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Impact of meteorological factors on active layer development in Central Spitsbergen

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ABSTRACT: The active layer thickness and soil temperature were measured at two sites during 2000 and 2001, one in Adventdalen (10 m asl.) and one at Sukkertoppen (373 m asl.), in central Spitsbergen, Svalbard. The active layer depth in Adventdalen varied from 95 to 99 cm, and was mainly controlled by the air temperature. On Sukkertoppen a snowpatch was present until 26th of August 2000, while in 2001 the snowpatch melted by the 1st of July. On Sukkertoppen the active layer depth varied from 77 to 80 cm, and was controlled by air temperature and soil moisture. Variations in the soil moisture content were a result of precipitation during the thawing season and meltwater from the snowpatch. The release of sensible and latent heat in combination with air temperature increased the soil temperature up to 17°C.

1 INTRODUCTION

General circulation models predict an amplified warming in the Arctic during the 21st century (Serreze et al. 2000). Active layer respond rapidly to a change in meteorological factors, and can be used as an indicator for climate change. Progressive deepening of the active layer over several years may cause thinning and degradation of the permafrost, which may in turn cause an increased release of CO_2 and other greenhouse gasses (Anisimov & Nelson 1997). The active layer depth has been widely studied the last decades, and guidlines have been introduced by the Circumpolar Active Layer Monitoring (CALM) program (Brown et al. 2000).

The active layer is defined as the layer above permafrost, which thaws and freezes each year (Burn 1998). Local climate, soil properties and the surface conditions are the factors controlling the temperature in the ground and thereby the depth of the active layer (Zhang 1995). The air temperature is the main factor affecting the soil temperature and active layer thickness, but snow cover, rain and other local factors such as vegetation, organic layer etc. may have a significant effect depending on the local conditions.

Snow cover has an insulating effect on the soil surface temperature (Pomeroy and Burn 2001). The insulating effect increases with snow depth. A deep snow cover early in the winter, which thereafter persists prevents any severe cooling of the ground. The time of snowmelt affects the timing of warming of the ground and the active layer development during summer.

During the thawing season convective energy in the form of sensible and latent heat may exceed the energy transported through conduction (Kane et al. 2001). Rain supplies sensible and latent heat to the soil when the temperature of the rain exceeds the soil temperature, causing a warming and deepening of the active layer (Hinkel et al. 2001). Water infiltrating the ground from rain or melt water can cause an abrupt warming of the active layer and thereby deliver considerable energy to the soil (Putkonen 1998). When the water freezes again latent heat will be released, and the temperature of the surrounding soil will increase.

This paper discusses the active layer thickness development in central Spitsbergen, the role of convective heat transfer during snow melt and precipitation during the thawing season in the active layer development.

2 LOCATION

2.1 *Svalbard*

Svalbard is located between 74°–81°N latitude and 10°–35°E longitude. The largest island of the Svalbard archipelago is Spitsbergen and the two study sites are located on Central Spitsbergen (Fig. 1). Svalbard is a high arctic area with a mean annual air temperature of −5.7°C (1971–2000 at Svalbard Airport). The precipitation is very low around 200 mm/year at Svalbard Airport, which is situated 7 km from the Adventdalen site. The precipitation during summer (June, July and August) is around 20 mm/month, and may fall as both rain and snow (Førland et al. 1997). The meteorological data used in this study are from the Aurora Station located only 100 m West of the Adventdalen site. Continuous permafrost is present on Svalbard with thickness ranging from 200–450 m, with thinner permafrost near the coast (Isaksen et al. 2000, Isaksen et al. 2001).

2.2 *The study sites*

The Adventdalen site (10 m asl.) is located at 78°12′N and 15°39′E (Fig. 2), on a terrace along the Adventdalen river, and is a part of the CALM network. The terrace

Figure 1. Map of Spitsbergen, and Adventdalen marked with a black star.

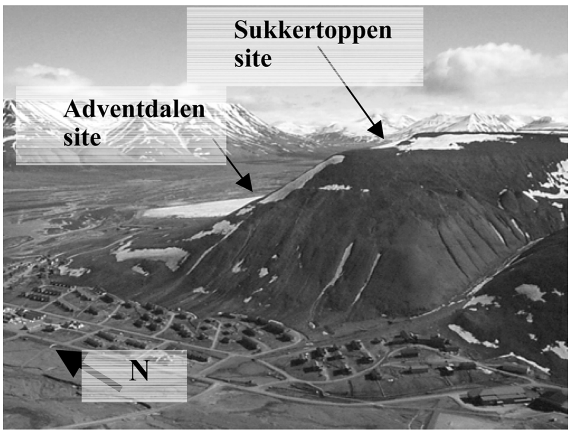

Figure 2. Photograph of the Sukkertoppen site and part of Adventdalen. Picture is from automatic digital camera installed on Plateaufjellet by Ole Humlum.

consists of aeolian material, and the surface is covered with *Salix polaris* and *Festuca rubra*.

A profile of temperature sensors were installed in August 2000 in the center of the site. The sensors were installed in the surface, 10, 20, 50, and 110 cm depth, the lowest was installed in the permafrost. The temperature was logged every hour throughout the year by Tiny Tag miniature dataloggers.

The Sukkertoppen site (373 m asl., 78°13′N and 15°38′E) is located on a small terrace (Fig. 2), and a snowpatch is present most of the year. The soil consists primarily of weathered shales and some sandstones, resulting in a high clay content. In front of the snowpatch the vegetation cover is dense and consists mainly of mosses, while it is sparse in the rest of the site. At the Sukkertoppen site one profile of temperature sensors was installed in front of the snowpatch and one below the late lying snowpatch. In this paper will only the profile in front of the snowpatch be used, due to break down of loggers at the other profile. The thermistors were installed in the surface, 10 20 40 and 70 cm. The temperature was logged as described for the Adventdalen site.

The active layer depth was determined by probing on a grid as described in the CALM (Brown et al. 2000). The Adventdalen site is 100×100 m with a grid size of 10 meters and a total of 121 points. The Sukkertoppen site is $130 \times 100 \times 70$ m and trapezoid formed also with a 10 m grid size. The active layer is measured at each point with a 1 cm diameter metal rod forced manually to the permafrost surface.

3 RESULTS

3.1 *Active layer depth and thawing rates*

The development of the active layer depth was measured during the summer 2001 and partly in 2000 (Fig. 3). The measurements from 2000 showed the last part of the thawing season because the sites were not installed until the middle of July. The average active layer depth at the end of the thawing season in 2000 and 2001 was nearly the same, 95 and 99 cm at the Adventdalen site and 80 and 77 cm at the Sukkertoppen site. The thaw depth could have increased more in 2000, but the temperature profiles indicated freeze up shortly after the last measurements. Average active layer depth at Sukkertoppen was measured as an average of all points, and points covered by snow were set to 0 cm.

The active layer depth at the two sites showed the same pattern, with a rapid deepening in the beginning of the thawing season. Towards the end of the thawing season the thawing rate decreased as the active layer was reaching the maximum depth. The difference in active layer depth in 2000 and 2001 between the two sites deviated by 18–20 cm at the end of the season (Fig. 3), but with a larger difference in the beginning of the thawing season. This may be due to the snowpatch at the Sukkertoppen site. The snowpatch melted the 26th of August 2000, but in 2001 the snow was melted by the 1st of July. The snow cover is marked as number of measuring points covered with snow. The presence of the thaw. The snow will prevent the soil from thawing and cause the delay in the development of the active layer depth. The altitudinal difference may cause a lower air temperature on the Sukkertoppen site leading to the difference in active layer depth.

The standard deviation at the Sukkertoppen site was between 2 and 27 cm. This large deviation is mainly

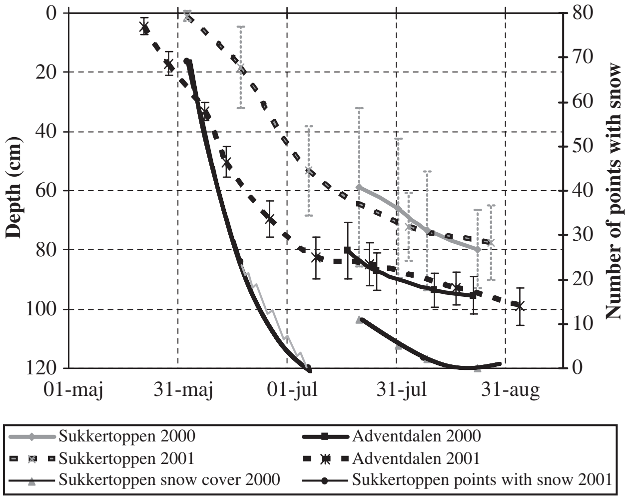

Figure 3. Active layer depth at the Adventdalen (black) and Sukkertoppen (gray) site in 2000 (full lines) and 2001 (dotted lines). The size of the snowpatch is presented as points covered by snow. The vertical bars indicate the standard deviation.

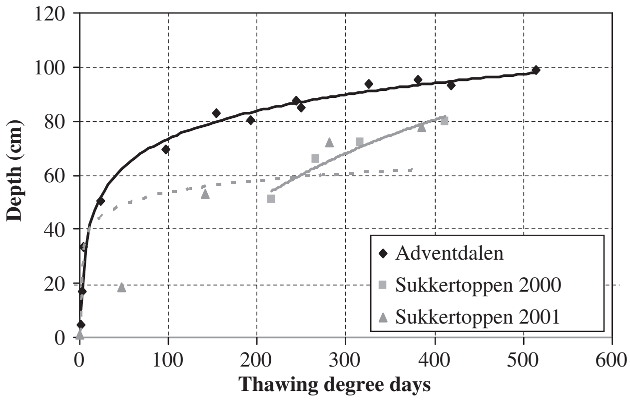

Figure 4. The active layer depth as a function of thawing degree days (TDD). The data from Sukkertoppen is separated in 2000 and 2001 due to difference in location of air temperature measurements.

due to the snowpatch preventing thawing of the ground in parts of the site. The 18th of June 2001 the active layer depth showed a maximum of 67 cm, while the ground was still frozen under the snowpatch. The standard deviation at the Adventdalen site ranges from 2 to 10 cm, due to the homogen snow and vegetation cover.

3.2 *Thawing degree days and active layer depths*

The active layer depth during the thawing season was compared with thawing degree days determined from air temperature data collected at the Aurora station (Fig. 4). The air thawing degree days (TDD) were calculated as average degree per day above zero accumulated over time (Zhang et al. 1997, Nelson et al. 1997).

The active layer depth increased logarithmically, with TDD, with a large slope in the beginning of the thawing season, indicating a large change in active layer depth. At the end of the thawing season the curve flattened as the active layer reached the maximum depth.

The Adventdalen site showed a faster response to positive air temperatures due to the thin snow cover, which melted by the end of May 2001. The thawing was rapid until the active layer reached 50 cm at the Adevntdalen site, then the thawing rate decreased. The logarithmic fit was used, because the logarihtmic fit better describes the relationship between active layer thickness and TDD. The linear fit with the square root of TDD suggested by Hinkel & Nicholas (1995) does not explain the fast thawing in the beginning of the thawing season at the Adventdalen site. The correlation values were $r^2 = 0.99$ at the Adventdalen site for both years and $r^2 = 0.70$ at the Sukkertoppen site for 2001.

The snowpatch covers one third of the Sukkertoppen site in the beginning of the thawing season, resulting in a lower average active layer depth. The correlation between the Sukkertoppen site and TDD showed a linear trend, due to the delayed thawing of the ground caused by the snowpatch. TDD is a poor indicator of energy available for warming and thawing the ground, when a snow patch is present as here. The high thawing rate at Sukkertoppen after 300 TDD is caused by the release of melt water from the snowpatch or maybe that more rain is falling on Sukkertoppen. The infiltrating water supplies the ground with substantial amounts of sensible and latent heat, if the temperature of the water is higher than the ground. For the Sukkertoppen site the correlation with the square root of TDD was better $r^2 = 0.9$.

The good correlation between active layer and thawing degree days (Fig. 4), indicates that the summer air temperature is the dominant factor controlling the active layer development. The difference in active layer depth between the two sites were close to zero at 0 TDD, but increased rapidly to 40 cm, indicating the delay in thaw that occurs at Sukkertoppen site due to persistence of snow cover. At the end of the thawing season the difference decreased again to approx. 20 cm (Fig. 4).

3.3 *Difference between the two years*

The major energy source during summer is the solar radiation, but periods with rain or melt water infiltrating the soil are also important factors (Hinkel & Outcalt 1994). The air temperature was higher in 2001 compared to 2000 (TDD increased with 150 in Adventdalen). The active layer at the Sukkertoppen site was deeper in 2000 compared with 2001, and three explanations are possible: (1) The ground temperatures could have been higher below the snowpatch from winter 2000 to summer 2000, due to the early snowfall in autumn 1999 causing a decrease in the heat loss. The higher soil temperature led to a deeper active layer, because less energy was required to thaw the soil during summer 2000. (2) The water content in the soil was much higher in the summer 2000, due to a larger amount of precipitation in form of rain in 2000 compared with 2001. Melt water was continuously released from the snowpatch until late August 2000, which also led to higher water content. The higher water content increases the conductivity and heat capacity of the soil. The loss of latent heat due to evaporation would also increase. The sum of these changes might have lead to a thicker active layer. (3) The mosses partly dried out in 2001 in the front of the snowpatch at the Sukkertoppen site, insulating the ground and leading to the shallower active layer in 2001 despite the warmer air temperatures (Williams & Smith 1989). Explanations 2 and 3 were the only ones supported by observations. It was shown that wet soil conducts the heat 6 times better than dry soil and wet mosses conduct 10 times better than dry ones (Bölter 1999).

3.4 *Snow melt and latent heat*

Adventdalen showed a shallow thawing in parts of the site 1st of May 2001. This episode was studied closer and the entire profile experienced an increasing soil temperature. The soil temperature started to increase as the air temperature rose at the 24th of April (Fig. 5).

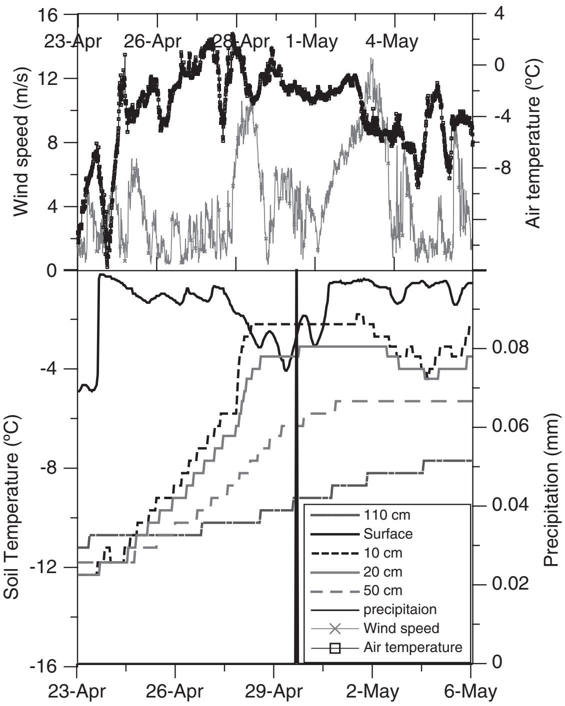

Figure 5. The soil temperatures in Adventdalen from 23rd of April until 6th of May 2001. The air temperature and wind speed from the Aurora station are presented in the upper graph. Precipitation is shown as a bar in the lower graph.

The surface showed a fast response and increased with almost 5°C within 12 hours. The soil temperature increased more gradually with depth, but the heating of the ground lasted for a longer period. This resulted in a soil temperature increase during that week of 10°C in 10 cm depth, 9°C in 20 cm depth, 7°C in 50 cm depth and 3°C in 110 cm depth within the measuring period.

The 29th of April the soil temperature in 10 and 20 cm depth increased dramatically, 4°C within 12 hours, the surface and air temperature decreased at the same time. The rapid increase in soil temperatures may be caused by melt water from the snow percolating to a depth of 20 cm. When the water freezes latent heat will be released, and the soil temperature will increase (Kane et al. 2001). Snow melt and thaw of the ground was observed the 1st of May in parts of the Adventdalen site, which supports that the heat can be due to water movement.

During the 14 days the wind speed showed large variations. Increased wind speed results in increase in turbulent heat transfer, i.e. sensible heat and evaporation. Heat transport in this way is limited and normally restricted to the surface of the active layer (Kane et al. 2001). The wind speed increased to 11 m/s the 29th of April, this may contribute to the strong increase in soil temperatures in 10 and 20 cm depth. The air temperature was −3°C the 29th of April, and the convective heat transport will be considered as limited. The soil temperature in 10 and 20 cm depth decreased again from the 2nd of May. The decrease in the soil temperature in 10 and 20 cm depth could also be a result of heat loss to the depth, and that conduction becomes the dominating process again (Hinkel & Outcalt 1994). The wind speed was 13 m/s during this period, and may have increased the convection, resulting in the lower temperatures in 10 and 20 cm depth. The surface temperature stayed around −1°C. Liquid water was most probably present, and freezing of the water occurred as the air temperature decreased resulting in the release of latent heat. This may explain the constant surface temperature. The snow cover and free water, with high apparent heat capacity, at the surface may explain that almost no daily variation is seen in the profile.

The amount of precipitation falling was very limited, and no effect on soil temperatures can be concluded. The increase in soil temperatures was related to an increase in air temperature and melt water infiltration from the snow cover.

3.5 *Rain and sensible heat*

The soil temperature was studied in detail for a short period in July 2001 to examine the effect of rain. Figures 6 & 7 show the soil temperatures and precipitation from 8th to the 13th of July 2001 on Sukkertoppen and in Adventdalen respectively. The large precipitation

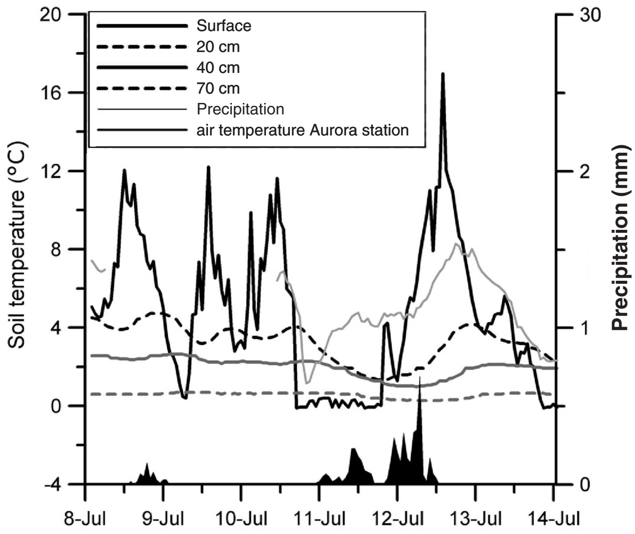

Figure 6. Soil temperature at Adventdalen and precipitation from 8th to the 13th of July 2001. The figure shows the response of soil temperature to precipitation.

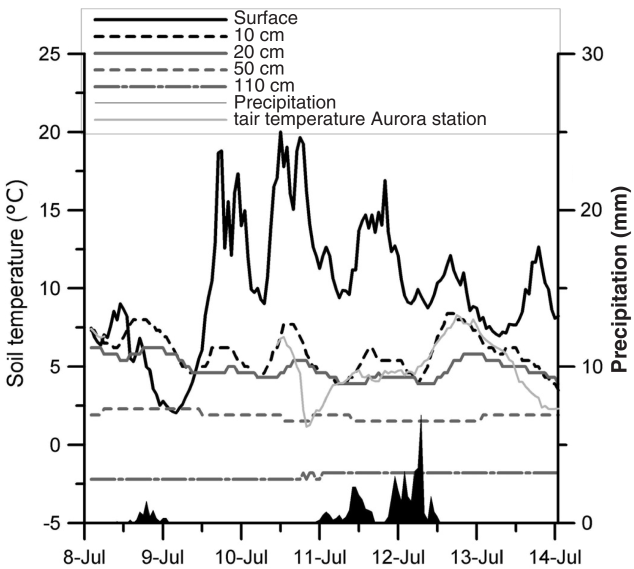

Figure 7. The soil temperatures in Sukkertoppen and precipitation from 8th to the 13th of July. The figure shows the response in soil temperatures to precipitation.

event on the 12th occurred in air temperature between 5 and 10°C. The surface temperature responded immediately and rose to 17°C at the Sukkertoppen site. The response of soil temperature to the precipitation showed a delay with depth. Most energy was released in the upper layers, and the signal diminished with depth. The Adventdalen site showed also an increase in soil temperatures and a lag in response with depth. The surface temperature did not show the same strong increase as was seen on Sukkertoppen. This may be caused by the cooling effect of evaporation, because dense vegetation is present at Adventdalen and only sparse vegetation is present above the temperature sensors at Sukkertoppen.

The precipitation falling during the 8th of July resulted in a slight increase in soil temperatures in 20 and 40 cm depth at Sukkertoppen, while the soil temperatures in Adventdalen decreased according to the air temperature. The precipitation during the 11th of July showed a small heating effect on the soil temperatures in Adventdalen but none on Sukkertoppen, this may be caused by the low air temperature. The drop in air temperature to almost 0°C the night to the 11th of July and the constant surface temperature, could indicated that the precipitation fell as snow. The surface temperature shows a daily variation, which follows the air temperature closely.

Both sites showed a daily variation to a depth of 20 cm, which indicates snow free conditions on the ground above the profiles. The variations are largest in the surface and the temperature amplitude attenuates with depth. This daily signal should be kept in mind when studying the effect of precipitation or melt water.

4 DISCUSSION AND CONCLUSION

The main factor controlling the active layer depth and ground temperature was air temperature, while precipitation and meltwater showed to be significant in periods. The infiltration of meltwater released in the beginning of the thawing season lead to rapid increase in soil temperatures down to 20 cm depth. The increase in soil temperature was caused by the release of latent heat. When soil temperatures are in the range of -6°C to 0°C the content of liquid water is significant (Hinkel & Outcalt 1994). These investigations showed a strong increase in soil temperatures when water was added, and latent heat released. A high water content also affects the soil when the air temperature decreases, as shown in Figure 5. The soil temperature stayed on a constant level until all water was frozen and the latent heat released was transported downward or upwards, as during the zero curtain in autumn (Hinkel & Outcalt 1994).

The surface received most energy from infiltrating water, and the energy supply attenuated with depth. The increase in soil temperature with depth showed a delay in time due to the transport time of the water (Fig. 6 & 7). When no delay is seen the water may be transported in cracks. If the water reaches the permafrost table, it will freeze and latent heat will be released increasing the soil temperature.

The amount of water added to the soil surface determines the insulating effect of the vegetation cover, hence a dry moss cover insulates 10 times more than a wet moss cover, and lead to a thinner active layer. In this investigation the soil moisture and the mosses showed to be significant in controlling the active layer development.

The maximum active layer depth in Adventdalen varied from 95 to 99 cm, and was mainly controled by the air temperature. On Sukkertoppen a snowpatch was present until 26th of August 2000, while in 2001 the snowpatch melted by the 1st of July. On Sukkertoppen the maximum active layer depth varied from 77 to 80 cm, and was controlled by air temperature and soil moisture. The active layer on Sukkertoppen decreased from 2000 to 2001, while the thawing degree days increased by 150 TDD at the Aurora Station. This was explained by the higher moisture content in 2000, leading to higher conductance and increased release of sensible heat and dry mosses provided insulation in 2001. These results show that variations in active layer thickness are not necessarily indicators of change in air temperature, but may be related to changes in moisture content and precipitation.

The air temperature presented as TDD represented 99% of the variation in the Adventdalen site, and air temperature could be used as to predict the active layer depth. The TDD explained 70% of the variation at the Sukkertoppen site. This low correlation was mainly due to the delayed thawing, which was caused by the presence of the snowpatch. This indicates that it is important to have localized studies, and that the relation between TDD and active layer depth vary between different locations. Sites with a thin homogeneous snow cover show a rapid thawing in the beginning of the thawing season. The logarithmic correlation between active layer depth and TDD describe this development better than the Stefan's solution (Hinkel & Nicholas 1995).

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REFERENCES

Anisimov, O.A. & Nelson, F.E. 1997. Permafrost zonation and climate change in the Northern Hemisphere: Results from transient general circulation models. *Climatic Change* 35. P. 241–258.

Bölter, M. 1999. Consequenses of Global Warming on Soil Processes in Arctic Regions. *Polarforschung* No. 66 (1/2) 1996. P. 1–10.

Brown, J., Hinkel, K.M. & Nelson, F.E. (eds.) 2000. The circumpolar active layer monitoring (CALM) program: Research designs and initial results. *Polar Geography*. 24 (2). P. 165–258.

Burn, C.R. 1998. The Active Layer: Two Contrasting Definitions. *Permafrost and Periglacial Processes* 9. P. 411–416.

Førland, E.J., Hanssen-Bauer, I. & Nordli, P.Ø. 1997. Climate statistics & longterm series of temperature and precipitation at Svalbard and Jan Mayen. *DNMI Klima Report No. 21/97 Klima*. P. 1–54.

Hinkel, K.M. & Outcalt, S.I. 1994. Identification of Heat-Transfer Processes during Soil Cooling, Freezing and Thaw in Central Alaska. *Permafrost and periglacial processes* 5. P. 217–235.

Hinkel, K.M. & Nicholas, J.R.J. 1995. Active Layer Thaw Rate at a Boreal Forest Site in Central Alaska, U.S.A. *Arctic and Alpine Research*. 27 (1). P. 72–80.

Hinkel, K.M., Paetzold, F., Nelson, F.E. & Bockheim, J.G. 2001. Patterns of soil temperature and moisture in the active layer and upper permafrost at Barrow, Alaska: 1993–1999. *Global and Planetary Change.* 29. P. 293–309.

Isaksen, K., Vonder Mühl, D., Gubler, H., Kohl, T. & Sollid, J.L. 2000. Ground surface-temperature reconstruction based on data from a deep borehole in permafrost at Janssonhaugen, Svalbard. *Annals of Glaciology* 31 P. 287–294.

Isaksen, K., Holmlund, P., Sollid, J.L. & Harris, C. 2001. Three deep Alpine-Permafrost Boreholes in Svalbard and *Scandinavia. Permafrost and Periglacial Processes 12.* P. 13–25.

Kane, D.L., Hinkle, K.M., Goering, D.J., Hinzman, L.D. & Outcalt, S.I. 2001. Non-conductive heat transfer associated with frozen soils. *Global and Planetary Change* 29. P. 275–292.

Nelson, F.E., Shiklomanov, N.I., Mueller, G.R., Hinkel, K.M:, Walker, D.A. & Bockheim, J.G. 1997. Estimating Active-Layer Thickness over a Large Region: Kuparuk River Basin, Alaska, U.S.A. *Arctic and Alpine Research.* 29 (4). P. 367–378.

Pomeroy, J.W. and Brun, E. 2001. Physical Properties of Snow. In: *Snow Ecology.* (Eds.) Jones, H.G., Pomeroy, J.W., Walker, D.A. and Hoham, R.W. 378 pp. Cambridge University Press.

Putkonen, J. 1998. Soil thermal properties and heat transfer processes near Ny-Ålesund, northwestern Spitsbergen, Svalbard. *Polar Research* 17 (2). P. 165–179.

Serreze, M.C., Walsh, J.E., Chapin III, F.S., Osterkamp, T., Dyurgerov, M. Romanovsky, V., Oechel, W.C., Morision, J. Zhang, T. & Barry, R.G. 2000. Observational Evidence of Recent Change in the Northern High-Latitude Environment. *Climatic Change* 46. P. 159–207.

Williams, P.J. & Smith, M. W. 1989. *The Frozen Earth.* Cambridge: Cambridge University Press.

Zhang, T. 1995. Impact of the Seasonal Snow Cover on Ground Thermal Regime. *The American Society of Mechanical Engineers* 95-WA/HT-47. P. 1–7.

Zhang, T., Osterkamp, T.E. & Stamnes, K. 1997. Effects of Climate on the Active Layer and Permafrost on the North Slope of Alaska, U.S.A. *Permafrost and Periglacial Processes* 8. P. 45–67.