Active Layer Thickness Model And Predictions From Jotunheimen Boreholes

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Abstract— Four boreholes located in Juvvass, Jetta and Tron in southern Norway were used to measure the active layer thickness (ALT). An empirical modelling approach [Heggem et al., 2006], was used to estimate the spatial distribution of ALT. The method takes degree days, thermal diffusivity and water content into account.

Keywords— Borehole, Active Layer Thickness, Permafrost

1 Introduction

The exploration and investigation of permafrost is getting more important as it is an indicator of global warming with consequences as slope instability, natural hazards and release of greenhouse gas as the permafrost melts and the active layer grows. The active layer corresponds to the uppermost layer of material above the permafrost that is subjected to the freeze-thaw cycle [Heggem et al., 2006]. The mean air temperature is increasing, but the response on ground temperature (GT) differs because of the effect of snow- or sediment cover, vegetation, types of surcial material and bedrock. Research in the Jotunheimen area (fig. 2) has shown that in a ten years period, between 1999 and 2009, the ground temperature in the upper 10 meters has increased between 0.015°C to 0.095°C [Hipp et al., 2014].

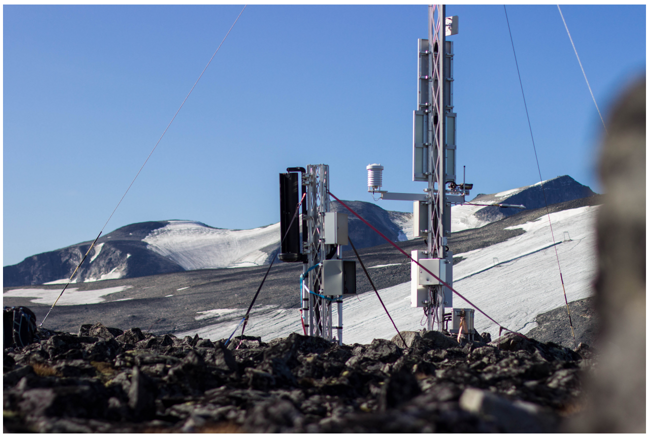


Fig. 1: Juvvass in Jotunheimen. Note the blocky ground that exits in the area. Credits: Arthur Dujardin.

A precise way to measure the active layer thickness is to use borehole data. Because this is a cost- and time demanding task, an empirical model [Heggem et al., 2006] was implemented. With this approach it's possible to cover bigger areas in a shorter amount of time with the information of thawing degree days (TDD) and land cover dependent variables. The aim of the study is to calculate ALT as being a function of TDD and ground structure and compare the results with measured ALT.

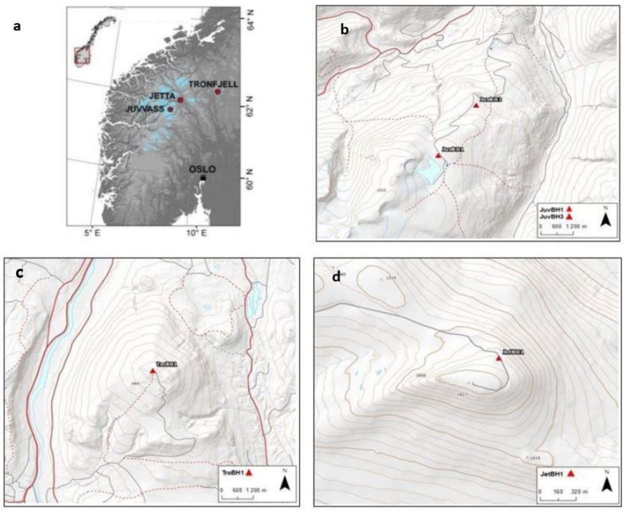
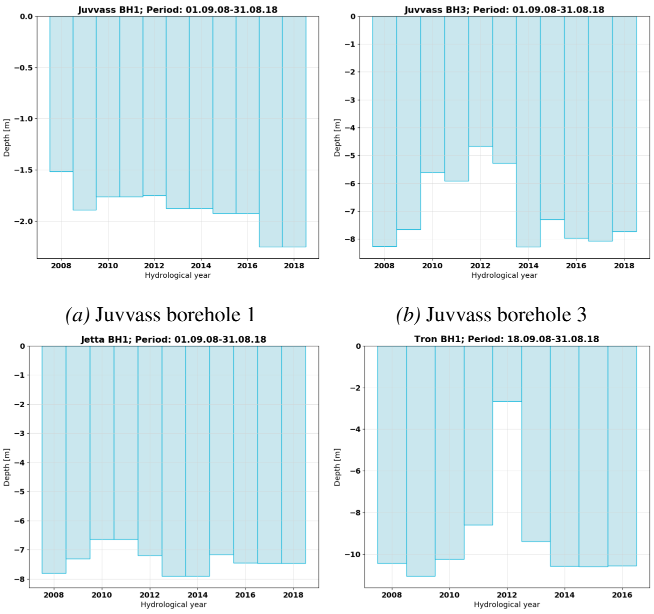


Fig. 2: Locations of the study sites and boreholes in Norway. (a) Site distribution in Norway (b) Juvvass borehole location (c) Tron mountain borehole location (d) Jetta borehole location

Based on the temperature measured in the boreholes, ALT was calculated using python for two boreholes (BH) in Juvvass, one in Tron and one at Jetta. The selected boreholes differ in location, elevation and surrounding material. A combination of parameters leads to an ALT indicated by the model results (fig. 3).



(a) Juvvass borehole 1 *(b)* Juvvass borehole 3

(c) Jetta borehole 1 *(d)* Tronfjell borehole 1

Fig. 3: Active Layer Thickness evolution from the past ten years.

Thermal conductivity and the ground surface temperature during the summer is the main factors controlling the ALT behavior [Smith and Riseborough, 1996, Farbrot et al., 2011]. Ground temperatures respond differently to warming, depending on the surface material, ground properties and soil water content. In mountain areas the sediments are coarse and well-drained, so it contains less water and lack a thermal buffer between permafrost and the active layer [Gruber and Haeberli, 2009]. The presence of permafrost is generally controlled by the heat flux between air and soil given by the time integrals over freezing and thawing seasons [Smith and Riseborough, 1996].

2 Study Area

The borehole arrays are situated at Juvvass (62°N, 8°E) in Jotunheimen, Jetta (62°N, 9°E) close to Gudbrandsdalen valley and at the Tron Massif (62°N, 11°E) in Alvdal [Farbrot et al., 2011]. The borehole locations are shown in fig. 2. The measurements were done between the hydrological years 2008 and 2018. Table 1 shows some of the parameters discussed in this article, that has an impact on the ALT at the different sites.

Table 1: Parameters of thermal diffusivity, ground composition, elevation and local topography for each location.

Borehole	Elevation (Farbrot et al)	Snow cover (Farbrot et al)	Sediment (Hipp et al)	Thermal diffusivity Sed./bedrock [W K^{-1} m^{-1}]	Local topography (Farbrot et al)
JuvBH1	1851	Thin/absent	Block field	0.39/1.59	F
JuvBH3	1561	Thin/absent	Coarse moraine	0.20/0.80	F
TronBH1	1640	Yes	Block field	0.20/0.61	F
JettaBH1	1560	Yes	Bedrock	_/0.92	S, Cv

2.1 *Juvvass*

2.1.1 *Borehole 1*

Juvvass BH1 has the thinnest depth of active layer ranging from 1,5 m to 2,2 in the period from 2008 to 2018. The borehole is located at the highest elevation in this study. The low pressure at higher altitudes causes a cooler temperature in mountains. Because of the short summers, the positive temperatures do not have time to melt the permafrost and the active layer thickness remains relatively stable [Farbrot et al., 2011]. The trend analysis (fig. 5) of the temperature shows a low gradient linear increase.

This corresponds well to the slow increase in the active layer from 2008 to 2018. The snow cover at Juvvass is usually thin or absent, which makes the surface dry and water content in the ground is low, so the ALT is well correlated with local summer air temperatures on an interannual basis [Isaksen et al., 2007].

2.1.2 *Borehole 3*

Juvvass BH3 shows a wide range in ALT during the time period with a decrease in ALT from 2008 to 2013 and increase from 2013 to 2018. The borehole is located at a lower elevation than the other boreholes in this study. The upper layer is coarse moraine followed by bedrock. The results reflects how the block field act as a buffer dampening the effect of the air temperature fluctuations on the ground. The thermal diffusivity is 0,8 in bedrock and 0,2 in sediments [Farbrot et al., 2011]. The site has a total absent of snow and therefore a lower surface offset compared to the snow-covered sites (fig. 6). That makes the permafrost more accessible to the air temperature during winter. The ALT-pattern in the period correspond well to the mean GST during the same period (fig. 4). In 2013 there was an increase in the permafrost and the mean GST was at its lowest point during this period. After this the temperature increased and so did the ALT.

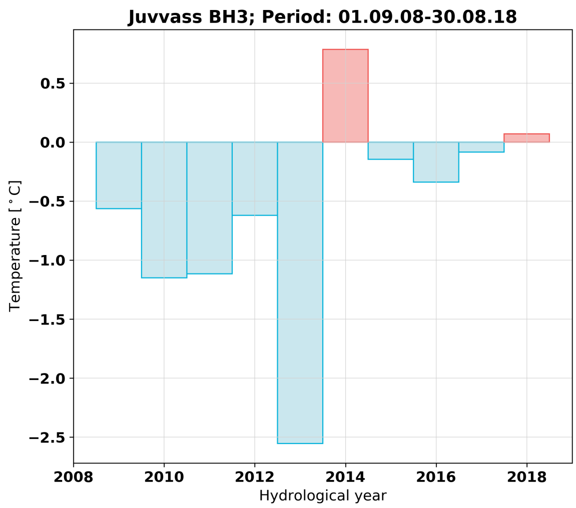
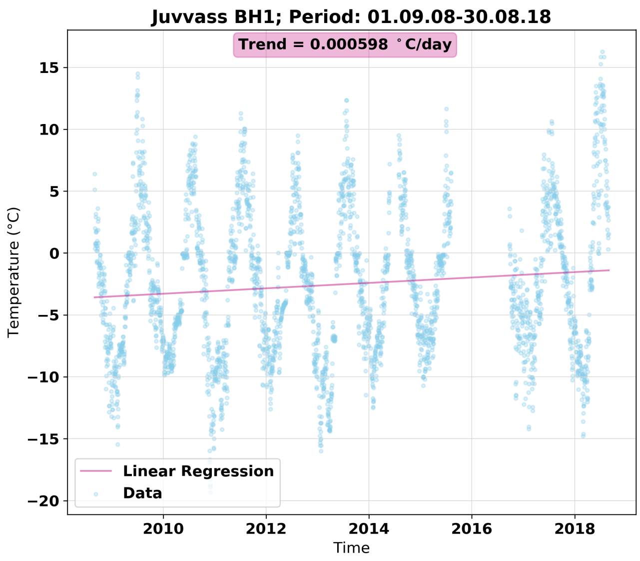
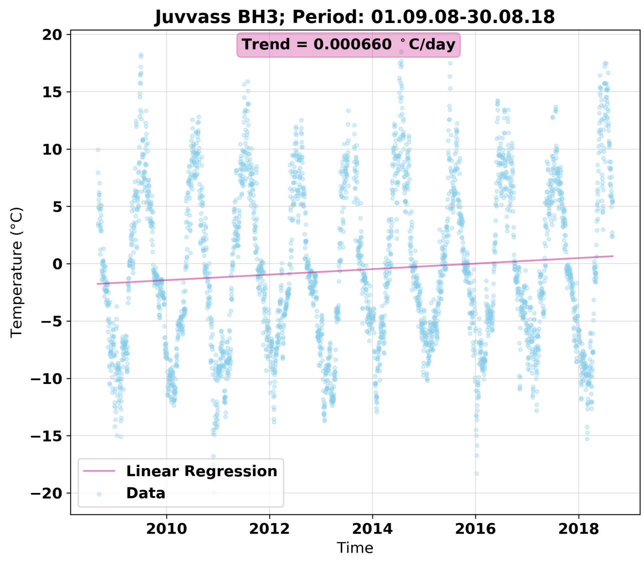


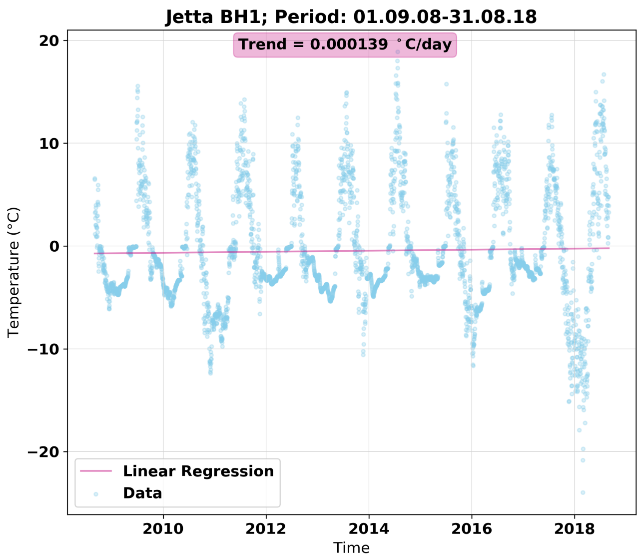
Fig. 4: GST for JuvBH3



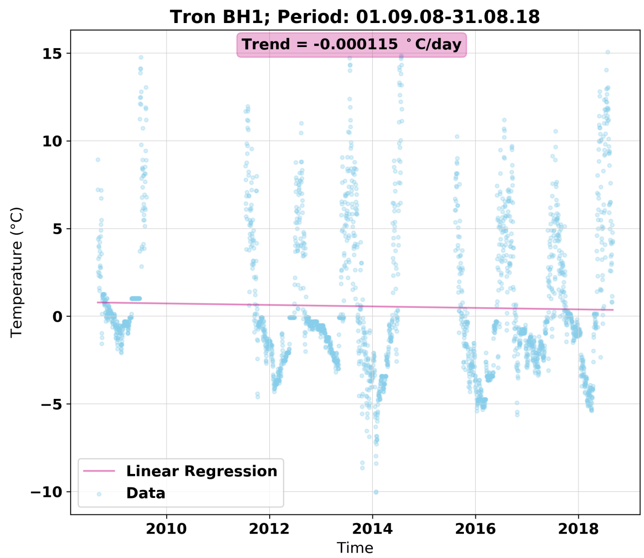
(a) Juvvass borehole 1.



(b) Juvvass borehole 3.



(c) Jetta borehole 1



(d) Tronfjell borehole 1

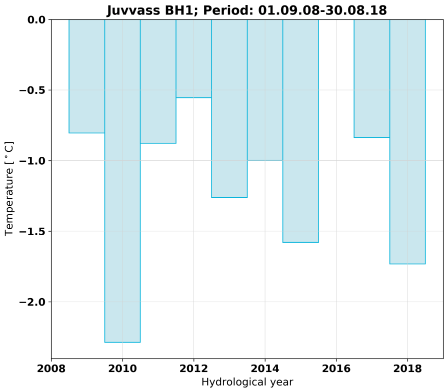
Fig. 5: Trend analysis from the past ten years.

2.2 *Jetta*

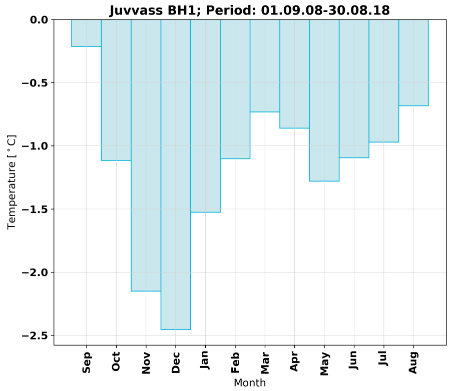
JetBH1 has a stable active layer depth during the time period ranging from 6,5 to 7,9 meters. The site is located at a lower elevation and the borehole is drilled in bedrock. There is usually a thick snow cover during the winter, preventing the cold air to penetrate far in the bedrock. This is shown in the surface offset (fig. 6e,f). Because of the absent of sediment cover, the ALT is more sensitive to climate variations. The thermal diffusivity of bedrock is much higher than block field (table 1) leading to a slower reduction in annual amplitude with depth [Farbrot et al., 2011].

2.3 *Tronfjell*

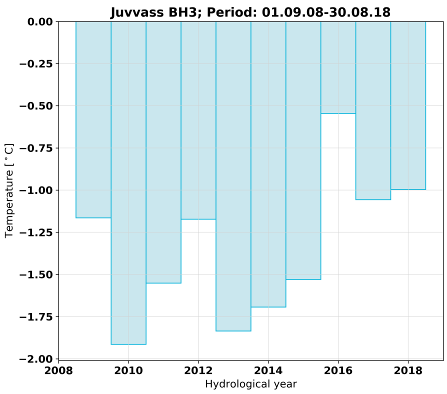
The ALT at Tron mountain is the largest in this study with a maximum ALT of 10,5 meters. The thickness has been relatively stable disregard the loss of data in 2013 and 2018. The borehole is drilled in block field which in theory can have a cooling influence in the subsurface temperature [Gruber and Haeberli, 2009]. Water drains easily which corresponds to a high surface offset(fig.6g,h) due to advective heat transport. Because of the low water content, the thermal buffer that is supposed to slow the increasing ALT down, is here less efficient. As with JetBH1, the borehole is covered by thick snow in winter times [Hipp et al., 2012].



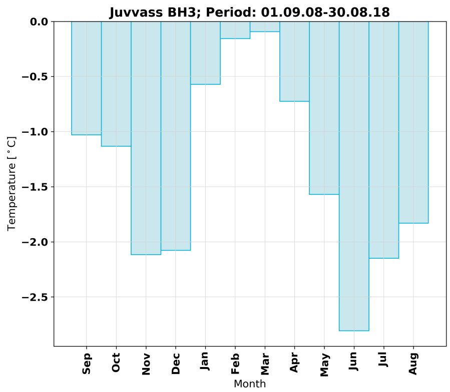
(a) JuvBH1 Yearly



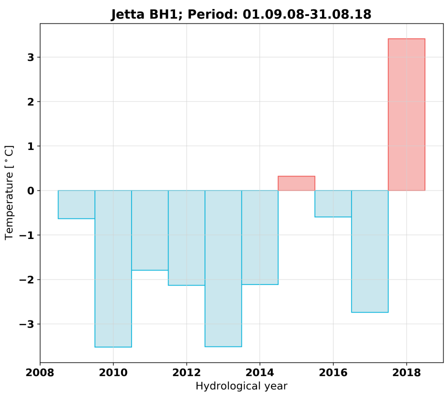
(b) JuvBH1 Monthly



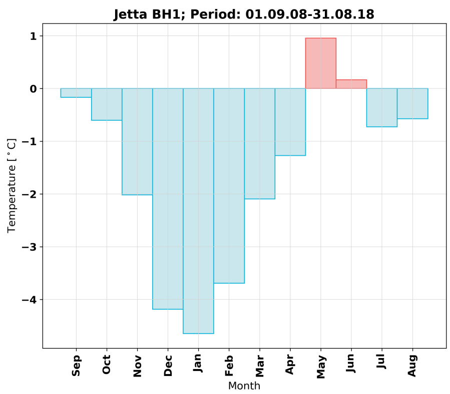
(c) JuvBH3 Yearly



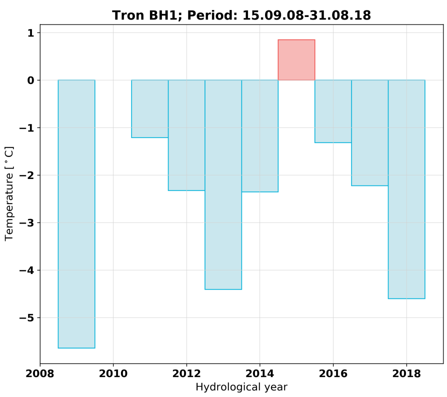
(d) JuvBH3 Monthly



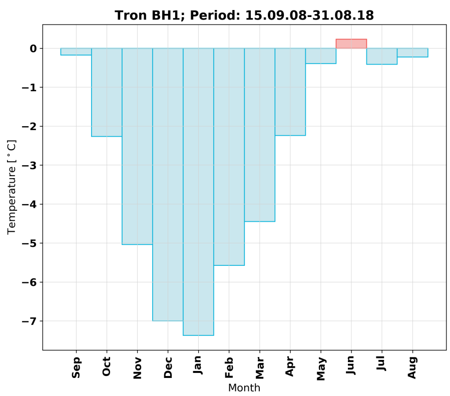
(e) JetBH1 Yearly



(f) JetBH1 Monthly



(g) TrBH1 Yearly



(h) TrBH1 Monthly

Fig. 6: Yearly and monthly surface offset average from the past 10 years for each sites.

3 Model

An ALT model based on thawing and freezing degree-days (TDD and FDD) were implemented in Python. Data from boreholes in a variety of landscapes were collected from a ten-year period. For the model to fit each borehole, it needed to be calibrated by using specific parameters (table 1).

3.1 Method

To consider the seasonal change of temperatures over time, surface temperatures were described as a sine wave function:

$$\forall t \in \mathbb{R}, \quad T(t) = A\sin(t) + b \tag{1}$$

The amplitude A and parameter b were determined manually [Heggem et al., 2006]. This method has been applied to both ground and air surface temperatures (fig. 7, 8). A better way to estimate these parameters will be to use mean square methods, as it minimize quadratic errors.

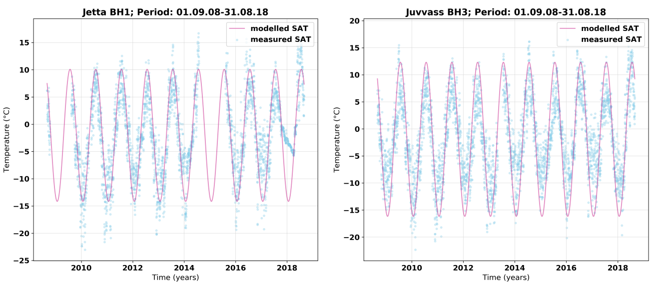


Fig. 7: Modelled surface air temperature on the different sites.

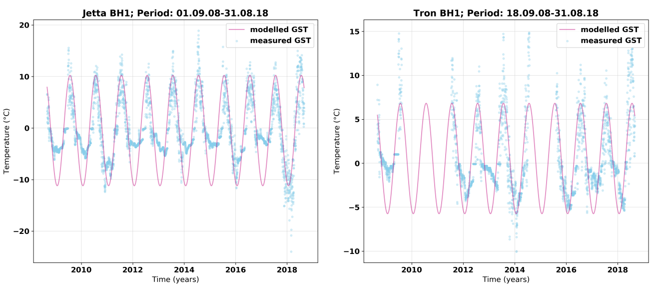


Fig. 8: Modelled ground surface temperature on the different sites. The modeled temperature does not follow reality: snow cover are not taken into account.

The method is simple to implement, but on the other hand the peaks are not well matched. In fact, some concave patterns seem to appear on some boreholes sites (fig. 8, Jetta and Tronfjell).

Then FDD and TDD has been calculated. FDD are the sums of daily temperatures where it was freezing, and the opposites for TDD (4, 5). Let $\mathfrak{T}$ the set of all temperatures for one year.

$$\mathfrak{T}_{FDD} = \{T \in \mathfrak{T} | T < 0\} \tag{2}$$

$$\mathfrak{T}_{TDD} = \{T \in \mathfrak{T} | T \geq 0\} \tag{3}$$

Then, FDD and TDD are defined as:

$$FDD = \sum_{T \in \mathfrak{T}_{FDD}} T \tag{4}$$

$$TDD = \sum_{T \in \mathfrak{T}_{TDD}} T \tag{5}$$

FDD and TDD are temperatures in cold and warm period respectively, and the coefficients n_F and r enable to weight these periods and influence Mean Annual Temperature (MAGST and MAAT) distribution:

$$MAT = \frac{n_F FDD + rTDD}{time} \tag{6}$$

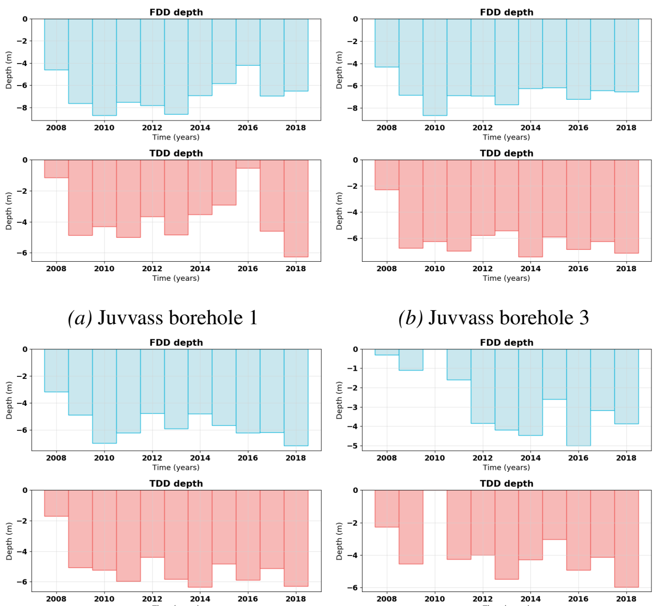
As the amplitude and intercept are highly dependent on the environment of the borehole location, each sine was matched to the measured temperature curves.

Finally, the depth of frost and thaw Z_{depth} has been computed with the FDD and TDD. As the DD are constant over time for a sine curve, there is no real interest to focus on this model anymore. However, a simple equation linking thermal diffusivity, soil density, latent heat of fusion can be used to model temperatures in depth (7).

$$Z_{depth} = \sqrt{\frac{2\lambda}{\rho_d w L} S \times DD} \tag{7}$$

3.2 Results

The depth of frost and the depth of thaw (fig. 9) were computed with the equation (7). The active layer thickness (fig. 3) are used as control data.



(a) Juvvass borehole 1

(b) Juvvass borehole 3

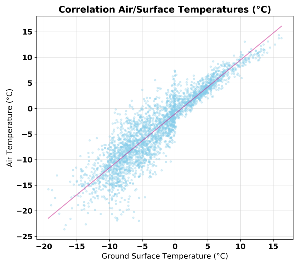
(c) Jetta borehole 1

(d) Tronfjell borehole 1

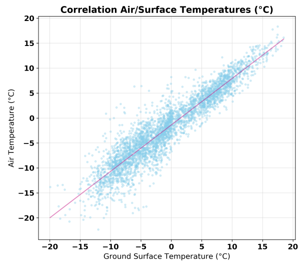
Fig. 9: Thawing and freezing depth at each sites. Parameters from table 1 were used.

3.3 Analysis

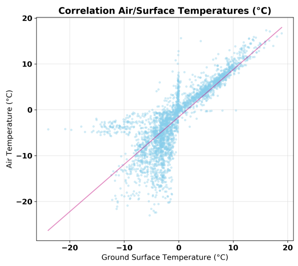
To better understand these results, a basic analysis of the data has been made. This analysis aims to extract correlation between some parameters and the meaning will be discussed. Correlation graph highlights dependencies between the variables used to model ALT. By plotting a set of variables (fig. 10, 11), patterns can be visualized – then there may be a causation relation. If not, causation between these variables does probably not exist.



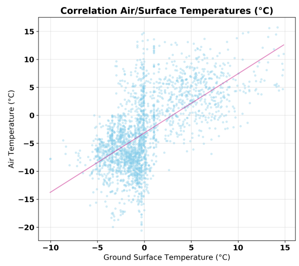
(a) Juvvass borehole 1



(b) Juvvass borehole 3



(c) Jetta borehole 1

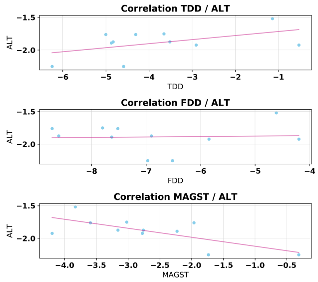


(d) Tronfjell borehole 1

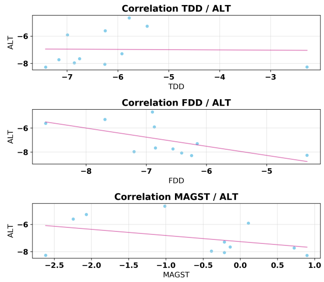
Fig. 10: Air and ground surface temperatures correlation. Figures (a) and (b) show a linear correlation between these two variables. The (c) graph highlights bias due to snow cover. The last graph is noisy due to errors and missing data, therefore no clear relationship can be underlined.

Ground surface temperature is highly correlated to air surface temperature (fig. 10). However, in presence of snow the correlation is changed below 0°C. Without snow cover, prediction of temperatures is much easier and can be determined using a linear regression. Snow cover has a strong impact on air and ground surface temperature correlation (fig. 10.c) The snow cover influenced the heat flow. In fact, temperatures do not travel by convection anymore, but by conduction. Therefore, physics laws are changed.

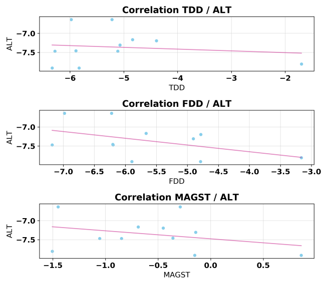
The analysis can be pushed to all relations between the variables. A non-exhaustive study has thus been made (fig. 11. The correlation patterns are complex, and the linear regression model is not really adapted. Nevertheless, the model underline that ALT increases with increased FDD, TDD and MAGST (fig. 11).



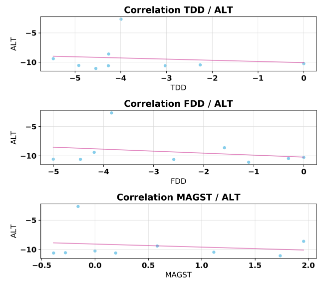
(a) Juvvass borehole 1



(b) Juvvass borehole 3



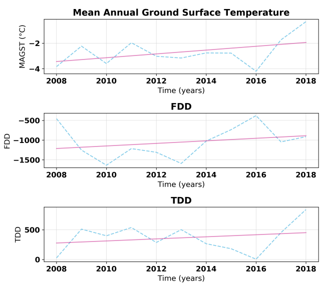
(c) Jetta borehole 1



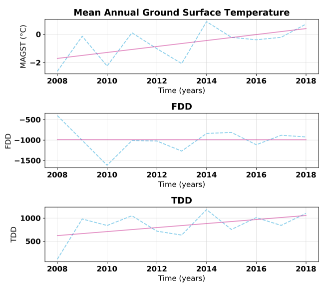
(d) Tronfjell borehole 1

Fig. 11: Correlation graphs between FDD, TDD, MAGST, ALT.

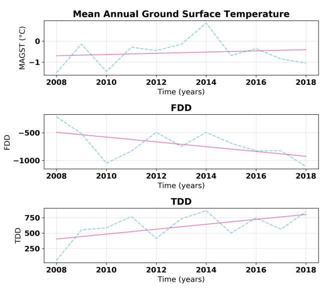
Global trend (fig. 12) and correlation analysis are an important step to validate the previous model. Thus, Mean Annual Ground Surface Temperatures (MAGST) and correlation between FDD, TDD, and ALT can be higlighted. The MAGST is skyrocketing (from –2°C to +1°C in ten years) at Juvvass borehole 3 (fig. 2). The TDD curve is rising as well even if the FDD are stable (-1000°C days).



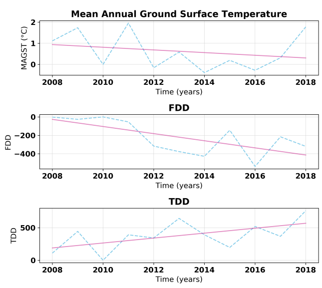
(a) Juvvass borehole 1



(b) Juvvass borehole 3



(c) Jetta borehole 1



(d) Tronfjell borehole 1

Fig. 12: Global trend of FDD, TDD, MAGST.

3.4 *Improvement*

The main advantages of this physical driven model is that it requires few parameters and data. The results are lower by a bias of 2 meters, that can be fixed by tweaking the parameters of the ground composition. However, the resulted trend does not match reality, extreme values of ALT at a specific time are not always determined by the model. The model could be improved by adding multiple parameters, like the ability to remember previous state. Recurrent Neural Network (RNN) with Long-Short Term Memory (LSTM) seems to be an alternative as the model remembers previous data. To build a Neural Network model a huge dataset need to be provided as training data however.

4 Conclusion

The measurements showed that JuvBH1 has the thinnest active layer. Interpretation on the results based on field parameters suggest that the ALT is due to its high elevation, cold winter- and summer temperatures in addition to a absent snow cover. JuvBH3 and JetBH1 reaches roughly the same thicknesses, but Jetta is much more stable during the ten years of measurements. The surface offset is higher in JetBH1 than JuvBH1. The measurements reveal that Tron has the thickest active layer. This is due to a thick snow cover during winter and a lack of thermal buffer. With knowledge of the measurements, a first physical based model has been implemented to predict ALT knowing DD and ground composition only. On the one hand, this model is fast to implement and requires few parameters. On the other hand, the results does not match always reality. Some parameters are neglected, like the past state of the area. In fact, an area with a thick ALT will need a long warm period to become thin, therefore TDD and FDD of one single year are not enough and a temporal algorithm may improve the results. The downside of this approach is that it requires a lot of data to train the model, as opposed to a physical driven model.

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