—Plenary Paper—

Heat and Water Transfer Processes in Permafrost-Affected Soils: A Review of Field- and Modeling-Based Studies for the Arctic and Antarctic

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Abstract

The main field experiments and modeling results of heat and moisture transfer processes of the Arctic and Antarctic are reviewed, following the historical development. Agreement exists that heat is mainly transferred via conduction in Arctic and Antarctic soils, but that latent heat and vapor migration are important factors for the thermal dynamic. Factors determining amount and type of heat transfer are soil water content and temperature gradient between atmosphere and soil.

Keywords: Antarctic; Arctic; heat transfer; permafrost; thermal processes; water transfer.

Introduction

An apparent discrepancy exists between numerical modeling results and field observations indicating water and vapor transfer in frozen soils. The latter includes depth hoar formation under snow, direct measurements of vapor flux out of the ground (e.g., Santeford 1978, Woo 1982), desiccation of upper soil layers (Hinzman et al. 1991) and ice growth from field and lab experiments (Parmuzina 1978, Chen & Chamberlain 1988) and accumulation of ice at the base of the active layer/top of permafrost (Yershov 1998, Solomatin & Xu 1994).

Due to page limits, we review available literature on heat and water transfer processes in Arctic and Antarctic soils only; thus results from alpine, high elevation and temperate regions are excluded from this paper. Furthermore, we limited the review of heat and water transfer modeling to studies for which field data are available.

The very different climate conditions in the Arctic and Antarctic are reflected in the soil systems. While Arctic soils generally have free liquid water in active layer during summer, Antarctic soils are hyperarid in the dry valleys around the Ross Sea but gradually approach wetter conditions towards the east and Antarctic Peninsula (Beyer et al. 1999 and references within). These differences are reflected in motivation and approaches to model water and heat transport processes thus both regions are described separately. A quantitative understanding of the processes underlying the thermal and hydraulic dynamics of permafrost soils is paramount to anticipate consequences of a changing atmospheric forcing as well as to improve the parameterization of the soil-atmosphere interaction in climate models.

Thermal dynamics of permafrost-affected soils

The major stages for the seasonal thermal dynamics of the active layer at a permafrost site consists of four different characteristic periods: (i) cold period, (ii) warming period, (iii) thawed period, (ix) isothermal plateau. During the *cold period*, temperatures are well below 0°C. Most of the soil water is frozen and the entire ground may be considered as a solid medium. With the sun rising in late spring and the onset of snow melt, ground temperatures rise quickly, soil water content changes following the soil freezing characteristic curve. This *warming period* is terminated by the thawing front, a macroscopic phase boundary that separates partially frozen ground from the completely unfrozen soil during the *thawed period.* The propagation of the thawing front consumes a large proportion of the energy input from the positive net radiation. As the energy balance becomes negative in fall, the soil cools down to 0ºC starting to freeze from the surface. Upon further cooling the reverse phase transition sets in, from liquid to solid. It releases large quantities of latent heat and thereby opposes the cooling. This leads to a rapid equilibration of the temperature at 0 ºC in the entire thawed zone, indicated by the practically vertical isotherms. This is often referred to as the closing of the zero-curtain (Outcalt et al. 1996, Outcalt et al. 1990). As the active layer turns isothermal, large quantities of latent heat need to be removed to allow further cooling. This leads to the *isothermal plateau* where soil temperatures stay near 0 ºC for an extended time. It is eroded from above and from below, where temperatures in the air and in the underlying perennial ice are well below the freezing point. Eventually, the isothermal plateau disappears, giving way to the *cooling period* where regular conduction removes the remaining surplus heat from the active layer. It is transferred through the snow layer, which is a major modulating factor, to the atmosphere.

While thermal processes may be the same in wet soils of east Antarctica and Antarctic Peninsula, in the hyperarid soils of dry valleys the isothermal plateau due to release of latent heat does not exist. However, based on changes in air temperature and lack of incoming radiation, temperature gradient in soils reverses in October, which causes a quasi-isothermal soil during a short period of time (Hagedorn et al. 2007, Pringle et al. 2003) but this isothermal temperature is well below 0ºC.

Heat and water transfer processes

Permafrost-affected soil can potentially have five components (soil matrix, ice, water vapour, water, air). Conduction, heat transfer through gradients, is widely accepted to be the dominant mechanism of heat transfer in soils. Other nonconductive heat transfer mechanisms associated with the convection of water, either in the liquid or in the vapor phase, are possible with appropriate gradients (pressure, gravitational, density, vapor pressure, and chemical). A good summary of potential heat transfer processes in permafrost affected soils is provided by Kane et al. (2001). They summarized the importance of non conductive heat transport based on data sets from Alaska as the following: (i) infiltration and refreezing of water in frozen soil accelerates warming of soil; (ii) free convection of fluids is not an important heat transfer process; (iii) migration of water and vapour could be important but has not been quantified yet. The large value of the enthalpy of evaporation, which exceeds that of melting by a factor of 7.4, makes vapor an efficient means for the transport of thermal energy.

Heat and Water Transfer Processes in Permafrost-Affected Soils: Arctic

Most of the available English-language literature up to the end of 1990s is reported from Alaskan sites and is based on temperature and electric potential measurements and one dimensional thermal diffusion modeling. When the snow cover becomes isothermal and snow melt starts during the warming period, the soil rapidly warms at all depths, presumably because of the infiltration and refreezing of snow melt water and of migrating vapor into the frozen soil. Most studies agree that nonconductive heat transfer processes must be responsible for the rapid warming of the soil (Putkonen 1998, Hinkel & Outcalt 1994).

Conversion of latent heat is thought to be most important during the summer when moisture evaporates from the surface and the active layer thaws. Evaporation consumes 25–50% of the total incoming energy at a Siberian study site on Northern Taymyr peninsula (Boike et al. 1998) and 30–65% in northern Alaska (Kane et al. 1990). According to Outcalt et al. (1998), evaporative cooling at the surface of the active layer was responsible for the deviation between observed and modeled soil temperatures of the active layer and upper permafrost. Thawing of the active layer is another important sink for thermal energy. It consumes up to 40% of the total net radiation at the Siberian site (Boike et al. 1998). Generally, a high percentage of the total heat flux into the ground (between 70 and 100% is converted into latent heat (Rouse 1984, Boike et al. 1998). Conduction of heat, transport of thermal energy by convection of water, either in the liquid or vapor phase, has been discussed. Hinkel et al. (1993) identified infiltration of summer precipitation as an effective method to transfer heat to the base of the active layer, especially in drained, organic soils. Pore water convection during the summer thaw period, driven by the density inversion of water, has been proposed as the initiator for the formation of sorted circles (Krantz 1990, Ray et al. 1983), but Hallet (1990) argued that this process is unlikely and that it has not been observed in finer-grained sediments typically found in patterned ground. Putkonen (1998) calculated a Peclet number much smaller than 1 for this site and concluded that advection of heat due to water motion is negligible.

When net radiation decreases during the fall, the soil is cooled to a practically isothermal condition, the so-called zero curtain at 0°C. The large amount of latent heat which must be removed from the profile through an almost isothermal soil stabilizes soil temperatures at 0° for a prolonged time. Hinkel & Outcalt (1993, 1994) suggested that internal distillation driven by osmotic gradients transfer heat across this isothermal zone. In contrast, Romanovsky & Osterkamp (2000) accurately predicted soil temperatures for sites in Central and North Alaska during the freeze back using a conductive heat exchange model by including effects of unfrozen water and therefore excluding moisture migrating as a transport mechanism. Snow melt infiltration was the only non conductive heat transfer responsible for soil warming.

Putkonen (1998) estimated that the maximal possible vapor and latent heat flux under given soil thermal properties was two orders of magnitude smaller than conductive heat transport, hence being insignificant for western Spitsbergen. Through the application of electronic instrumentation measurement techniques, such as Time Domain Reflectometry for determination of soil moisture in frozen soils, highly precise and frequent temperature and moisture data have been obtained from various field sites. Roth & Boike (2001) found an excellent agreement between projected and measured temperatures for the cold period which demonstrates that during this time, heat transport on Spitsbergen (Bayelva site) can be described by effective conduction. Furthermore, they found that the production of latent heat and the associated migration of water vapor is an important agent in the thermal dynamics at this site for all four periods and that it is the dominating process in the isothermal plateau since heat conduction is practically negligible there. Unimpeded vapor migration is possible down to some 0.9 m, restricted by a massive ice rich layer. This contrasts findings of sites for which it was stipulated that upon closing of the zero curtain, internal distillation and water advection cease for the rest of the winter (Hinkel & Outcalt 1994, Romanovsky & Osterkamp 2000).

Differences in latent heat production using the model by Roth & Boike (2001) were presented by Overduin & Kane (2006). Their patterned ground site, covered by mud boils, is located in Northern Alaska (Galbraith Lake). One of the contrasting differences in winter heat transfer processes was the continuous latent heat production after freeze back until spring in the middle part of the profile It is hypothesized that water advection in the frozen soils was possible through the unfrozen water film attached to the soil particles. Subsequent freezing of water was the source of the latent heat production, resulting in ice formation and large heave rates in the center of the mudboil. While these two Arctic sites are very similar in terms of soil parent material, surface cover and topography, the soil water/ice content and climate conditions vary. Firstly, the site at Galbraith lake is water saturated, thus the pore spaces are filled with ice during winter. The soil at the Bayelva site is water saturated only in the lower part of the profile below about 0.7 m depth. Secondly, Galbraith, located in the Arctic climate is much colder (average January air temp. ~ -24°C) compared to the warmer, maritime influenced Svalbard climate (average January air temp. ~ -13°C). In addition, Galbraith has no or little snow cover, whereas the Bayelva site experiences a snow depth up to about 1 to 1.5 m, modulating the ground thermal regime and thus reducing the thermal gradient between air and soil temperature. It is postulated that the large temperature gradient at Galbraith Lake was also responsible for the large heave (up to 12 cm) which is about an order of magnitude higher compared to the Bayelva site (about 2 cm).

Heat and Water Transfer Processes in Permafrost-Affected Soils: Antarctic

Due to the very dry climate in dry valley soils of Antarctica, the majority of water is present as ice which occurs 0.1 to 0.5 m below surface in approximately 36% of soils in Antarctica (Bockheim 2002). Liquid water is limited to scarce infiltration after snow events (Friedman 1978, Gooseff et al. 2003), water films adsorbed to grain boundaries (Anderson & Morgenstern 1973), and to brines in ice cement (Dickinson & Rosen 2003). Only a small fraction of water is present as water vapor, which is the phase that is transported between atmosphere, soil pore space and ice. The main motivation to study vapor transport and thermal regime in Antarctic soils of Dry Valleys is to estimate the stability of subsurface ice in Antarctic soils, since this ice is important for geomorphologic development of patterned ground formation, e.g. contraction cracks (Sletten et al. 2003) and since Antarctic soils are the best terrestrial analogue to Martian soils (Schorghofer 2005).

Sugden et al., (1995) and van der Wateren & Hindmarsh (1995) did the first back on the envelope calculation of vapor transport to evaluate the stability of ground ice using steady state vapor diffusion modeling. Both yielded very different results; Sudgen et al. (1995) used geothermal gradients to determine soil and ice temperature and assumed vapor saturated atmosphere. He estimated sublimation rates of 10^{-4}mm a^{-1}; van der Wateren & Hindmarsh (1995) used meteorological data and assumed vapor unsaturated atmosphere and estimated a rate of 1 mm a^{-1}. This fast sublimation rate could be confirmed in a more detailed modeling approach by Hindmarsh et al. (1998).

McKay et al. (1998) calculated vapor transport using soil temperature, air temperature and relative humidity records collected at Linnaeus Terrace (1550 to 1700 m elevation). Parameters like tortuosity and porosity were determined on investigated soil material. Thermal conductivity was modeled from temperature profiles and yielded 0.6±0.1 $Wm^{-1}K^{-1}$ for dry soil and 2.5±0.5 $Wm^{-1}K^{-1}$ for ice cement which are close to values determined by Putkonen et al. (2003). Based on Fick's diffusion they found that ice is lost at rates at ~0.2 mm a^{-1}, highlighting the very dry atmospheric conditions in the dry valleys. Based on a comparison between frost point of atmosphere and ice cemented soil they suggest that increase of 40% moisture to all humidity values could stabilize ground ice.

Schorghofer (2005) modeled ice sublimation in Beacon Valley (~1500 m asl.) constrained by climate and soil temperature data and found rates comparable to those of McKay et al. (1998). He found that advection caused by changes in surface pressure has negligible effect on sublimation. By exploring possible scenarios to stabilize subsurface ice, he suggests a decrease in annual air temperature by 5°C or increase in relative humidity of 50%, a rather unrealistic value.

Hagedorn et al. (2007) modeled vapor transport based on multi-year climate and soil temperature record in Victoria Valley which is about 400 m asl. and where ice occurs 0.2 to 0.4 m below surface. Vapor transport is calculated using Fick's diffusion incorporating a reaction term for ice precipitation and allowing vapor diffusion into the ice cement. Initially a linear vapor density gradient between ice cement and atmosphere was assumed. Using this approach they yielded sublimation rates close to those observed by McKay et al (1998). However, part of the vapor is transported from ice surface into the ice cement and most of it precipitates in upper ice cement slowly closing the pore space. Transient ice will form in dry soil during winter but completely disappears during beginning of summer. Snow cover will reduce vapor loss to atmosphere but to completely offset sublimation rates it would need to remain for several months. As suggested by McKay et al. (1998) and Schorghofer (2005) they also found that decreasing air temperature or increasing moisture will reduce sublimation but those scenarios do not seem to be very realistic under current climatic conditions. The most likely process which stabilizes ground ice in Antarctica seems to be occasional recharge by snow melt water.

Studies modeling thermal conductivity and heat fluxes based on field measurements are rare in Antarctic soils of the Dry Valleys. Putkonen et al. (2003) measured the sensible heat flux based on the difference between measured net radiation and ground heat flux in Beacon Valley using in situ measurements of soil thermal properties and 1-dimensional thermal conductivity model (Putkonen 1998). At this site, soils consist of ~20 cm dry sublimation till underline by massive ice. They found that mean annual ground heat flux is close to zero indicating long term thermal equilibrium. The annual mean net radiation is positive (24 Wm^{-2}) suggesting a net advection of sensible heat into atmosphere from this area. Measured values for thermal conductivity in dry debris are ~2 times smaller (0.2 $Wm^{-1}K^{-1}$) as values found from modeling (see above 0.4 $Wm^{-1}K^{-1}$). The difference between modeled and measured values may well be in the range of the instrument uncertainty.

Pringle et al. (2003) used temperature data collected on three sites from Table Mountain with different lithology and ice contents to calculate apparent thermal diffusivity (ADT). They found strong dependence of ADT with abundance of ice and determined an ice-fraction dependency of heat capacity of 1.7 to 1.8 $MJm^{-3}\,°C^{-1}$ causing a range of conductivity of ice rich soils between 2.5 to 4.1 $Wm^{-1}\,°C^{-1}$. Pringle et al. (2003) treated the heat transfer as purely conductive due to the very dry conditions and absence of liquid water. The lower value of heat conductivity is in good agreement with values from Putkonen et al. (2003) found for the massive ice. The generally low thermal conductivity found in Antarctic soils is an order of magnitude lower as in Arctic soils (6-26 times lower) reflecting the very dry conditions.

Summary and Future Potentials

Arctic versus Antarctic heat and water transfer processes

Other than during freeze back and snow melt infiltration, heat is largely transferred through conduction in soils at both regions. In non saturated Arctic soil, vapor migration occurs during all thermal periods while water advection occurs in frozen saturated soils. In dry Antarctic soils, vapor diffusion is a main process of water transport. The total amounts of water transferred are generally rather small; however, over longer terms could be significant, for example for the formation of patterned ground features (for example circles, ice wedges).

Snow melt is an important event for recharge of ground ice in Antarctica and a significant latent heat input for Arctic soils.

Factors affecting the heat transfer processes

The main factors determining the heat transfer are (i) phase composition of soil (specifically available pore space) which enables vapor diffusion and/or water advection (ii) the temperature gradient between atmosphere and soil which is largely affected by the snow cover.

What should happen next?

We need further detailed case studies (experimental and modeling) to face the challenge of highly nonlinear and strongly coupled processes which lead to a complex phenomenology. We still lack accurate methods for measuring relevant state variables of the system, for example the phase density of ice or water vapor, and even more so by the lack of sufficiently accurate instruments for measuring fluxes of thermal energy and of water. The processes of water and heat dynamics in permafrost soils, i.e. their potential relative weight should be assed quantitatively which is a topic of a future publication

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