage to field observations and this is done very well in this study. However, as soon as simulations are compared to measured field data, especially Figure 4 shows that there are still large discrepancies between modelled data and observations and the model is not yet able to reproduce freeze/thaw processes observed in the field. For example, it is definitely not sufficient when summer data at one depth of the profile fit to summer simulations of one test case and winter data at the same depth of the profile fit to winter data of another test case. Here, the challenge is to set up a conceptual model and to find a parameterization that is able to reproduce observations (temperature, moisture, ice content) at all depths during the complete time series before processes occurring at the site can be interpreted and quantified safely. Finding such a paramterization could be quite some effort, so probably it is the better choice for this paper to reduce the study to the synthetic cases and remove the sections comparing measured and modelled data. The alternative would be to "calibrate" the model such that simulations are able to reproduce the field observations.

AR #2 MAJOR COMMENT: *It is not our intention or aim to conduct a model calibration; rather our general main objective is to investigate effects of different soil water retention properties on active layer dynamics. This site is chosen on the basis of previous initial investigations (Schuh, 2015) showing that the site is very dry and unsaturated and potentially highly influenced by cryosuction effects. Therefore in this study we conduct a scenario analysis where we investigate different van Genuchten parameter combinations applicable for the site conditions with the objective to improve the understanding of the physical processes governing the dynamics of an unsaturated active layer as found at/consistent with the UNISCALM site. We derive our simulation test cases from field information (temperature and pressure boundary conditions and sediment properties) and again use field site data (ALT and water content measurements as well as cryostratigraphic information) to place the analysis and model results in the context of this particular site. The comparison between field site observations* *and model results is done to classify the different scenarios with regard to certain field site characteristics, for example the measured water content at the field site (Fig. 4) is compared to simulations not only as an indicator for the correct amount of water in the system, but also to derive information on thaw progression.*

We revised the manuscript insofar as to avoid misinterpretations of our intentions with the study and the quantitative comparisons, starting by the introduction and a clearer statement of the purpose of our study (page 3, lines 30ff). We also eliminated the quantification of root mean squared errors (RMSE) for the differences between simulated and measured ground temperatures in section 3.3 (page 8, lines 30ff) and section 4.1 (page 9 lines 20) to avoid implications of a calibration study.

Specific comments:

RC #3: P 1, L 28: correct “temperatures”

AR #3: *Corrected: “temperatures”.*

RC #4: P 2, L 26: Which controlling factors? Please add related information.

AR #4: *Information was added: “[…] key controlling factors of active layer development, mainly air temperature and solar radiation, […].”*

RC #5: P 3, L 18-21: The two specific aims are very closely related. Please reformulate the major aims of the study.

AR #5: *The objective of the study has been revised and reformulated as follows: “The aim is to study how soil moisture retention properties affect moisture and ice (re-)distribution as well as subsurface temperature and active layer thickness variations in the partially saturated active layer under multiple freeze-thaw cycles. In a scenario analysis approach, the different soil moisture retention properties are expressed through careful selection of relevant parameter values derived from field information, and simulation results are put in the context of the particular UNISCALM study site and other relevant permafrost environments.” (page 4, lines 22ff).*

RC #6: P 4, L 29: correct “100 m x 100” m or “100 x 100 m2”

AR #6: *Corrected: “100 m x 100 m”.*

RC #7: P 5, L 10: please add probe to Table 2

AR #7: *We previously stated the probe as “”DL6 Data Logger” in Table 2. This notation was misleading; we now changed it to “Delta-T profile probe” to comply with the text.*

RC #8: P 6, L 28: The vertical resolution of the model (0.1 m) is rather coarse. Especially, close to the ground surface, resolutions of 0.01 m or even less are often required to adequately reproduce temperature and moisture gradients. Did the authors check the performance of the model in this regard?

AR #8: *Numerical convergence is assured by careful selection of convergence criteria, combined with the use of robust numerical computation routines (for details we refer to Painter et al., 2016, which is now also cited in our revised version). The mesh resolution is selected based on model needs and intention/purpose of the investigation performed; here a mesh of 0.1 m is deemed sufficient since we focus on general active layer dynamics for homogeneous soil texture and using ground surface temperature as thermal boundary condition. As such, surface heat attenuation processes (snow cover, ponding, vegetation, etc) which otherwise may require more careful consideration of near-surface and surface mesh discretization are avoided.*

Painter, S.L., Coon, E.T., Atchley, A.L., Berndt, M., Garimella, R., Moulton, J.D., Svyatskiy, D., Wilson, C.J., 2016. Integrated surface/subsurface permafrost thermal hydrology: Model formulation and proof-of-concept simulations. Water Resources Research. doi:10.1002/2015WR018427

RC #9: P 6, L 31: please add reference for the chosen parameter set

AR #9: *References were added to Table 3:*

Andersland, O.B. and Ladanyi, B. (1994): An introduction to frozen ground engineering. Dordrecht (Springer), ISBN: 978-1-4757-2290-1.

Fitts, C. (2013): Groundwater science. 2nd edition, Oxford (Elsevier), doi: 10.1016/B978-0-12-384705-8.00016-9.

Freeze, R.A. and Cherry, J.A. (1979): Groundwater. Hemel Hempstead (Prentice), ISBN: 978-0133653120.

Huang, P.M.; Li, Y. and Sumner, M.E. (eds.) (2012): Handbook of soil sciences – properties and processes. 2nd edition, Boca Raton (Taylor & Francis), ISBN: 978-1-4398-0305-9.

Kirsch, R. and Yaramanci, U. (2006): Geophysical characterization of aquifers. In: Kirsch, R.(ed.), Groundwater geophysics - a tool for hydrogeology. Berlin (Springer), pp. 439-457,ISBN: 978-3-540-29383-5.

Ochsner, T.E.; Horton, R. and Ren, T. (2001): A new perspective on soil thermal properties. Soil Sci. Soc. Am. J. 65, pp. 1641–1647.

Schwartz, F.W. and Zhang, H. (2003): Fundamentals of ground water. New York (Wiley),ISBN: 978-0-471-13785-6.

Wesley, L.D. (2010): Fundamentals of soil mechanics for sedimentary and residual soils. Hoboken (Wiley), ISBN: 978-0-470-37626-3.

RC #10: P7, L 9-14: Please clarify initial condition: As far as I understand, capillary pressure was linearly interpolated with 0 hPa at 1.2 m depth and -120 hPa at ground surface?

AR #10: *We first put the water table at about -2 m by assigning a pressure of about -200 hPa as top boundary condition and then interpolating linearly with depth. Then we froze the model domain, resulting in the water table to move up to about -1.2 m. We clarified this in the manuscript by reformulating the describing the model setup (page 7, lines 27ff).*

RC #11: P 7, L 21: please correct: linearly

AR #11: *Done.*

RC #12: P 8, Sect. 4.1: Table 5 is not very well suited for comparing measured and modeled data. A plot like Figure 4 would be much more helpful for assessing the quality of the different models.

AR #12: *We took into consideration to display a graph of selected data only and to move Table 5 to the supplementary materials. Eventually we decided to keep Table 5 in the text. We believe that in the results section covering the differences in ALT with regard to certain retention properties it is important to show the complete findings, i.e. the two field site datasets and all seven model scenarios, including their statistical characteristics. This is not practicable in a plot due to the large number of simulation cases which obfuscates comparison. Also, since we would like to avoid the direct comparison between field observations and model results (see our response to major comment above [AR # 2]), we feel that the table is more suitable.*

RC #13: P 9, L- 13: correct “system”

AR #13: *Done.*

RC #14: P 9, Section 4.2: Case studies discussed in the text and shown in Fig. 4 are not the same. Simulations shown in Fig. 4 do not reproduce measured values.

AR #14: *The discussion regarding soil moisture development (Figure 4) has been revised and is now focused exclusively on those three scenarios shown in Figure 4. We also added a note to the caption of Figure 4 stating that "The remaining simulation cases (not shown) reside within the limits of the min and max cases." About the match between modeled and observed soil moisture please refer to our response to the major comment above (AR #2).*

RC #15: Sect. 5: The general discussion of the influence of α and n on the processes occurring in the soil profile is well done and okay as long as it is based on the synthetic cases.

AR #15: *Please refer to our response to the major comment concerning the comparison of simulations to field data (AR #2).*

Soil moisture redistribution and its effect on inter-annual active layer temperature and thickness variations in a dry loess terrace in Adventdalen, Svalbard

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Abstract. High resolution field data for the period 2000-2014 consisting of active layer and permafrost temperature, active layer soil moisture, and thaw depth progression from the UNISCALM research site in Adventdalen, Svalbard, is combined with a physically-based coupled cryotic and hydrogeological model to investigate active layer dynamics. The site is a loess-covered river terrace characterized by dry conditions with little to no summer infiltration and an unsaturated active layer. A range of soil moisture characteristic curves consistent with loess sediments are considered and their effects on ice and moisture redistribution, heat flux, energy storage through latent heat transfer, and active layer thickness is investigated and quantified based on hydro-climatic site conditions. Results show that soil moisture retention characteristics exhibit notable control on ice distribution and circulation within the active layer ~~caused by~~through cryosuction and subject to seasonal variability and site-specific surface temperature variations. The retention characteristics also impact unfrozen water and ice content in the permafrost. Although these effects lead to differences in thaw progression rates, the resulting inter-annual variability in active layer thickness is not large. Field data analysis reveals that variations in summer degree days do not notably affect the active layer thaw depths; instead, a cumulative winter degree day index is found to more significantly control inter-annual active layer thickness variation at this site. A tendency of increasing winter temperatures is found to cause a general warming of the subsurface down to 10 m depth (0.05 to 0.26˚C/yr, observed and modelled) including an increasing active layer thickness (0.8 cm/yr, observed and 0.3 to 0.8 cm/yr, modelled) during the 14-year study period.

Keywords: Active layer; Permafrost; Numerical modelling; Circumpolar Active Layer Monitoring (CALM).

1 Introduction

Permafrost environments have been identified as key components of the global climate system given their influence on energy exchanges, hydrological processes, carbon budgets and natural hazards (Riseborough et al., 2008; Schuur et al., 2015). Over the last 30 years, air temperatures in Polar Regions have increased by 0.6°C per decade, which is twice the global average (IPCC, 2013). On Svalbard, long-term records indicate an increase in mean annual air temperature of 0.2°C per decade since the beginning of the 20th century (Humlum et al., 2011), and permafrost warming has been detected to a depth of 60 m based on borehole measurements (Isaksen et al., 2007). The relationship between climate and permafrost temperatures is, however, highly complex. Changes in active layer thickness can be buffered from effects of changing air temperatures by vegetation, snow cover, and permafrost ice content and its thermal state, as well as by variable heat and water flows occurring in the active layer. The active layer is an important part of in cold regions, where thermal and hydrological processes determine local phenomena such as erosion, hydrological and ecosystem changes (Karlsson et al., 2012; Lyon et al., 2009; Walvoord and Kurylyk, 2016; Walvoord and Striegl, 2007), and has implications for solute and carbon transport (Frampton and Destouni, 2015; Giesler et al., 2014; Jantze et al., 2013) and the global carbon-climate feedback (Tarnocai et al., 2009). Also, the permafrost beneath the active layer limits percolation and subsurface water flow, allowing wet soils and surface ponding even in dry climates.

Both soil moisture and Tthe thickness of the active layer have beenis identified as an Essential Climate Variables (GCOS, 2015). Soil moisture is an important variable for energy exchange and governs the processes occurring at the land-atmosphere interface by partitioning incoming solar radiation into fluxes of latent and sensible heat. Also, soil moisture controls subsurface physical properties such as thermal conductivity and heat capacity, so that the movement of moisture within the subsurface is essential for understanding the water and heat balance of the ground, particularly in cold climates (Wu et al., 2015). Still, most studies on permafrost thaw projections mainly investigate the structural uncertainty in climate models, whereas the parametric uncertainty in soil properties is barely accounted for (Harp et al., 2016). Active layer thickness, in contrast, is one of the most distinct and used as an indicators of permafrost change degradation (GCOS, 2015), and which is why the response of the active layer to climatic variations has been studied using climatic and ground thermal monitoring in several Arctic regions (Frauenfeld, 2004; Lafrenière et al., 2013; Osterkamp, 2007). For example, long-term air and ground temperature time series have been evaluated as explanations for recent permafrost warming along a north-south transect through Alaska (Osterkamp, 2007). Lafrenière et al. (2013) found that the timing of snowmelt was a more significant factor controlling active layer temperature than snow accumulation at an arctic site in Canada, and Frauenfeld (2004) used ground temperature data collected at 242 stations across Russia to estimate thaw depths and identify long-term changes in active layer thickness. On Svalbard, Roth and Boike (2001) quantified the soil thermal properties and conductive heat fluxes for an experimental site near Ny-Ålesund based on subsurface temperature data and soil moisture measurements. Akerman (2005) monitored active layer depths over several decades in the Kapp Linné area with regard to periglacial slope processes, and found active layer deepening to correlate well with increaseds in air temperature. Isaksen et al. (2007) reported rising permafrost temperatures with accompanying increases in active layer depths, when evaluating thermal monitoring data for the 100 m deep Janssonhaugen borehole penetrating a bedrock hill in inner central Adventdalen over a period of six years. For the period 2000-2007, Christiansen and Humlum (2008) used a combined consideration of thermal monitoring data and Circumpolar Active Layer Monitoring (CALM) measurements to derive key controlling factors of active layer development, mainly air temperature and solar radiation, at the UNISCALM study site in Adventdalen, central Svalbard.

The physics of thermal conduction and latent heat transfer has been the basis of several studies on permafrost dynamics and active layer processes (Hinzman et al., 1998; Kane et al., 1991; Shiklomanov and Nelson, 1999; Smith and Riseborough, 2010; Zhang et al., 2008). Studies have also proceeded beyond analysis of monitoring data to explore active layer dynamics; Westermann et al. (2010) used ground penetrating radar to identify the link between soil moisture content and thaw depths at Ny-Ålesund, and Watanabe et al. (2012) applied electrical resistivity tomography to identify the seasonal variation in thaw depth in an alluvial fan in Adventdalen. Also, increasing air and permafrost temperatures in a 100 m deep borehole located in Tarfala, Sweden have been observed and mechanistically linked through numerical modelling (Jonsell et al., 2013; Pannetier and Frampton,

~~2016), and a numerical study based on generic wet permafrost environments related to a site at Barrow, Alaska, indicates organic layer thickness and snow cover as key features controlling active layer thickness (Atchley et al., 2016).~~ Several recent advances in permafrost and active layer model development have been made, in particular in the field of coupled thermal-hydrogeological models of partially frozen ground (Bense et al., 2009; Karra et al., 2014; McKenzie et al., 2007; Painter, 2011). This has enabled studies on effects of permafrost degradation on changes in groundwater flows (Kurylyk et al., 2016; Scheidegger and Bense, 2014; Sjöberg et al., 2016), in particular showing expected increase in base flow and decrease in seasonal variability in discharge under warming (Frampton et al., 2013, 2011; Walvoord et al., 2012) and increased pathway lengths and delays in solute mass transport and breakthrough due to non-linear active layer thickness increase (Frampton and Destouni, 2015).

In this study, a comprehensive long-term monitoring data set collected between 2000 and 2014 at the UNISCALM research site in Adventdalen, Svalbard, which includes ground temperature, soil moisture, and active layer thaw depth progression, is applied to a physically-based numerical model for partially frozen ground to investigate subsurface processes controlling active layer dynamics. This site is characterized by little precipitation and dry unsaturated conditions in the active layer. In this particular environment, ~~S~~soil water retention is a critical but also highly uncertain parameter, which we investigate based on a range of characteristic retention curves commonly ascribed to the dominant sediment type (silt loam) of the location. ~~The aim is to study soil moisture content and redistribution within the active layer and its effects on subsurface ground temperatures and inter-annual active layer thickness variations subject to site-measured ground surface temperature variations. Specifically, we study 1) How retention properties affect soil moisture and ice distribution and redistribution in the partially saturated active layer under multiple freeze-thaw cycles consistent with site hydro-meteorological conditions; and 2) What the effect of different soil water retention properties on subsurface temperature and active layer thickness is over the course of the study period.~~ The aim is to study how soil moisture retention properties affect moisture and ice redistribution as well as subsurface temperature and active layer thickness variations in the partially saturated active layer under multiple freeze-thaw cycles. Using a scenario analysis approach, different soil moisture retention properties are expressed through careful selection of relevant parameter values derived from field information, and simulation results are then placed in the context of the UNISCALM site as well as other relevant permafrost environments.

2 Site description

Adventdalen, located in the central part of Svalbard, is a typical U-shaped valley that dissects a landscape with peaks, ridges and plateaus. The valley is partially filled by periglacial sediments primarily in the form of colluvial, alluvial, and aeolian deposits. During about four months of summer, mainly between June and September, the braided river system of Adventelva discharges into Adventfjorden (Killingtveit et al., 2003). The tributary streams draining to Adventelva have built up large alluvial fans on both sides of the valley, and several river terraces have been described that confine the braided channel system of Adventelva, and can extend up to several meters above river elevation (Bryant, 1982).

The UNISCALM site (78°12’ N, 15°45’ E) is located on a terrace on the southern side of Adventelva at an elevation of 10 m a.s.l. (Fig. 1). The upper 1.3 m of sediment has been described as horizontally layered loess, i.e. silt-dominated aeolian sediment (Christiansen and Humlum, 2008). Information from adjacent boreholes and several study sites in the downstream part of the valley supports this classification, and provides evidence of finegrained, silt-dominated largely deltaic sediment with interbedded clay and sand down to a depth of 60 m (Gilbert, 2014). The site is sparsely covered by typical arctic tundra vegetation consisting of mosses and low vascular plants like *Salix herbacea* and sedges (Bryant, 1982).

Cryostratigraphic information obtained from drilling shows ice saturation in the top permafrost and considerable excess ice (up to 50%) at around 2.0-4.5 m depth in several boreholes in lower Adventdalen, with total carbon content estimated and measured to be only about 1-5% (Cable et al., In review), so that no considerable thermal insulation effects through soil carbon are to be expected (Koven et al., 2009). Despite its location at the outlet of the valley Endalen, the UNISCALM site is not notably influenced by surface runoff or lateral subsurface flows since it is cut-off from the upper part of the alluvial fan filling lower Endalen by a road construction. Endalselva drains the valley and discharges directly into the local water reservoir Isdammen (Fig. 1), leaving the UNISCALM site unaffected from increased snow and glacial melt water runoff during spring and summer. Only snow, which covers the site at the~~in~~ end of winter and which does not sublimate, may infiltrate the ground during snow melt.

Permafrost is continuous in Svalbard and can extend to 500 m depth in the mountains, whereas in the valley bottoms, such as in Adventdalen, the permafrost thickness is estimated to be about 100 m (Humlum, 2005). Ground temperature records from a 10 m deep borehole (ASB-2) adjacent to the UNISCALM site show that between 2009 and 2013, the mean annual ground surface temperature (MAGST) ranged from -13.1°C in March to +9.8°C in July (Juliussen et al., 2010); also the depth of zero annual amplitude was observed at -9.85 m depth with a mean temperature of -5.5°C, and with an average annual increase of 0.05°C/yr.

Svalbard airport is the nearest official meteorological station located about 8 km northwest from the UNISCALM site (Fig. 1) and is closer to the sea and at a slightly higher elevation (28 m a.s.l.). Based on records from Svalbard airport (data from Norwegian Meteorological Institute, 2015) annual mean air temperature during the study period was -3.6 °C and mean annual precipitation was 195 mm; comparison with the latest climate normal 1981-2010 shows that the mean annual air temperature was noticeably lower (-5.1 °C) than during the study period (Tab. 1). Precipitation occurs mainly during winter and April, May and June are~~were~~ the driest months. Over the course of the study period, both precipitation and mean air temperature were subject to considerable inter-annual variations reflecting Svalbard's maritime setting (Fig. S1).

3 Method

3.1 Field data

In this study, an ensemble of active layer thaw depth, active layer and permafrost temperature, and active layer soil moisture data collected at the UNISCALM site was used (Tab. 2). The UNISCALM site consists of a 100 m x 100 m grid with 10 m spacing for thaw depth observations (Christiansen and Humlum, 2008). Measurements of thaw depth progression and active layer thickness were performed by probing all 121 grid points with a metal rod 8 to 15 times during the thaw season from May to September each year (except for the year 2000, where only four measurements exist). Active layer temperature was measured by Tinytag miniature data loggers with temperature probes inserted directly into the sediment in a profile in the centre grid point of the UNISCALM ~~grid~~site. The dataset encompasses hourly temperature measurements at the ground surface (0 m) and at 0.1, 0.2, 0.5, and 1.1 m depth. For the ground surface temperature measurements, two periods of missing data (31 August to 26 September

2001 and 26 April to 17 October 2004) were bridged using information from the next closest sensor at 0.1 m depth adopting a statistical data correction approach (Terink et al., 2010).

~~Near-surface~~ ~~P~~permafrost temperatures and volumetric soil moisture content were recorded next to the UNISCALM grid. Hourly permafrost temperatures were available at 2.0, 3.0, 5.0, 7.0 and 9.85 m depth in borehole ASB-2 for the period between September 2008 and August 2014 from the Norwegian Permafrost database, NORPERM (Juliussen et al., 2010). Volumetric soil moisture content was recorded using a PR2 profile probe (Delta-T) with sensing elements at 0.1, 0.2, 0.3, 0.4, 0.6, and 1.0 m depth. Soil moisture was registered with a 3-hour resolution for the period from July 2010 to August 2014. Temperature and soil moisture time series were converted into daily averages. Active layer thickness data was considered both for the centre grid ~~centre~~node, which is the point nearest the location of the active layer ~~ground~~ temperature measurements, as well as for the average of all 121 UNISCALM grid points.

To quantify and evaluate the active layer response to thermal forcing, we consider a summer degree day index $\mathrm{SDD} = \sqrt{\sum_i T_i}$ defined as the square root of the sum of positive daily ground surface (i.e. at 0 m) temperatures T_i from the onset of continuous thaw in spring until the start of active layer freeze-back in ~~fall~~ autumn (thereby restricting summed days i to a season essentially corresponding to summer). Complementary to SDD, we define the sum of daily ground surface temperatures between the summers T_j as winter-degree days at the ground surface $\mathrm{WDD} = \sqrt{\sum_j T_j}$ and use it as an indicator for the thermal conditions preceding the respective summer thaw. The consideration of all summer degree days ~~in~~ this way has been proven useful to assess active layer response in particular to inter-annual temperature variability (Smith et al., 2009).

3.2 Numerical model

Simulations were performed with a recently developed numerical model, the Advanced Terrestrial Simulator (ATS), which can couple several thermal, hydrological and hydrogeological processes for heat flux and water flow applicable to partially frozen ground in cold regions (Atchley et al., 2015; Coon et al., 2016; Painter et al., 2016). The focus of our study is on effects of soil moisture retention characteristics on subsurface heat and moisture propagation in the active layer and permafrost for a dry and relatively flat site; hence the physics presently considered are hydrogeological heat and flow processes. This includes accounting for partitioning of water between ice, liquid, and vapour phases, phase-dependent thermal conduction, latent heat transfer, moisture migration due to phase change (wetting and cryosuction), and heat advection through the movement of water. The model solves a numerically discretized version of conservation equations for heat and water mass transport in porous media, adopting Richard's equation with the unsaturated version of Darcy's law and accounting for phase partitioning by combined use of classical soil moisture retention curves and thermodynamic constraints derived from the Clausius-Clapeyron relation. Details of the underlying approach are provided in Frampton et al. (2011); Karra et al. (2014); Painter (2011). Since moisture migration in the active layer is dominated by unsaturated flow for the site considered, and since retention characteristics are the main focus of this study, a brief summary of governing constitutive equations for phase partitioning as used by the model are provided in the following.

Partitioning between ice, liquid and vapour phase saturation, denoted by s_i, s_l, and s_g respectively and constrained by $s_i + s_l + s_g = 1$, is achieved by simultaneously inverting two constitutive relationships each relating liquid saturation with ice saturation as (Karra et al., 2014)

$$\mathrm{s_l} = (1 - \mathrm{s_i})\mathrm{S_*}(\mathrm{P_{cgl}}) \tag{1a}$$

$$s_l = S_*[-\beta\rho_i h_0 \vartheta H(-\vartheta) + S_*^{-1}(s_l + s_i)] \quad (1b)$$

where S_* is the retention curve for unfrozen liquid-gas phases, P_{cgl} [Pa] is the liquid-gas capillary pressure, β [-] is the ratio of ice-liquid to liquid-air surface tensions, ρ_i [kg m^{-3}] is the mass density of ice, $h_0 = 334$ [kJ kg^{-1}] is the enthalpy of fusion, and T [K] is temperature with $\vartheta = (T - T_0)/T_0$ [-] and T_0 = 273.15 K. The Heaviside function H is used to make Eq. 1b applicable to both frozen and unfrozen conditions. The first relation Eq. (1a) expresses a retention curve for unfrozen water where the available pore space is reduced by the fraction of ice present. The second relation Eq. (1b) describes liquid saturation as a function of total water content, where the first term in the square brackets corresponds to the capillary pressure between ice-liquid phases when gas is absent (saturated conditions), and the second term is the addition to the ice-liquid capillary pressure when gas is present (unsaturated conditions). In our study, the retention curve S_* is expressed using the van Genuchten (1980) model,

$$S_*(P_c) = S_r + (1 - S_r)[1 + (\alpha P_c)^n]^{-m} \qquad \text{if } P_c > 0 \quad (2a)$$

$$S_*(P_c) = 1 \qquad \text{if } P_c \le 0 \quad (2b)$$

combined with the Mualem (1976) model for rescaling liquid phase permeability,

$$k_{rl} = (s_l)^{\frac{1}{2}}\left[1 - \left(1 - (s_l)^{\frac{1}{m}}\right)^m\right]^2 \quad (3)$$

where S_r [-] is residual saturation, P_c [Pa] capillary pressure, and α [Pa^{-1}] and $m = 1 - 1/n$ [-] are model parameters. The exponent m controls the shape of the soil moisture retention curve and can be related to the pore size distribution of the texture (Mualem, 1976; van Genuchten, 1980), where larger values generally correspond to smaller pore size variability, i.e. to well-sorted textures.

3.3 Model configurations

The model domain was configured as a 1D vertical column of the subsurface, with top corresponding to the ground surface and bottom at a depth of 10 m, and with a 0.1 m resolution of cell heights. A depth of 10 m was chosen since this corresponds to the approximate depth of zero annual amplitude measured at the UNISCALM site. Given the comparatively homogeneous soil composition at the site, the entire model domain was assigned the physical and thermal properties of silt loam (Tab. 3). D~~Then d~~ifferent soil moisture retention characteristics were investigated by varying the parameters α and m of the van Genuchten model Eq. (2), all within bounds applicable to silt loam (Tab. 4 and Fig. 2). In all scenarios, residual saturation S_r is set to zero, consistent with commonly adopted practice for silty soils (Destouni, 1991; Painter and Karra, 2014; Wang et al., 2015; Watanabe and Wake, 2009; Weismüller et al., 2011). A reference case is first defined using average values (α=8·10^{-4} Pa^{-1} and m=0.19) obtained from the UNSODA soil hydraulic database (Ghanbarian-Alavijrh et al., 2010) for silt loam soils. ~~Then~~Thereafter, both α and m were varied independently by ± 50% with respect to the reference case, resulting in model scenarios labelled as high/low α and high/low m (Tab. 4).~~'high alpha' (α=12·10^{-4} Pa^{-1}; average m), 'low alpha' (α= 4·10^{-4} Pa^{-1}; average m), 'high m' (m= 0.29; average α), and 'low m' (m=0.1; average α).~~ Two additional scenarios, 'max case' and 'min case', represent the high and low ends of the parameter range by combining high α ~~alpha~~ with high m, and low α ~~alpha~~ with low m, respectively. All of these parameter values are within the range of the variation for silt loam reported in the UNSODA database and in literature (Destouni, 1991; Wang et al., 2015; Watanabe and Wake, 2009).

Given that each combination of van Genuchten parameters will result in different soil moisture profiles, each simulation test case was set-up to attain unique ice-liquid-gas states. Still, despite the systematic approach of testing relevant parameter combinations, note that any potential nonlinearities arising from untested combinations within the parameter space remain unconsidered in this analysis. To be consistent with site conditions, each simulation case was initialized with unsaturated frozen ground to a depth of about -1.2 m and saturated below. This was done by assigning the ground surface a pressure of about -200 hPa, linearly interpolating to the bottom of the unfrozen model domain, and then freezing the column.

To enable systematic investigation of the different soil retention properties with initial conditions consistent with site conditions, each simulation case was initialized with unsaturated frozen ground to a depth of about -1.2 m and saturated below. This yields a system with ice-liquid-vapour in the upper part and ice-liquid in the lower, where the phase partitioning differs for the respective scenarios and is controlled by their respective retention curves. Thereafter, an annually periodic steady state was obtained by running multiple iterations (i.e. a spin-up) using a smoothed version of the observed ground surface temperature time series as surface boundary condition. The convergence criteriona was set as a maximum temperature difference between two consecutive iterations to be less than 0.1°C. This yielded an active layer thickness, defined by the 0˚C-isotherm, of approximately 1 m for most cases, which is also consistent with site conditions.

The simulation investigations were then carried out by directly adopting the daily ground surface temperature time series (i.e. temperatures measured at 0 m over the time period 2000-2014) as the top boundary condition of the model. The bottom boundary was assigned a linearly increasing temperature trend from -6.05 °C (September 2000) to -5.4 °C (August 2014), consistent with the increasing temperature trend of 0.05 °C/yr observed for the time period 2008 until 2014 at depth -9.85 m.

Lateral water fluxes through and infiltration into the system were neglected and no-flow boundaries assigned to all faces of the model domain. While recognizing that flowing water can have considerable thermal effects on active layer processes, its exclusion is considered an appropriate assumption for the dry UNISCALM site (cf. Sect. 2). Infiltration was determined to be of minor importance based on field evidence for a shallow snow cover of 20-30 cm (Christiansen and Humlum, 2008), large wind transport of snow and high evaporation and sublimation rates (Westermann et al., 2010), combined with findings from a previous modelling study indicating that inter-annual active layer variation at the site is largely unaffected by infiltration derived from the small amounts of early spring snowmelt and summer precipitation (Schuh, 2015).

Based on the local topographical setting with no drainage to the study site, field evidence for a shallow snow cover of 20-30 cm (Christiansen and Humlum, 2008), high wind erosion from unstable snow layers and high evaporation and sublimation rates (Westermann et al., 2010), combined with previous modelling studies indicating that inter-annual active layer variation at the site is largely unaffected by infiltration derived from the small amounts of spring snowmelt and summer precipitation (Schuh, 2015), infiltration was determined to be of minor importance and hence not further considered in the present studyThe simulated results for the different cases were then evaluated in the context of available field data such ascompared against field measurements considering active layer thickness, subsurface ground temperature and soil moisture. The simulated active layer thickness was defined as the deepest numerically calculated 0˚C-isotherm for each year. Differences between measured and simulated ground temperatures were quantified by a root mean squared error RMSE, averaged over a time period corresponding to the length of the available time series as

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2} \qquad (4)$$

~~where S_t and O_t are the simulated and observed daily temperatures, respectively, and N is the number of data points.~~

4 Results

4.1 Active layer thickness and subsurface temperatures

Model results show that the different assumptions regarding soil water retention properties impact subsurface temperatures and active layer thickness (ALT). The modelled ALT ranged from 90 to 130 cm considering all scenarios and years (Tab. 5). Cases with a small value for the van Genuchten parameter *m* (‘low m’ and ‘min case’) generally had ALTs in the range 100-130 cm, somewhat larger than moderate or high values of *m*, which had ALTs in the range 90 to 110 cm (e.g. ‘ref case’ and ‘high m’). Accordingly, the mean modelled ALT over the study period was 118-119 cm for the cases assuming a small value for *m* and 99-103 cm for the other cases. Overall, the smallest ALT were simulated for the years 2005 and 2008, and the largest for the years 2006, 2013, and 2014. This ~~can be~~ compares~~ed to~~ well with the measured ALTs~~thaw depth where the~~ at the UNISCALM grid ~~average~~ ranging~~ed~~ from 74 to 110 cm depending on year. The~~, and the~~ smallest ALT occurred in 2005 and the deepest in 2008, ~~and~~ with a mean of 98 cm over the entire time period (Tab. 5).

Inter-annual variation in simulated ALT was comparatively small for most of the scenarios with standard deviations of about 5-6 cm. For scenarios with low value for *m*, inter-annual variation in ALT was slightly higher with standard deviations of about 8-9 cm. The standard deviations based on measured thaw depth were close to 8 cm, both for the grid average as well as only considering the centre probing location. Depending on scenario, a trend of increasing ALT varied from 0.3 to 0.8 cm/yr for the entire study period, which can be compared to the trend of 0.8 cm/yr obtained from the UNISCALM grid measurements average (Tab. 5).

~~Active layer temperatures recorded at the UNISCALM site were generally mimicked best by scenario ‘max case’ with a depth-averaged root mean squared error (RMSE, Eq. 4), of 0.07°C in the active layer (Tab. 6). Most other scenarios represented summer temperatures well but generally underestimated winter temperatures (not shown), resulting in mean RMSE values up to 0.18°C (Tab. 6, e.g. case ‘low alpha’). Note also RMSE values are generally smaller at the intermediate depths (0.2 m and 0.5 m) and larger near the surface (0.1 m) or near the top of permafrost (1.1 m). In the permafrost, the simulations generally overestimated the seasonal temperature amplitude both in summer and winter, but to a lower degree than in the active layer (not shown). In the permafrost, the depth-averaged RMSE ranged between 0.05°C in scenario ‘high alpha’ to 0.10°C in scenario ‘low alpha’ (Tab. 6).~~ The observed tendency of increasing ground temperatures (Tab. 6) over the study period was represented well by the simulations, irrespective of the chosen soil water retention parameters, where the average of all scenarios resulted in a trend of 0.25˚C/yr at 0.1 m depth, and decreasing to 0.05˚C/yr at 9.85 m depth, consistent with the corresponding trends obtained from the measured active layer and permafrost temperatures. Also, note that the observed increase in ground surface temperature can be ascribed exclusively to increasing winter temperatures, since the trend in summer temperature on the ground surface was essentially stable (-0.05°C/yr) over the study period, in contrast to the relatively strong increase in winter ground surface temperature (+0.25°C/yr).

4.2 Ice and water content

By model design, the permafrost was fully saturated below a depth of about 1.2 m in all scenarios. However, depending on the retention curve parameterization the different scenarios exhibit different fractions of ice and unfrozen water content in the permafrost. The scenarios with large m=0.29 (‘high m’ and ‘max case’) have greatest volumetric ice contents of 39%, followed by scenarios with intermediate m=0.19 (‘high alpha’, ‘ref case’, and ‘low alpha’) with approx. 36% ice content, and scenarios with m=0.1 (‘low alpha’ and ‘min case’) with only 26% ice content (Fig. 3). The remaining fraction to full saturation, i.e. 1%, 4%, and 14%, respectively, consists of unfrozen liquid water (porosity was assigned to 40%, cf. Tab. 3, consistent with field conditions).

Although no additional infiltration is imposed so that the total water mass in each modelled system~~s~~ is constant over time, the ~~different~~ retention curves yield~~cause~~ different ~~initial~~ phase partitioning resulting in different initial~~so that the various model cases may differ in~~ total water mass. During freezing of the active layer, water becomes repartitioned according to phase state and migrates by cryosuction, and both ice content and distribution vary considerably between scenarios (Fig. 3). Total ice content is observed to be mainly a function of α in the retention curve (Eq. 2) with lower values resulting in higher ice content; the largest total ice content was obtained for the case ‘low alpha’ (30-35%), followed by ‘ref case’ and ‘min case’ (25-30%), ‘high m’, ‘low m’, ‘high alpha’ (15-25%), and ‘max case’ (12-18%). However, the ice distribution and spatial layering with depth was mainly a function of ~~the value of~~ m. For low values m=0.1 no ~~particular~~ distinct ice layering was observed, instead the ice distribution was relatively homogeneous throughout the active layer (Fig. 3c). For the other cases, layers of increased ice content developed more clearly with increasing m, typically with a tendency of a narrow layer of higher ice content just below the ground surface as well as within a layer above the permafrost table. ~~The layering~~This stratification was most pronounced for large ~~where *m* was highest (~~m=0.29~~;~~ (Fig. 3d). Note also the vertical position and depth extent of the layers vary over time for all cases, indicating different ice redistributions occurring in each freeze-up season.

During summer, the simulated water content in the approximate centre of the active layer, i.e. at 0.6 m depth, was between 15-38% depending on model scenario (Fig. 4c), with slight increase with depth (Fig. 4d). The increase in water content generally coincided with the onset of thaw in spring and with the location of the thawing front. Note the timing of increase and subsequent drop of the water content deteriorates with depth. Except for scenarios assuming a small value m=0.1 (e.g. ~~‘low m’ and~~ ‘min case’), the model cases show a delayed increase and a premature and prolonged decrease in water content in the lowermost active layer (i.e. at 1.0 m depth, Fig. 4d).

Moderate peaks in measured water content can be seen in the field measurements at depth 0.1 m (Fig. 4b, black line), which are significantly attenuated already at 0.6 m and 1.0 m depth (Fig. 4c and d, black line). These could correspond to brief infiltration events, for example caused by snow melt at onset of thaw, confined to the uppermost thawed soil layers, while parts below remain frozen (cf. temperatures at 0.5 m and 1.1 m depth, Fig. 4a), thereby momentarily saturating the top part of the active layer. Aside from the peaks at 0.1 m depth, the scenarios ‘max case’ and ‘high m’ reflect the observed total water content in the thawed active layer (15-25%) to a high degree, whereas the other scenarios (e.g. ‘min case’) overestimated it considerably. In winter, the amount of unfrozen water seems to be best represented by scenarios using an average value m=0.19, e.g.~~i.e.~~ ‘ref case’~~, ‘low alpha’, and ‘high alpha’~~. Water contents for scenarios ‘low/high α’ and ‘low/high m’ lie within the range of, and show the same behaviour as, scenarios ‘min case’, ‘ref case’ and ‘max case’ (not shown).

5 Discussion

5.1 Soil moisture and ground ice distribution

Even for the same soil type considered (silt loam), the specific choice of retention parameters consistent within the range applicable for that texture class, as exemplified by the seven simulation cases studied here (Tab. 3), clearly has an influence on the amount and redistribution of both liquid water and ice in the active layer with its annual freeze-thaw cycles (Fig. 3 and Fig. 4). The water retention parameters tested in the different scenarios also impacted the unfrozen water content in the active layer as well as in the permafrost. The parameter α normalizes capillary pressure (Eq. 2) so that the main effect of a decrease or increase in α results in a general shift of the retention curve up or down, resulting in a higher or lower overall liquid saturation, respectively (cf. Fig. 2). This parameter is varied by almost one order of magnitude between the different cases, causing a maximum difference in water content of about 10% in the active layer (corresponding to a change of about 25% in terms of saturation). The parameter m controls the overall shape and slopes of the retention curve. This way, it is significant for cryosuction and thus redistribution of ice in the active layer during freeze up. The retention curves with small values m=0.1 exhibit relatively smooth overall slopes even for low saturations (cf. Fig. 2), and do not result in high cryosuction effects. Instead, scenarios with high m=0.29, and comparatively steeper slopes for low saturations, result in the greatest changes in capillary pressure and hence greater cryosuction. A reason for this is the respective fraction of water that remains unfrozen even at temperatures below 0˚C. Given a certain soil water content in the active layer, a drop in subsurface temperature of about 10°C, as typically observed in winter, results in an increase in capillary pressure since liquid water undergoes a phase change to ice. The liquid water content is thereby reduced, resulting in an effective drying out of the pore space and yielding a hydraulic gradient towards the freezing front. For retention curves with high m value displaying a higher non-linearity at low saturations, this increase in capillary pressure leads to a small fraction of unfrozen water (~1% for m=0.29). In contrast, for the same increase in capillary pressure, retention curves with low m value yield higher unfrozen water contents (~14% for m=0.1). As a consequence, cryosuction and the resulting moisture migration to the freezing front is greater for scenarios assuming higher m since such cases undergo greater phase change and greater effective drying of the pore space.

This is reflected in the simulated ground ice ~~pattern~~ redistribution pattern, where scenarios with high m values ('high m', 'max case') typically showed well-defined layers of ice in the upper and lower parts of the active layer, whereas cases with low m values ('low m', 'min case') did not exhibit such a distinct variable ice pattern (Fig. 3c). The parameter m relates to physical soil properties, specifically the pore size distribution and pore connectivity/tortuosity, where large m is generally considered to correspond to a small variability in pore size distribution, i.e. corresponding more to a well-sorted texture. Note also that ~~the~~ parameter m controls relative permeability in the Mualem model (Eq. 3 and Fig. 2, inset) and hence hydraulic conductivity. At the UNISCALM site, the sediment has been described as a well-sorted loess sediment and thus may be more consistent with larger m values. Furthermore, the comparison against soil water content in the active layer (Fig. 4) revealed that scenarios using an average m=0.19 or large m=0.29 seemed more consistent with observed unfrozen water content during the frozen period. In scenario 'max case' the soil water content during the thaw period is lowest of all scenarios, and at a level which is consistent with field measurements (~10-20%).

Based on simulated results, we infer that the higher ice content in the top-most parts of the active layer developed by cryosuction caused by the downward moving freezing front, whereas the ice in the deeper parts of the active layer may be a combination of cryosuction-induced moisture migration together with water percolating down by gravity during the thaw period. Here the cryosuction-effect may either counteract percolation or enhance it, depending on if one or two-sided freezing occurs. Considering the downward ~~s~~ moving freezing front from the ground surface, this should cause a cryosuction-induced moisture migration towards the freezing front, i.e. move moisture upwards and thereby work against gravity-driven percolation flow (and creating a higher ice content in the upper part of the active layer). A freezing front moving upwards from the top ~~of~~ permafrost would, however, cause a cryosuction-induced moisture migration downwards, thereby working together with percolation flow (and causing a middle part of the active layer with only little ice). For two-sided freezing, the rates of heat propagation, which in turn would also depend on the variability of the surface temperature and the thermal state of the permafrost below, would govern the strength of cryosuction-induced moisture migration from the respective fronts and their net effect on moisture movement combined with percolation in the active layer. Considering the general spread of increased ice content at approximate depths 0.5-1.0 m (e.g. Fig 3a), cryosuction-induced moisture migration may be occurring in both directions, i.e. consistent with two-sided freezing, at least for cases with moderate to high values of *m*.

Field investigations indicate downward freezing from the ground surface may cause ice lenses to form mainly in the upper active layer, and two-sided freezing may cause segregated ice and a dryer middle active layer to form (French, 2007). Also, an augmented amount of ice lenses near the bottom of the active layer and top of permafrost is generally interpreted as ice segregation through upward freezing from the permafrost table or caused by percolation and moisture migration down to the permafrost (Cheng, 1983; Mackay, 1972). At the UNISCALM site, lenticular cryostructures at the top of the permafrost have been observed (Cable et al., In review; Gilbert, 2014), and recent sediment core retrieval in March 2015 on a river terrace near the UNISCALM site showed increased ice lenses in the upper active layer as well as at the top of the permafrost, whereas the middle active layer was comparably dry showing further evidence for both downward and upward freezing. Boike et al. (1998) identified two-sided freezing at a comparable study site in Siberia using frost probing and water content information. It therefore seems likely that two-sided freezing occurs at the UNISCALM site, even if the downward freezing component is ~~seems to be~~ dominant. ~~Also the simulation cases considered here are consistent with these general observations of two-sided freezing, at least for cases with moderate to high *m* values, corresponding to smaller pore size variability and hence well-sorted textures.~~

5.2 Thaw progression and refreezing

Soil moisture and ground ice distribution impact subsurface temperatures and temperature gradients since heat propagation into and out of the ground is largely controlled by both phase-dependent thermal conductivity and latent heat transfer. The model results showed that scenarios assuming a small *m* value (‘low m’, ‘min case’) resulted in greater ALT and greater inter-annual variations in ALT, as well as larger increasing trends of ALT over the study period (Tab. 5). The timing and duration of thaw in the upper active layer was essentially the same for all cases (Fig. 4b), whereas it was delayed and underestimated in the lower active layer for cases with large *m* value (Fig. 4d). A more detailed consideration of the thawing process, here exemplified for year 2011 (Tab. 7), further showed that to thaw the upper 1 m of the model domain, 58-60 days were required in scenarios using small *m* values (‘low m’, ‘min case’), 74-76 days in scenarios using average *m* values (‘ref case’, ‘high alpha’, ‘low alpha'), and 78-85 days in scenarios using large *m* values ('high m', 'max case'). This is altogether evidence for a more efficient heat propagation into the ground for scenarios assuming a low *m* value, and thereby a clearer reflection of the influence of ground surface temperature dynamics on the deeper subsurface.

Tab. 7 also helps understand the different thaw progression rates by summarizing the prevailing moisture conditions in the upper 1 m of the model domain (essentially corresponding to the active layer) at the end of winter and just prior to the onset of thaw in 2011. An effective thermal conductivity κ_e was calculated based on the fraction of ice, water, and air content (excluding the soil matrix) at that point in time, and the total latent heat *L* was determined directly from the respective ice mass. Accordingly, effective thermal conductivities clearly reflect the phase partitioning, with lowest κ_e=0.34 and κ_e=0.47 J kg^{-1} K^{-1} found for settings with largest air fractions of 24% ('max case') and 18% ('high m') respectively, and highest κ_e=0.73 J kg^{-1} K^{-1} occurring for a nearly ice-saturated setting with small air content of 3% ('low alpha'). The latent heat buffer depended on the simulation case and ranged from *L*=20 ('max case') to *L*=42 MJ ('low alpha'). The thaw rate is, however, highest in scenarios 'low m' and 'min case', which are combining medium to high effective thermal conductivity (κ_e=0.54 to 0.60 J kg^{-1} K^{-1}) with medium to low latent heat consumption (*L*=27 to 31 MJ). In contrast, as shown in scenario 'max case', heat propagation can be severely hindered by high air content resulting in low effective thermal conductivity, even if it only contains a small amount of ice (*L*=20 MJ). For the active layer freeze-back in autumn the same processes apply in reverse, i.e. heat flux is inverted flowing from the subsurface up and out of the ground. For scenario 'max case', this implies a slow progression of the freezing front, visible in the gentle drop of liquid water content simulated in the lower active layer (Fig. 4d). However, upward freezing from the permafrost table causes an earlier freeze-back of the active layer bottom, so that, despite a less efficient heat transfer in some cases, active layer freeze-back is completed at about the same time in all scenarios.

Furthermore, model simulations show that not only the amount of soil moisture, but also the distribution of ice within the active layer impacts the progression of the thawing front. Fig. 5 compares the ice content profile before the onset of thaw in 2011 to the respective thaw rate when the ground surface temperatures become positive. As shown previously (cf. Fig. 3), model scenarios 'ref case' (black), 'high m' (green) and 'max case' (orange) resulted in a distinct stratification of ice, whereas 'low m' (blue) shows almost a linear increase in ice content towards the permafrost table (Fig. 5a). In all scenarios, thawing the upper 10 cm of the ground occurs at a relatively low rate between (1.3-1.4 cm/d) (Fig. 5b) mainly because air temperatures are still low, but also because of latent heat consumption due to the increased ice content in the thin layer just beneath the surface. Once the thawing front passes the ice layer at 5 cm depth, the thaw rate ~~temporarily~~ increases to its maximum of 5 cm/d, fuelled by markedly increasing air temperatures (not shown) and regardless of the respective soil moisture content. Below 20 cm depth, all scenarios show a generally decreasing thaw rate, but with notablye case-specific differences only between 40 cm and 60 cm depth. Here, discrepancies originate from the particular ice-liquid-gas composition in the thawing ground and its effect on heat propagation, as discussed above. Furthermore, enhanced thaw due to advective heat transport through previously frozen water is likely to occur in more saturated systems such as 'ref case' (e.g. at -50 cm depth). Scenarios 'high m' and 'low m' show discrepancies in their thaw rate, while having comparable ice contents. In 'high m', the thaw rate drops to 1.4 cm/d when reaching the clearly defined ice-rich zone at -60 cm depth, whereas the thaw rate at that depth is much higher (2.5 cm/d) in the 'low m' case, characterized by a more stable ice content profile.

5.3 Inter-annual active layer variation and permafrost development

Despite the differences in heat propagation through the subsurface and the resulting greater ALTs in scenarios using ~~high~~ low *m* values, the inter-annual variation in ALT over the study period follows a consistent pattern irrespective of soil water retention properties. The large inter-annual air temperature variations in Svalbard are mainly due to the extreme maritime location with particularly high temperature fluctuations during the long Arctic winter (Humlum et al., 2003). Accordingly, the winter $\sqrt{WDD}$~~WDD~~ index (cf. Sect. 3.1) shows a high variability over the study period and ranges between -40 and -54 (with coefficient of variation CV=0.09), compared to relatively stable summer conditions where $\sqrt{\mathrm{SDD}}$~~SDD~~ ranges between 26 and 31 only (CV=0.04) (Fig. 6~~5~~a-b and Fig. 7~~6~~), consistent with similar calculations reported by Christiansen et al. (2013). The field measurements of thaw depth show comparatively small inter-annual variations, except for the years 2005 and 2008 where probing of the CALM grid identified exceptionally small and large thaw depths of 74 cm and 110 cm, respectively (Fig. 6~~5~~a-b and Tab. 5, grid average). Recall also the ground surface temperature measurements indicate essentially constant or slightly cooling summer temperatures with a trend of -0.05 ˚C/yr, but with a notable winter warming trend of +0.25˚C/yr over the time period 2000-2014.

Note that the smallest thaw depth during the study period, measured in 2005, occurred after three consecutive and comparatively cold winters 2002-2004 (Fig 6). The greatest thaw depth, measured in 2008, occurred after two moderate and warm winters 2006 and 2007. Although the active layer (by definition) responds to the current year's summer warming, such decreased versus increased temperature changes from previous years will affect the subsurface thermal state by depth lags in heat propagation and energy storage. Note also that although the ~~SDD~~ $\sqrt{SDD}$index in 2005 is rather low, consistent with the shallow active layer occurring that year, it is also low in 2008, which is inconsistent with the deep active layer occurring in 2008. This, combined with the previously mentioned observation that the $\sqrt{SDDs}$~~SDD~~s vary much less than the $\sqrt{WDDs}$~~WDDs~~, supports the proposition that $\sqrt{WDDs}$~~WDDs~~ and hence winter temperature and duration are the more dominant factors controlling active layer thickness at the UNISCALM site on Svalbard.

A mechanistic explanation for this is that active layer thickness will in general not respond symmetrically to colder versus warmer surface conditions. Colder summers can directly cause a decrease in ALT by not providing sufficient heat for a typical thaw depth, as seen in 2005, whereas an increase in ALT by warmer summers can be impeded by ice-rich conditions at the permafrost table causing a latent heat buffer. Thus, a relatively moderate increase in summer thermal conditions as observed by the SDD index may not necessarily provide sufficient heat to thaw fully or near-fully ice saturated permafrost. Such a buffering function of an ice-rich upper permafrost conforms to the concept of a transition zone (Shur et al., 2005). Accordingly, latent heat buffer effects may counterbalance thaw in warmer years, so that the transition zone increases overall thermal stability in the underlying permafrost. Only after a sufficient number of consecutive warm winters or years would such a transition zone eventually degrade enabling the active layer to deepen.

In contrast to the field observations, the simulated ALTs showed a more pronounced correlation to SDD (with R^2=0.41-0.87~~0.41 for 'max case'~~) and a comparatively weak correlation to WDD (with R^2=0.12-0.19~~0.19 for 'max case'~~) (Fig. 5c-d for four selected scenarios). The predominant effect of summer conditions is reflected in the shallow ALTs that have been simulated for the years 2005 and 2008 (Tab. 5). Both these years were characterized by cold summers with SDD = 26 and 27, and preceded by average winters with WDD = -47 and -45, respectively. The large thaw depth in 2008 is, however, not captured by the models. Assuming that the thaw depth occurring in

2008 is caused by heat storage in the permafrost, this could indicate that thermal storage effects are not correctly captured by the current setups. The missing sensitivity of soil water retention parameters to inter-annual ALT variation is consistent with previous studies (Harp et al., 2016). This might be explained by the fact that in areas subject to a seasonal freeze/thaw cycle, the water retention parameters mainly control the seasonal soil moisture (re-)distribution during freezing and thaw (cf. 5.1). While we found the different retention curves to affect the rate of thaw progression and thus the respective annual thaw depth, the total period of active layer development from thaw to freeze-back was similar in all cases (cf. Sec. 5.2). Water retention characteristics therefore seem to be relevant mainly on a short time scale during thaw and freeze-up.

Several studies have identified significant correlation between summer degree days and active layer depths (e.g. Christiansen, 2004; Smith et al., 2009). However, Osterkamp (2007) found warming winters to be a main cause for increasing permafrost temperatures in the Arctic Coastal Plain, Alaska, while summers even showed a slight cooling. The importance of winter conditions for thaw during the subsequent summer has also been emphasized by Burn and Zhang (2010). For their study site in the Mackenzie Delta, Canada, they found that observed variation in ALT could only partially be explained by the varying summer temperatures, and they showed that ALT was also influenced by preceding winter conditions because of a change of energy components entering the ground. After warmer winters less energy was required to warm the subsurface (sensible heat), so that more energy could be used to thaw the ground (latent heat). Wintertime snow cover thickness and duration has been shown to exhibit control on~~ver~~ the ground thermal regime (Lafrenière et al., 2013). Also, Mackay and Burn (2002) investigated 20 years of active layer development after the artificial drainage of Lake Illisarvik in A~~a~~rctic Canada, where they identified the warming of the subsurface following increases in snow depths as the major controlling factor for the observed variation in ALT as opposed to summer weather conditions.

The limited effectiveness of increased summer temperatures for increasing ALT identified here for the UNISCALM site calls for a more cautious consideration of thermal influencing factors. In the Arctic, the future temperature rise is expected to be most pronounced during winter and precipitation is expected to increase (IPCC, 2013) especially as snow during autumn and winter (Kattsov et al., 2005). Increased snow thickness and/or duration should affect the ground thermal regime such that progressive active layer deepening and permafrost warming may be expected even if summer temperatures remain stable or decrease. At the same time, the effect of active layer deepening may lag behind surficial warming by several years if an ice-rich transition zone near the permafrost table exists.

6 Summary

The active layer dynamics at a dry loess-covered terrace site in central ~~on~~ Svalbard was studied based on a high-resolution field data set combining active layer and permafrost temperatures, soil moisture, and active layer thaw depth progression in conjunction with a physically based coupled permafrost-hydrogeological model. Simulations were configured based on site conditions and then used to investigate how different soil moisture retention curves consistent with the silt loam sediment texture observed at the site impacted active layer thickness, heat propagation and subsurface temperatures, as well as moisture and ice redistribution by wetting and cryosuction. The main conclusions related to the stated investigation questions are:

- Even when constrained to a single sediment type (silt loam), the specific choice of retention parameter values leads to different moisture and ground ice distributions. In particular, well-sorted textures with small pore size variability (large exponent *m* in the van Genuchten retention curve) lead to more distinct subsurface ice heterogeneityredistribution and stratification.

- The seasonal temperature variability during freeze-up exhorts exerts significant control on cryosuction leading to inter-annual differences in subsurface ice redistribution.heterogeneity.
- The choice of retention parameter values also impacts thermal properties through phase partitioning, as well as the amount of unfrozen water content at temperatures below freezing, resulting in different latent heat consumption and heat propagation rates in both the active layer and top permafrost.

Uncertainty in retention parameters can have significant impacts on predicted thermal development as well as ice distribution and water migration.

- The simulations showed that the highest thaw rates occur for textures which result in medium to high effective thermal conductivity and medium to low latent heat consumption, corresponding to poorly-sorted textures with large pore size variability (small exponent *m*). These high thaw rates also led to both greater active layer thickness, and slightly greater inter-annual variations in active layer thickness.
- Water retention characteristics control the local progression of the thawing front due to the unique ice-liquid-gas composition in the subsurface, the existence of ice layers with varying ice content, and possible advective heat transport in more saturated systems.
- Active layer thickness, as observed in the field, responded primarily to the cumulative temperature during the preceding winters, as opposed to cumulative summer temperatures during thaw.
- Deepening of the active layer at this site is mainly controlled by consecutive years of winter warming; an immediate response is impeded by a latent heat buffer caused by ice-rich conditions near and below the permafrost table.

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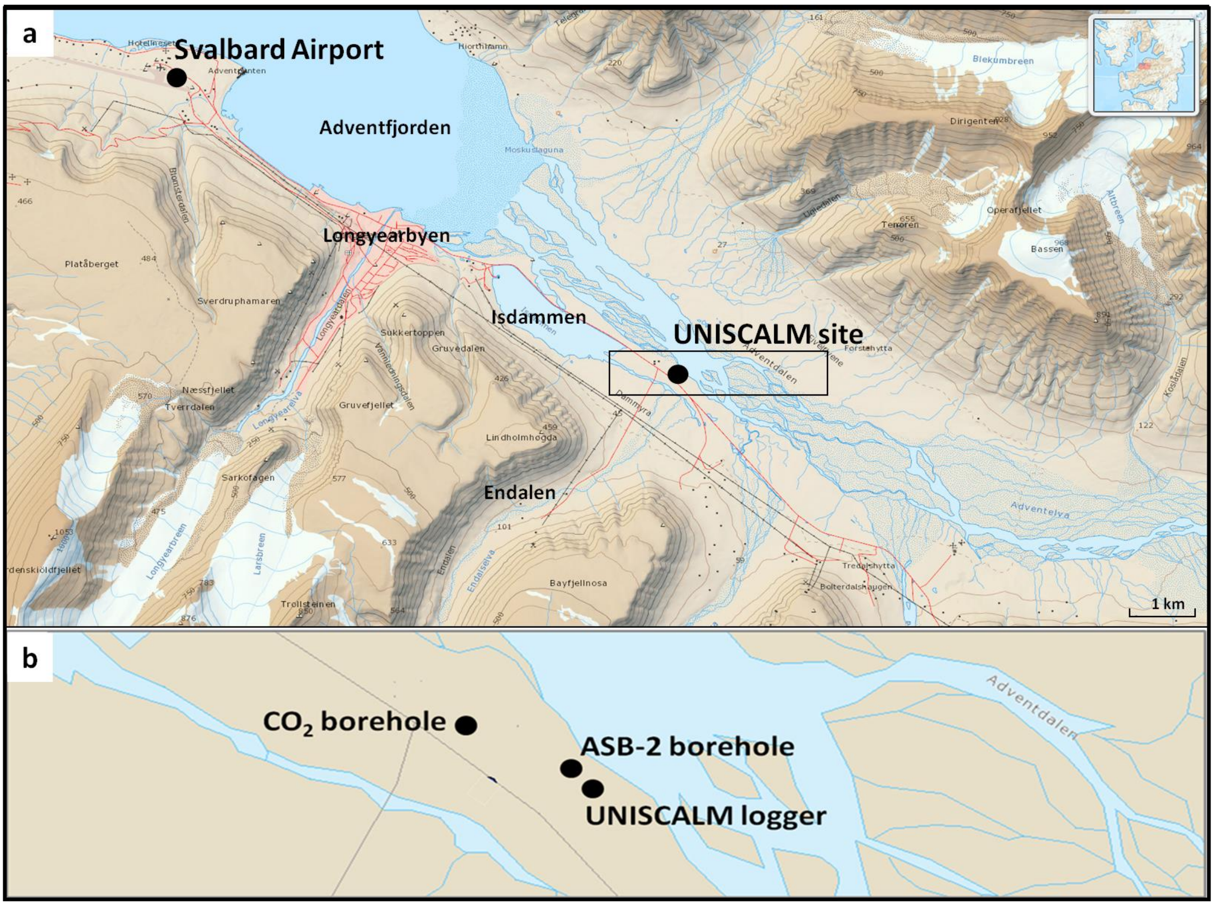

Figure 1: Lower Adventdalen in central Spitsbergen, Svalbard, showing the location of the UNISCALM site. The meteorological station is located at Svalbard Airport (Data: Norwegian Polar Institute).

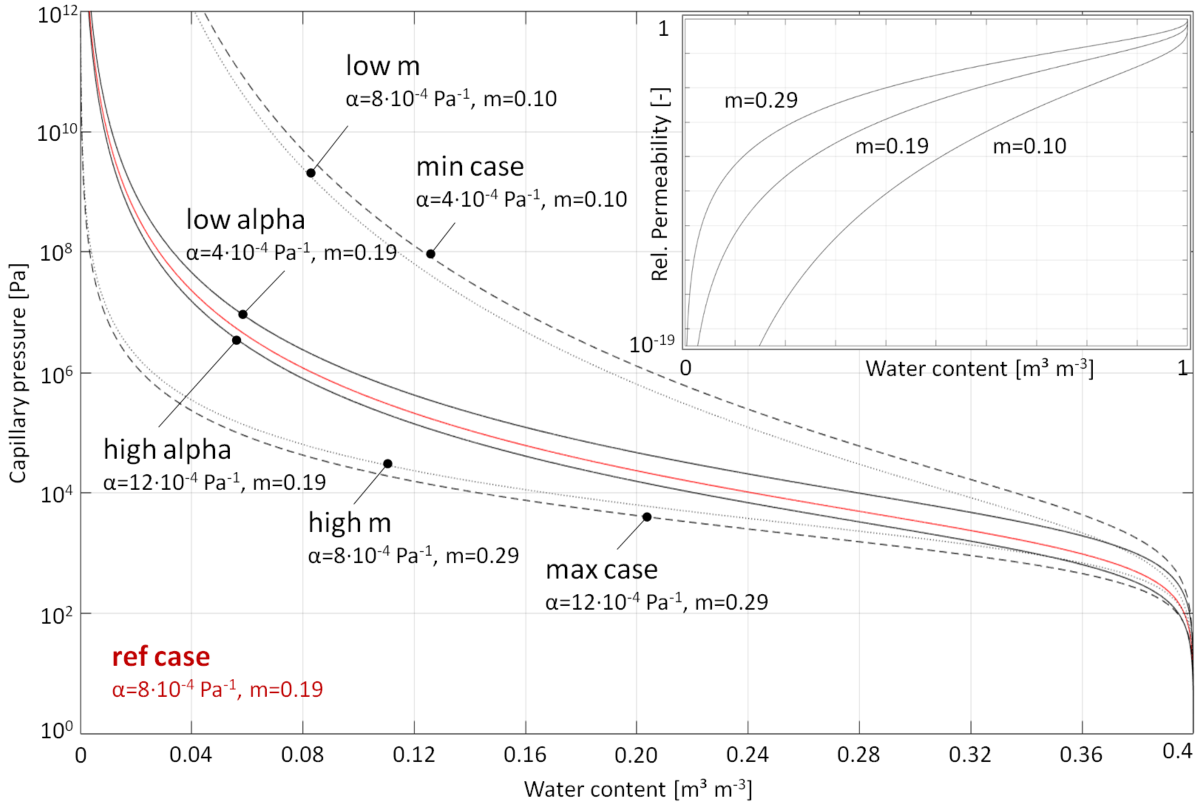

Figure 2: Retention curves S_* described by the van Genuchten model (Eq. 2) and as used in the different model scenarios; residual saturation set to zero for all cases. (Inset) Relative permeability described by the Mualem model (Eq. 3).

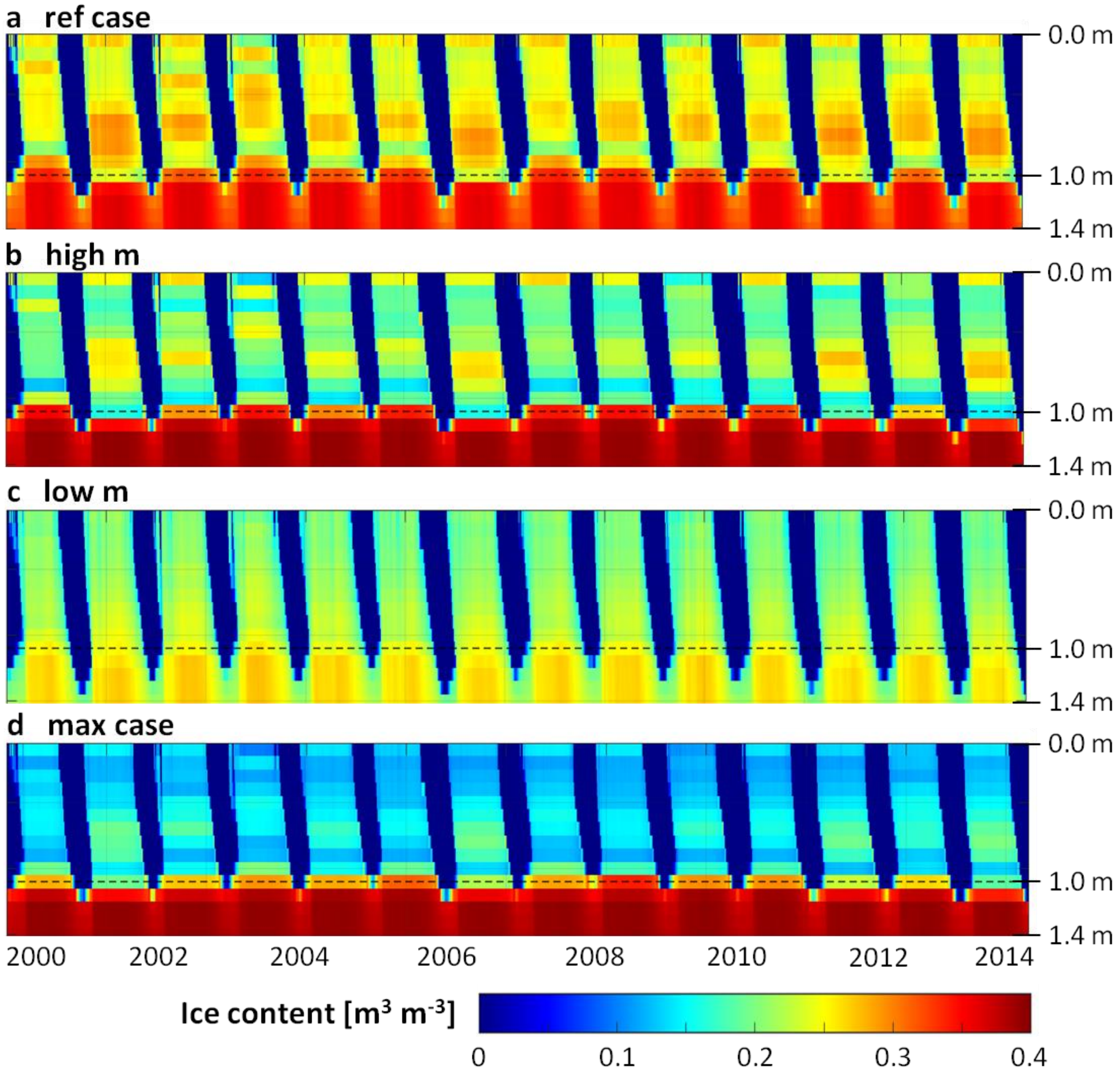

Figure 3: Ice content [m^3 m^{-3}] in the active layer and upper permafrost over the study period as simulated in four selected scenarios

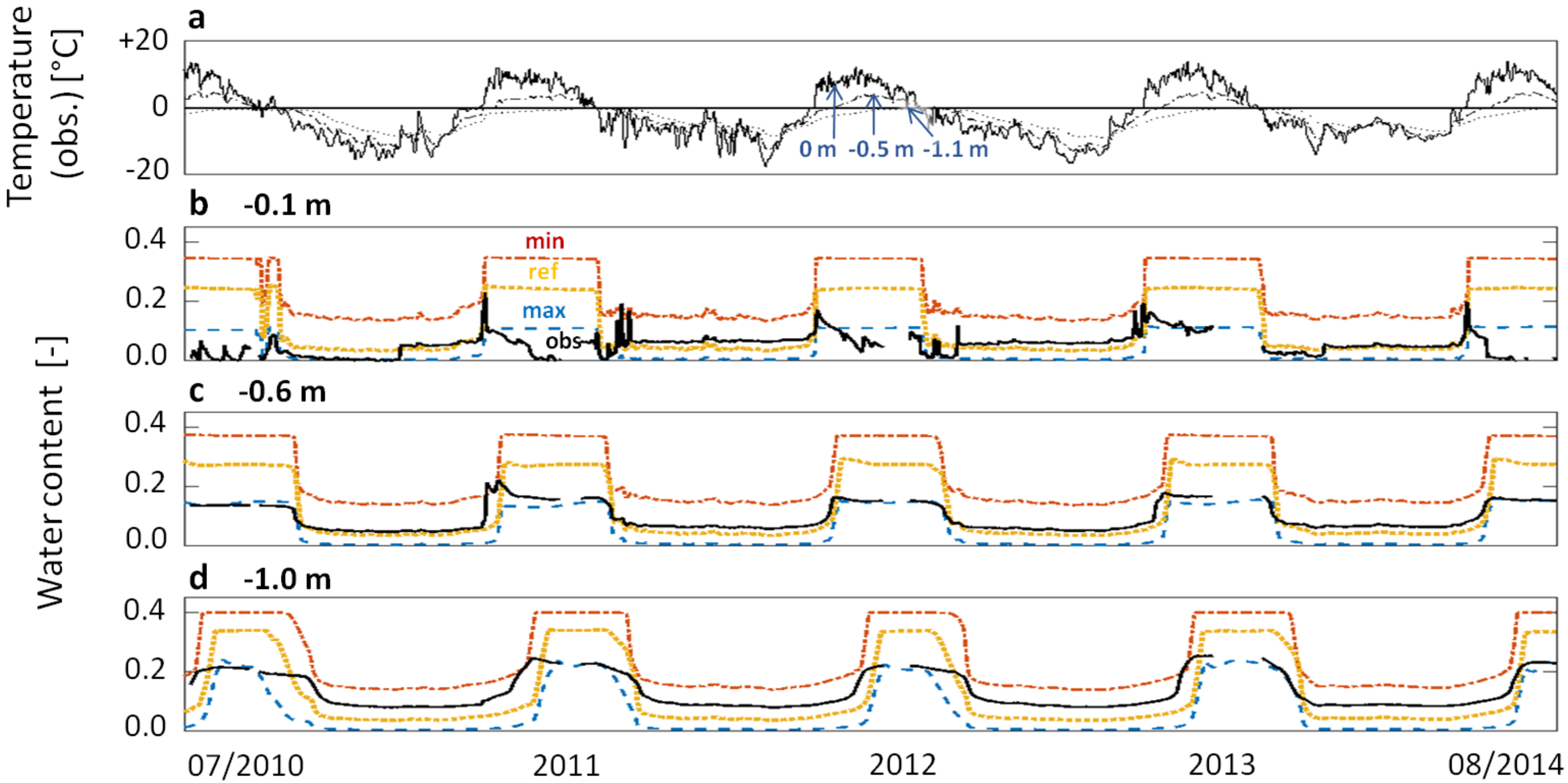

Figure 4: (a) Daily measured ground temperatures on the surface 0 m (solid) and at depths 0.5 m (dashed) and 1.1 m (dotted) between July 2010 and August 2014. Also volumetric water content at depths (b) 0.1 m, (c) 0.6 m and (d) 1.0 m as observed (solid black) and modelled (showing ref case, min case and max case in yellow, red and blue respectively). The remaining simulation cases (not shown) reside within the limits of the min and max cases.

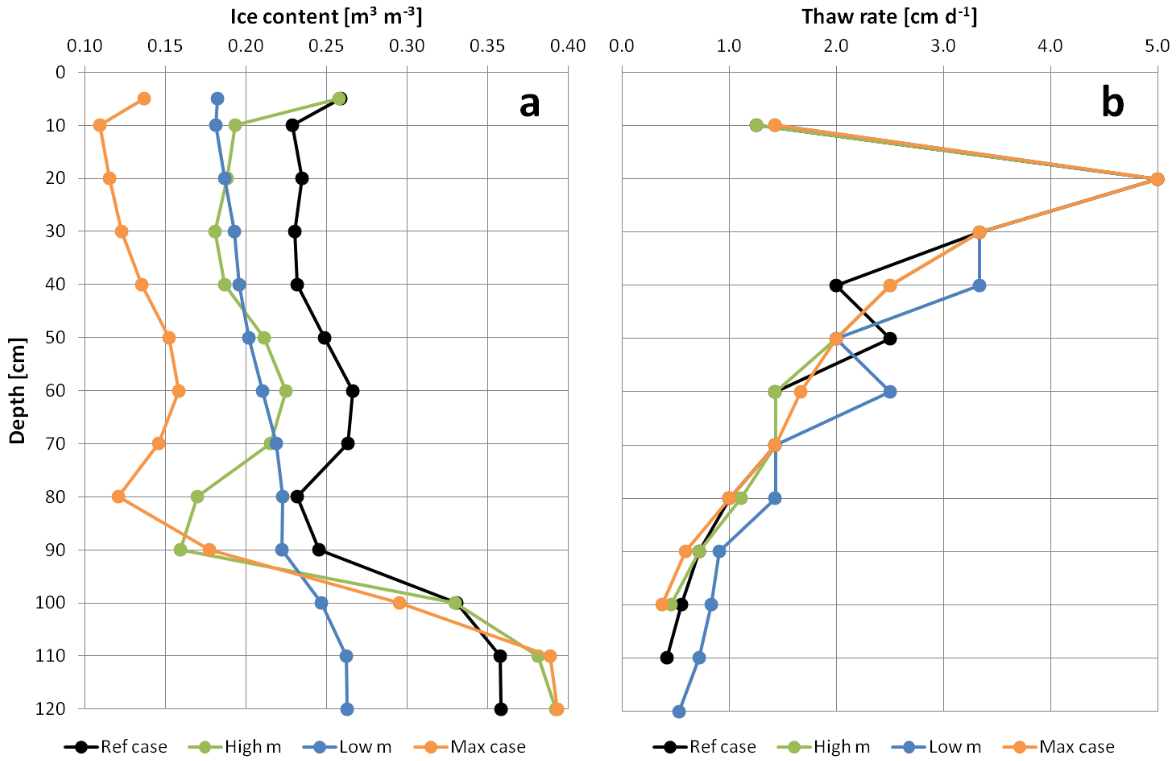

Figure 5: Comparison of (a) simulated ice content distribution with depth at the end of winter 2011 (01.05.2011) and (b) the corresponding modelled rate of active layer thaw starting after the first day of positive ground surface temperatures (25.05.2011), exemplified by four selected model scenarios.

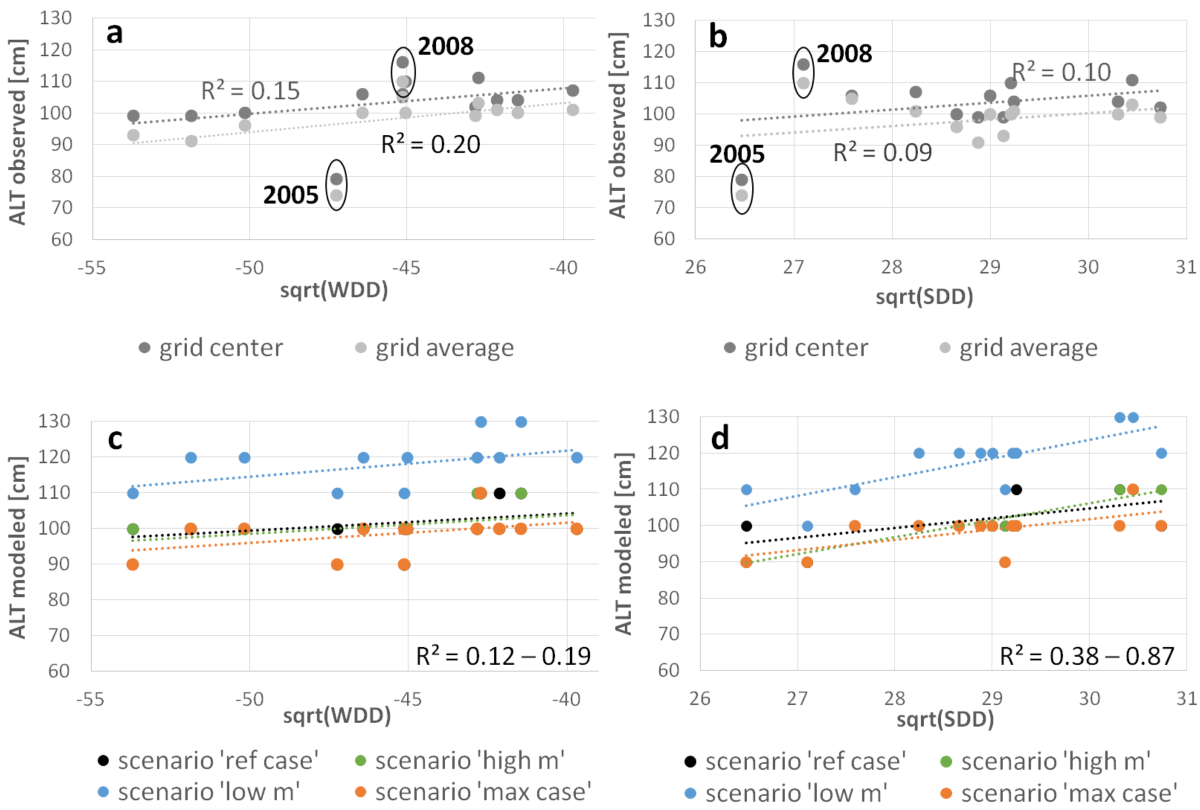

Figure 6: (a,b) Correlation of observed and (c,d) modelled active layer thicknesses to thermal conditions at the ground surface, considering winter degree days (WDD) and summer degree days (SDD) separately. Observed active layer measurements include information both from the grid centre (dark grey) and the grid average (light grey). Modelled active layer thickness is shown for selected scenarios 'ref case' (black), 'low m' (blue), 'high m' (green) and 'max case' only (orange).

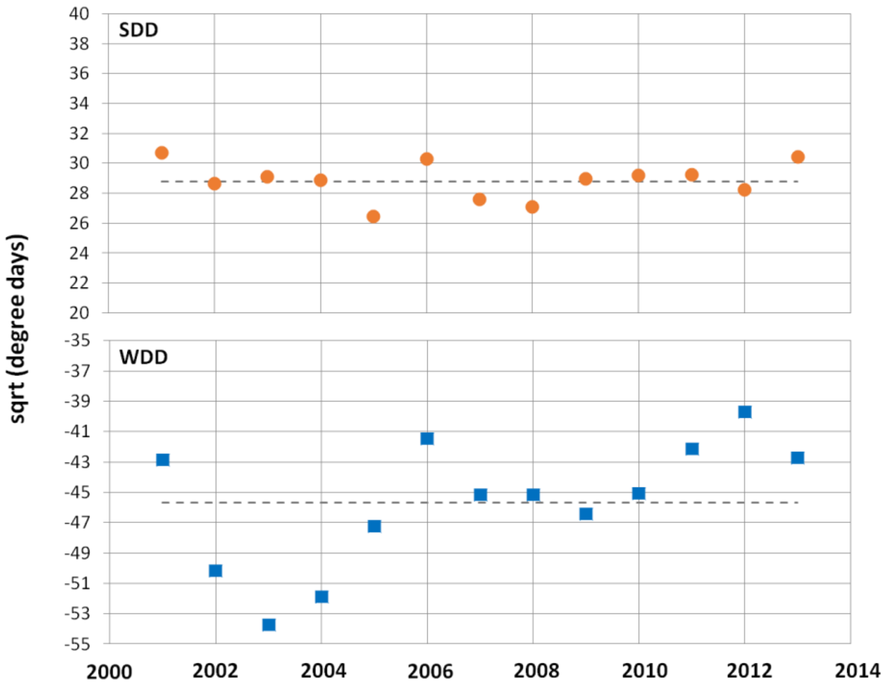

Figure 7: Summer-degree days SDD (circles) and winter-degree days WDD (squares) as an indicator for the thermal conditions at the ground surface over the course of the study period. The dashed lines indicate the respective means over the time period.

Table 1: Mean monthly and annual temperature [°C] and precipitation [mm] at Svalbard airport for the study period 2000-2014. Statistics (mean Ø and annual sum Σ) for the latest climate normal 1981-2010 are included for comparison (Data: Norwegian Meteorological Institute).

	2000-2014													**1981-2010**
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Mean, Sum**	**Mean, Sum**
T [°C]	-9.5	-10.0	-12.9	-8.7	-1.8	+3.7	+7.0	+6.2	+2.1	-3.5	-6.7	-8.5	Ø -3.6	Ø -5.1
P [mm]	20	12	15	9	8	7	21	20	22	21	19	22	Σ 195	Σ 187

Table 2: Field data used (Data: UNIS, NORPERM).

Method	**Data**	**Period**
Tinytag individual thermistor probes connected to miniature temperature loggers	Ground surface temperature (0.0 m) [°C] Subsurface temperature (-0.1, -0.2, -0.5, -1.1 m) [°C]	01.09.2000- 31.08.2014
GeoPrecision thermistor string with data logger	Subsurface temperature (-2.0, -3.0, -5.0, -7.0, -9.85 m) [°C]	17.09.2008- 14.04.2014
Delta-T profile probe	Soil moisture (-0.1, -0.2, -0.3, -0.4, -0.6, -1.0 m) [m^3 m^{-3}]	01.07.2010- 31.08.2014
Frost probing of CALM grid	Active layer thaw depth [cm]	01.09.2000- 31.08.2014

Table 3: Physical and thermal subsurface properties used in model simulations.

Material property	**Units**	**Value**	**Reference**
Residual saturation	-	0	e.g. Destouni, 1991; Painter and Karra, 2014; Watanabe and Wake, 2009
Porosity	-	0.4	e.g. Fitts, 2013; Schwartz and Zhang, 2003
Permeability	m^2	10^{-12}	e.g. Freeze and Cherry, 1979
Density	$kg\ m^{-3}$	2650	e.g. Andersland and Ladanyi, 1994
Heat capacity	$J\ kg^{-1}\ K^{-1}$	850	e.g. Andersland and Ladanyi, 1994; Fitts, 2013; Ochsner et al., 2001
Thermal conductivity (saturated)	$W\ m^{-1}\ K^{-1}$	1.7	e.g. Woo, 2012
Thermal conductivity (dry)	$W\ m^{-1}\ K^{-1}$	0.27	e.g. Woo, 2012

Table 4: Van Genuchten parameters α and m (Eq. 2) consistent with silt textures and as assigned in the seven model scenarios.

	Ref case	**High alpha**	**Low alpha**	**High m**	**Low m**	**Max case**	**Min case**
Van Genuchten α (Pa^{-1})	$8\cdot10^{-4}$	$12\cdot10^{-4}$	$4\cdot10^{-4}$	$8\cdot10^{-4}$	$8\cdot10^{-4}$	$12\cdot10^{-4}$	$4\cdot10^{-4}$
Van Genuchten m (-)	0.19	0.19	0.19	0.29	0.10	0.29	0.10

Table 5: Active layer thickness (ALT) for the study period 2000-2014 and corresponding statistics, as measured at the UNISCALM grid (average of all grid points and also the centre location, which is nearest the temperature logger) and as obtained from simulations.

	Measured ALT (cm) UNISCALM site		**Modelled ALT (cm) Different soil moisture retention properties**						
Year	**Grid average**	**Grid centre**	**Ref case**	**High alpha**	**Low alpha**	**High m**	**Low m**	**Max case**	**Min case**
2000	95	100	100	100	100	100	110	100	110
2001	99	102	100	110	110	110	120	100	130
2002	96	100	100	100	100	100	120	100	120
2003	93	99	100	100	100	100	110	90	110
2004	91	99	100	100	100	100	120	100	120
2005	74	79	100	100	100	90	110	90	110
2006	100	104	110	110	110	110	130	100	130
2007	105	106	100	100	100	100	110	100	110
2008	110	116	90	90	90	90	100	90	100
2009	100	106	100	100	100	100	120	100	120
2010	100	110	100	100	100	100	120	100	120
2011	101	104	110	110	110	100	120	100	120
2012	101	107	100	100	100	100	120	100	120
2013	103	111	110	110	110	110	130	110	130
2014	103	110	110	110	110	110	130	110	130
Statistics for time period 2000-2014									
Min	74	79	90	90	90	90	100	90	100
Max	110	116	110	110	110	110	130	110	130
Mean	98	104	102	103	103	101	118	99	119
Std. dev.	7.9	8.1	5.4	5.7	5.7	6.2	8.3	5.7	8.8
Trend [cm yr^{-1}]	0.8	1.0	0.5	0.3	0.3	0.3	0.8	0.6	0.6

Table 6: Subsurface temperature trends [°C yr^{-1}] as recorded and modelled (mean of all scenarios). Trends in the active layer (down to 1.1 m depth) are calculated for the period 09/2000-08/2014, and trends in the permafrost (from 2.0 m to 9.85 m depth) for the period 09/2008-08/2014. Summer is here defined as the period of continuous positive temperatures during the thaw season and winter as the remaining part of the year.

	Trend [°C yr^{-1}]										
Depth [m]	**0.00 (summer)**	**0.00 (winter)**	**0.10**	**0.20**	**0.50**	**1.10**	**2.00**	**3.00**	**5.00**	**7.00**	**9.85**
Observed	-0.05	0.25	0.23	0.26	0.19	0.17	0.14	0.15	0.11	0.07	0.05
Modelled (mean of all scenarios)	n.a.	n.a.	0.25	0.24	0.2	0.16	0.13	0.11	0.09	0.07	0.05

Table 7: Simulated thaw progression to 1 m depth including the water phase state after the onset of positive ground surface temperatures in May 2011.

Simulation scenario	Time to thaw 1 m depth [days]	Mean thaw rate [cm d^{-1}]	Vol. ice content [-]	Vol. unfrozen water content [-]	Vol. air content [-]	Effective therm. cond. K_e [J kg^{-1} K^{-1}]	Total latent heat [MJ]
Ref case	75	1.3	0.25	0.05	0.10	0.58	33.6
High alpha	74	1.4	0.22	0.04	0.14	0.50	28.7
Low alpha	76	1.3	0.32	0.06	0.03	0.73	42.3
High m	78	1.3	0.21	0.01	0.18	0.47	28.1
Low m	58	1.7	0.21	0.14	0.05	0.54	27.4
Max case	85	1.2	0.15	0.01	0.24	0.34	20.2
Min case	60	1.7	0.23	0.16	0.02	0.60	30.8