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Chapter

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ABSTRACT

This chapter deals with the thermo-hydrological determinants of weathering fluxes in boreal watersheds, and with the insights on this matter that may be expected from a mechanistic modelling approach. Focus will be placed on the weathering fluxes in the permafrost dominated watersheds of the basaltic region of the Putorana Plateau in Central Siberia, one of the largest and most pristine boreal forested areas (Pokrovsky et al., 2005).

In the first part of this chapter a qualitative model of the thermo-hydrological functioning of the surfaces of the watersheds of this region will be presented. This qualitative model is based on quantitative geochemical measurements available in the literature (e.g. Pokrovsky et al., 2005, Prokushkin et al., 2007, Bagard et al., 2011). A discussion on the couplings between water and energy fluxes and matter fluxes is briefly presented. The importance of phase changes and advective transfers is emphasised.

In the second part of this chapter, after a short review of published numerical tools dealing with the coupled transfer of water and energy in the active layer of permafrost areas, perspectives associated with the use of modern numerical techniques are discussed. A modelling efforts toward this direction is introduced, which has been initiated in the framework of OpenFOAM®, an open source tool box for computational fluid dynamics

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that allows multi-physic coupling and massively parallel computing (e.g. Weller et al., 1998). Finally, an example of a set of results is presented. These results illustrate the importance of the snow cover and the moss/soil organic horizon thickness on the thermo-hydrological behaviour of the soil active layer depth of this area.

Keywords: permafrost, active layer, Central Siberia, weathering, mechanistical modelling, thermo-hydrological processes

INTRODUCTION

The weathering of continental silicated rocks is considered one of the main sinks of atmospheric carbon (Berner, 1992). Thus, in the context of global changes, the study of this phenomenon is a key point for our understanding of the dynamic of the green house effect. It has been shown that basaltic rock accounts for about 30% of the uptake of atmospheric carbon associated with the weathering of continental silicated rocks (Dessert et al., 2003). The Putorana Plateau is constituted of traps over an area of about 1 500 000 km^2 (Pokrovsky et al., 2005), so it is one of the largest areas in the world where basaltic rock weathering takes place. The observed global warming, at least partly due to anthropogenic carbon, seems to be particularly strong in boreal areas (e.g. IPCC, 1998). Such global warming is strongly suspected to induce the thawing of boreal permafrost, with a decrease in the permafrost extension and an increase in active layer thickness, even if these points are still a matter of debate (e.g. Serreze et al., 2000, Zhang et al., 2005, Frauenfeld et al., 2007). This could be the source of severe positive feedback on global warming through the release of organic matter contained in the frozen soil layers (Zimov et al., 2006, Khvorostyanov et al., 2008a). On the other hand, the impact of the potential increase in the thickness of the soil layers affected by weathering due to the prospective increase in the active layer thickness has not yet been assessed. The weathering process, as well as the dynamics of the active layer, in basaltic boreal areas such as the Putorana Plateau are therefore potentially important determinants of the global carbon cycle and the global warming scenario. Weathering and active layer dynamics are both closely linked to the thermo-hydrological regimes occurring in the soil of these regions, which may be subjected to major evolutions due to climate change. Indeed, the Putorana Plateau is an ideal place for studying weathering and permafrost dynamics in boreal basaltic areas, since it is one of the largest areas of this kind and since it is almost completely pristine (Pokrovsky et al., 2005).

As mentioned previously, the thermo-hydrological state of a soil exerts a strong control on its weathering and thus on the associated atmospheric carbon consumption (and also on other environmental aspects, such as water resources; e.g. Quinton et al. 2011). One can see, for example in Figure 1, a dependence of the weathering flux on the hydrological (run-off, computed) and thermal conditions (annual mean surface temperature, measured, 1982–1990) at 22 sites with silicated outcrops around the world. This illustration of the relationship between the thermo-hydrological state and weathering flux is taken from Beaulieu et al. (2010).

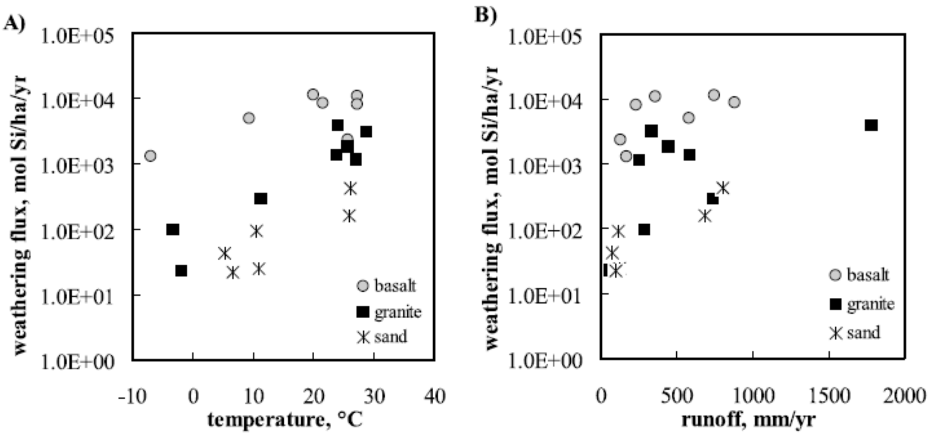

Figure 1: Illustration of correlations between weathering fluxes and (A) thermal regimes and (B) hydrological regimes for 22 representative silicated sites around the world (exerpt from Beaulieu et al., 2010).

On these two graphs one can see positive correlations between the weathering flux an (i) the surface temperature and (ii) the run-off. The first correlation may be associated with an increase in geochemical reaction kinetics with temperature. The second correlation may be related to an increase in the transfer of dissolved ions generated by the weathering of the soils. Thus both effects, thermal and hydrological, are important in weathering phenomenon. Moreover, there is a strong coupling between the hydrological and thermal processes in permafrost areas: snow melt and phase changes of the water in the active layer. The latent energy released by the freezing of water in the active layer at the beginning of winter and the latent energy needed for the thawing of this active layer in the hot season is a major coupling between thermal and hydrological processes. Indeed, it results in a strong dependency of the thermal dynamics of the active layer on its water content, which results in a damping of the thermal evolution of the soil (Farouki 1981, Hinkel et al., 2001). This may have a strong impact even at continental scale (Takata and Kimoto, 2000, Poutou et al., 2004, Gouttevin et al., 2012). Other forms of coupling exist, for example through the insulation effect of the snowpack (Frauenfeld et al., 2004). Another example is the occurrence of advective heat transport in the active layer, which has been reported in surficial permafrost during spring flood, as shown in Figure 2 (Hinkel et al., 1997, 2001).

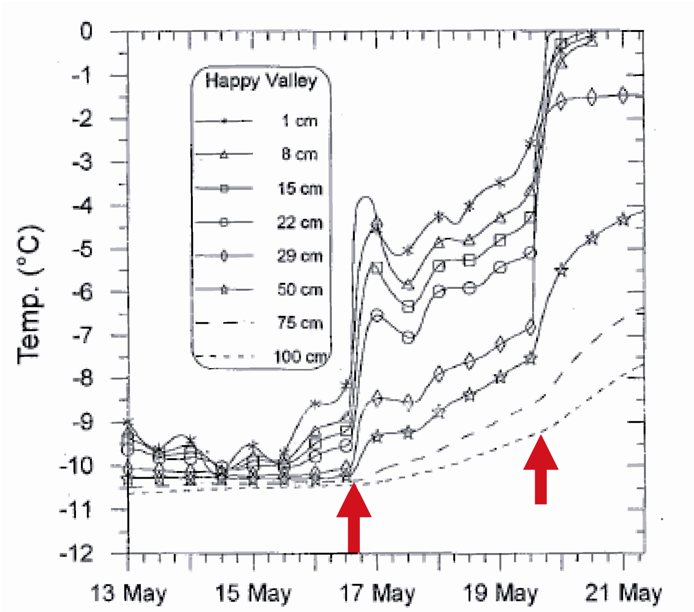

Figure 2: Monitoring of temperature profiles along depth during a spring flood period in a permafrost area of northern Alaska (extracted from Hinkel et al., 1997).

One can see on this graph some sharp jumps in temperature, even at 30 cm depth within the permafrost. These jumps take place at the same time as the primary snowmelt events of the year occur in this area. These fast jumps in temperature at tens of centimetres from the surface cannot be generated by thermal diffusion, they can only be explained by advective transfers of heat through the soil layers. Thus a modelling of the active layer thickness of the permafrost and of the potential impact of global warming on its dynamic needs to fully couple thermal and hydrological effects in order to represent the physics at stake. Indeed, current continental scale modelling of the carbon cycle in boreal areas does take into account such a coupling with conceptual approaches of modelling, but they still have high parameter sensitivities (e.g. Zhuang et al., 2003, Khvorostyanov et al., 2008b). Performing modelling studies of element cycles with a fully mechanistic modelling approach at smaller scales would allow stronger constraints on the processes involved to be obtained. Indeed, the need for developing such mechanistic modelling tools is now recognised (e.g. Frampton et al., 2011, Grenier et al., 2012).

Putorana Plateau watersheds have been studied for years in order to constrain weathering phenomenon in basaltic boreal areas (e.g. Pokrovsky et al., 2005, Prokushkin et al., 2007, Bagard et al., 2011). It has been an opportunity to build a qualitative model of the thermo-hydrological processes at work on the basis of quantitative geochemical field measurements. Thus it would be the ideal place to develop fully mechanistic modelling studies of the thermo-hydrological dynamics and of the weathering process at a small watershed scale, because it is a very pristine area and because of the careful characterisation and monitoring of this area. In the first part of this chapter we will focus on the current qualitative knowledge on thermo-hydrological regimes encountered in this area. In the second part, we will deal with the mechanistic modelling approaches of the thermo-hydrological processes in permafrost dominated areas, with a brief overview of the literature, a discussion on the use of modern numerical techniques in this context, and an illustrative example of results.

THERMO-HYDROLOGICAL PROCESSES IN THE NEAR-SURFACE PERMAFROST OF THE PUTORANA PLATEAU

This summary of current knowledge about the thermo-hydrological regime of the watersheds in the Putorana Plateau is based on several studies conducted on catchments within the Nizhniya Tunguska River and in the Kochechum River watersheds. Temporally, three main phases may be determined in the thermo-hydro-geochemical functioning of Putorana Plateau watersheds: winter season (roughly from October to the beginning of May), spring flood (mid-May and June), and summer-fall season (July to September) (Prokushkin et al., 2009). The Central Siberian Plateau is mainly covered with taïga (below 800 m a.s.l.), forest-tundra (between 800 and 1000 m a.s.l.) and tundra (above 1000 m a.s.l.), and it is a permafrost dominated area (from discontinuous permafrost in the south to thick continuous permafrost in the north) (Brown et al., 1998). The hydrological compartments that may be considered are the following: surficial organic layer (including both moss-lichen stratum and soil organic horizons), soil active layer (the layer thawed during the frost-free period), surface water (rivers), and deep groundwater (i.e. brines underneath the permafrost) (Pokrovsky et al., 2005).

The study of the time variations and spatial variations of the major cations dissolved in the riverwaters associated with these different compartments shows that the most important flux of matter associated with weathering occurs during spring flood, although weathering could occur prior to the spring flood (e.g. under freeze-thaw cycles, in this case those products are released to rivers by snow-melt waters). For example, more than 50% of the total export of dissolved cations in the river occurs during spring flood (Pokrovsky et al., 2005). Trace elements studies also indicate an intense leaching of the organic layer during spring flood (Pokrovsky et al., 2006). Quantitative and statistic analysis of dissolved organic matter in the riverwater indicate a clear difference in thermo-hydrological behaviour between the north aspected slopes and the south aspected slopes (Prokushkin et al., 2007), a difference which may be driven for example by the difference in solar radiation input on both slopes. This difference in thermo-hydrological conditions between north and south aspected slopes is even visible in the landscapes of this region, as shown in Figure 3.

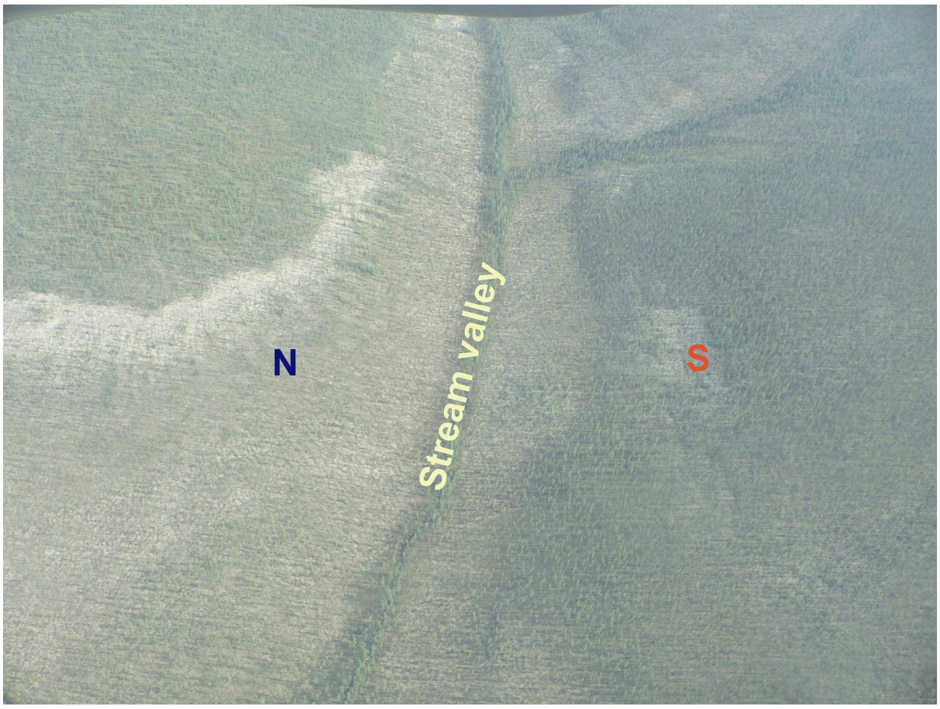

Figure 3: North and south aspected slopes in a valley of the Putorana Plateau.

The occurrence of deep brine supplied to the river through taliks has been shown to be a determinant for the chemical composition of the riverwater in winter (Bagard et al. 2011). Overall, the thermo-hydrological functioning of the watershed of the Putorana Plateau can be sketched from these studies as shown in Figure 4.

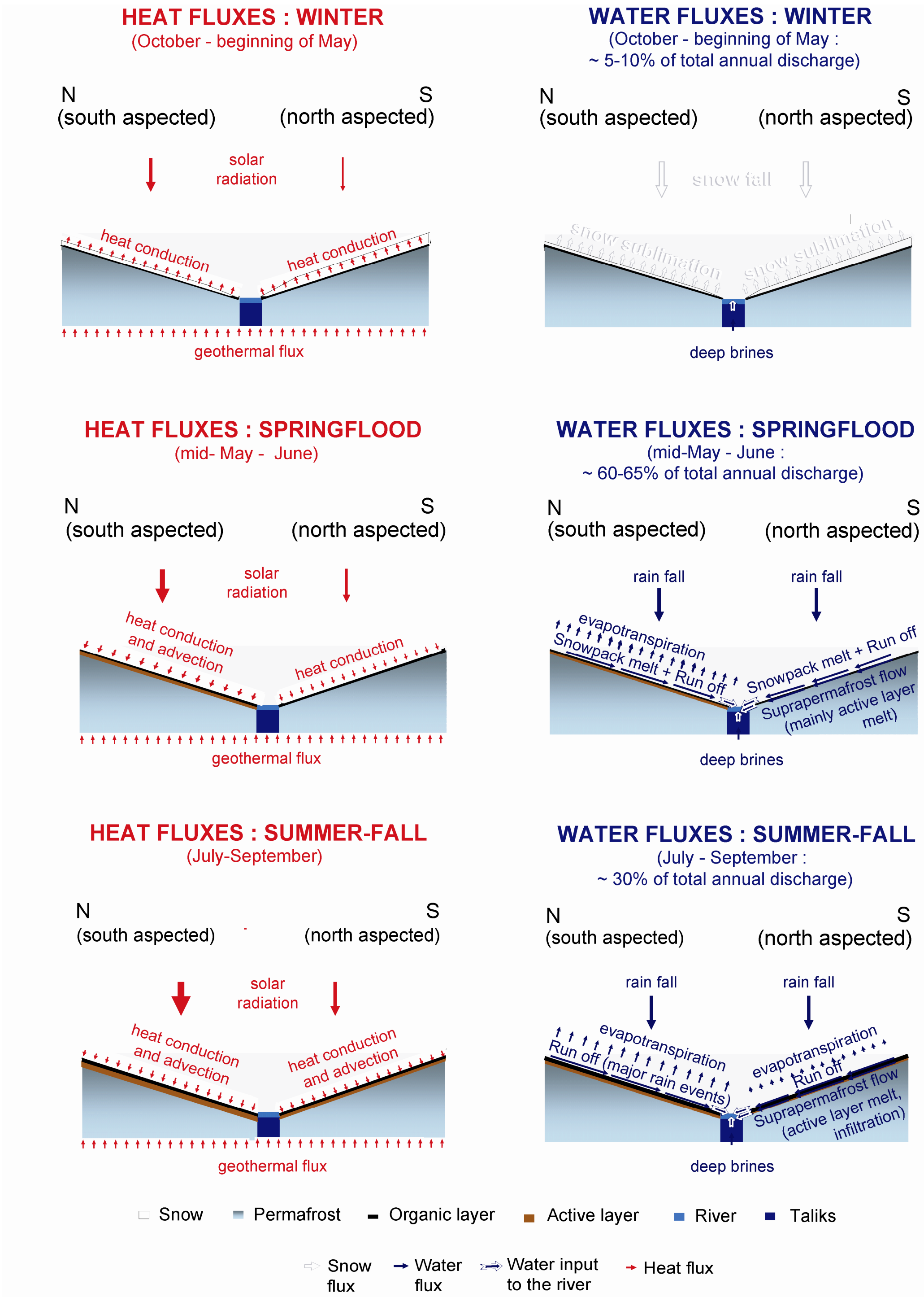

Figure 4: Scheme of thermo-hydrological functionning in Putorana Plateau: couplings between thermal and hydrological fluxes and north aspected / south aspected slope contrasts (mainly according to Pokrovsky et al., 2005, Prokushkin et al., 2007, Bagard et al., 2011).

The information contained in this scheme may be summarised as follows:

- Winter time: the soil water is completely frozen, and the meteoric waters are in the form of snow. One can observe a thicker snow pack in the north aspected slope, due to smaller snow sublimation than in the south aspected slope, in relation to the difference in solar radiation heat supplies. The water flux in rivers is at its lowest level of the year (5–10% of the total annual discharge, according to Pokrovsky et al., 2005). The water flowing in the river is almost exclusively of deep origin, with a below-permafrost brine supply through taliks.

- Spring flood: melting of the snow pack and beginning of the thawing of the active layer, mainly in the south aspected slopes, even if first surficial ice-rich permafrost horizons of the north aspected slopes start to melt at the end of the spring flood. The meteoric waters are liquid, and then migrate to the river through organic layer leaching on both slopes. The infiltrations of rain waters or snowmelt waters may be the cause of heat advection to the frozen ground through the active layer, and thus increase the thawing rate. This advective heat transfer first occur in the south aspected slopes in which such an active layer exists earlier, and then at the end of spring flood in the north aspected slopes. Transpiration starts with vegetal activity, which is more intensive in south aspected slopes at this time of the year. Then, even if the thawing of permafrost is stronger in the south aspected slopes, most of these waters are transpirated and few of them reach the stream. The largest part of the total annual discharge of the river occurs (60–65%, according to Pokrovsky et al., 2005), and the water in the river is a mix between run-off waters and snow melting from both slopes, and, at the end of the spring flood, soil ice melting of the north aspected slope (and a small proportion of deep brines).

- Summer: During the summer season, an active layer develops on both slopes, and it is deeper in the south aspected slope. During this period, the water in the river is a mixture of run-off water and north aspected slope infiltration water and active layer ice melting (and a small proportion of deep brines). In the south aspected slopes infiltration occurs, but precipitation is not sufficient to reach the unpermeable layers and then to be released to rivers by lateral flux. Due to a thicker active layer and stronger canopy effects than in the north aspected slopes, almost all the infiltrated waters are re-emitted to the atmosphere through evapotranspiration. Even the run-off water input to the river from these south aspected slopes is limited to major rain events, because of the higher water storage capacity of the deeper thawed soil than in the north aspected slopes.

Several remarks may be made at this point. First, the strong coupling between thermal and hydrological processes is obvious: the thickness of the snow pack in relation to solar exposure, advective transport of heat in the active layer, phasing of the origin of soil waters in rivers in relation to the active layer thickness differences … Second, one can see that we have highly-contrasted thermo-hydrological functioning, both temporally (“flashy” transfers during spring flood) and spatially (north aspected slopes versus south aspected slopes). Finally, the export of water (and thus the associated flux of organic matter) from the south aspected slopes is smaller during the summer season than in spring flood, and than that observed in the north aspected slopes. If one consider that the “south aspected slope’s behaviour” may be regarded as the possible future behaviour of the north aspected slopes in the context of climate warming, then it could be anticipated that in the future these large areas will uptake more atmospheric carbon than now. It would be an opposite effect to the one of a potential release to rivers of organic matter currently entrapped in the permafrost surficial layers. Then the impact of various scenarii of climate change (dry or wet, more or less strong, etc.) need to be carefully assessed due to the complexity of the considered system, with strong couplings, contrasted behaviours, and contradictory effects.

MECHANISTICAL MODELLING OF THERMO-HYDROLOGICAL BEHAVIOUR OF SOILS IN PERMAFROST-DOMINATED AREAS

Quantitative modelling of the thermo-hydrological processes may allow a better understanding of the active layer dynamics, and its possible evolution in the context of climate change. Such complex systems (coupled, contrasted, evolving) require an a priori approach to modelling (as far as possible), in order that the basic assumptions of the modelling do not hide the true functioning of the studied system. To the knowledge of the authors, the most a priori method of modelling is the mechanistical modelling approach, i.e. the resolution of the equations of conservation obtained from the continuum mechanics. It is the modelling approach with the most limited and precisely identified a priori assumptions on the functioning of the modelled system. This leads to predictive modelling under the assumptions of the model. It allows for example to test the likelihood from a physical point of view of a scheme of functionning of the studied system through numerical experiments. An example of such an approach is shown below. The predictivity of mechanistic modelling is a major strength of these approaches compared to conceptual modelling (Li et al., 2008, Yeh et al., 2011, Miller et al., 2013). Conceptual modelling approaches are based on the calibration of transfer functions that empirically relate the input of the considered system (for example rain and snow falls and air temperature) and the desired output (active layer thickness or water content, for instance). In the case of conceptual models, the study of a system in evolving conditions is very difficult, since there is no theoritical reason that a calibration made with given input data will still be pertinent with other input data (for example in the case of climate change) (van der Ploeg et al., 2012). However the drawbacks of the mechanistical approach are that it requires a good knowledge of the physical and geometrical characteristics of the system under consideration (Carrera-Hernandez et al., 2012), and that it leads in general to systems of equations that are not analytically solvable. Thus numerical approximate resolution is required, with potentially high costs in terms of computation power and computation time (Miller et al., 2013).

In the field of a freezing soil-water system, numerous works have been done to establish one-dimensional mechanistic models (e.g. Kennedy and Lielmezs, 1973, Harlan, 1973, Guymon and Luthin, 1974, Jame and Norum, 1980, Mu and Ladanyi, 1987, Seregina, 1989, Hansson et al., 2004). They consist in establishing governing equations for water and heat fluxes within a variably saturated and variably frozen soil column, as well as the numerical procedure to solve these equation. These one-dimensional models are built on the assumption that the humid air phase is at a constant pressure (atmospheric pressure) within the soil, leading to a one equation model of mass (water) transfer, namely Richards' equation. In this equation, gravity and capillarity are taken into account. The equation of heat transfer takes into account the conductive and advective transport of heat. These two equations are coupled through water phase changes and the advective transport of heat, as well as through the dependency of the hydrodynamic and thermal properties of the soil on its liquid and ice water contents. Most of these models neglect the coupling between soil mechanics and thermo-hydrological fluxes, such as ice lenses formation, frost heave, etc. (e.g. Kennedy and Lielmezs, 1973, Harlan, 1973, Guymon and Luthin, 1974, Jame and Norum, 1980, Seregina, 1989, Hansson et al., 2004). Nevertheless, some works do take into account these soil mechanics – thermo-hydrological fluxes couplings (e.g. Mu and Ladanyi, 1987). The study of these additional couplings is beyond the scope of this chapter, but one can find an introduction to these problems in Andersland and Ladanyi (1994).

One-dimensional modelling does not consider topographical effects, at least directly, and only allows a schematic (layered) description of the pedology and geology of the studied cases. Thus efforts have been made to build two-dimensional models. For example, some works have developed two-dimensional simulations in the context of both martian and terrestrial permafrost, using a two-phase flow approach in order to deal with peculiar conditions of pressure and temperature encountered on the surface of Mars (Painter, 2011). This tool has been successfully used to deal with the two-dimensional modelling of terrestrial permafrost (Frampton et al., 2011, Sjöberg et al., 2012.). Two-dimensional tools for saturated freezing soils (Grenier et al., 2012, Jost, 2012) have also been developed to study the behaviour of the Paris Basin at the time scale of the ice ages. Nevertheless, no fully three-dimensional tools have yet been developed. One of the major obstacles to conducting three-dimensional thermo-hydrological modelling of variably saturated and variably frozen soils is the huge computation power and computation time that it would require. Indeed, the numerical resolution of such sets of equations requires small time steps and fine spatial resolution (e.g. Romanovsky et al., 1997). An open source tool developed in the area of computational fluid dynamics, namely OpenFOAM® (Jasak, 1996, Weller et al., 1998, www.openfoam.com), has recently shown its capability in dealing with modelling with intensive numerical costs in the field of soil hydrodynamics (Orgogozo et al., 2012, 2013, Submitted), mainly through the use of massively parallel computation. A first attempt to apply this tool to the study of freezing soils is currently being undertaken, and a little one-dimensional example of results is shown below.

With this example we intend to illustrate the importance of the insulation effect of the snow cover and organic layer on the soil active layer depth dynamics in central Siberia permafrost dominated areas, with a very simplified physical approach. Our approach is the following: if we neglect the snow pack effects and the presence of an organic layer, do we find realistic (i.e. not too far from observations) thermo-hydrological behaviour in our soil column. So we consider a loam column of 4 m in thickness, partially saturated with water, with no organic layer. We have to seek a sinusoidal air temperature annual variation that leads to an active period and a maximum active layer thickness that are comparable to those observed on Putorana Plateau watersheds (June to September and about 1 m, respectively), without considering the effect of the snow pack (i.e. by considering that the temperature at the top of the soil is equal to air temperature). The temperature at the bottom of the soil column has been assumed to be equal to the annual mean of the air temperature (-5°C). For this illustrative example we have not considered any water flow, so that no advective transfer of heat occurs. The resulting simplified equation system is shown below.

Heat transfer equation:

$$\nabla\left(\mathbf{K}_{\mathbf{T}}^{*}.\nabla T\right)=C_T^{*}\frac{\partial T}{\partial t}-L_T^{*}\frac{\partial \theta_i}{\partial t} \tag{1}$$

Phase change equation:

$$\theta_i=\begin{cases} 0 \text{ if } T>T_f+\Delta T,\ \text{i.e. } \theta_{tot}=\theta_i+\theta_l=\theta_l \text{ with } \theta_i=0 \\ \dfrac{\theta_l}{\dfrac{1}{2}+\dfrac{\left(T-T_f\right)}{2\Delta T}} \text{ if } T_f+\Delta T\geq T\geq T_f-\Delta T,\ \text{i.e. } \theta_{tot}=\theta_i+\theta_l \\ \theta_{tot} \text{ if } T_f-\Delta T>T,\ \text{i.e. } \theta_{tot}=\theta_i+\theta_l=\theta_i \text{ with } \theta_l=0 \end{cases} \tag{2}$$

Effective thermal conductivity:

$$\mathbf{K}_{\mathbf{T}}^{*}=\left(1-\phi\right)\mathbf{K}_{\mathbf{T},soil}+\theta_l\mathbf{K}_{\mathbf{T},water}+\theta_g\mathbf{K}_{\mathbf{T},ice} \tag{3}$$

Effective volumetric calorific capacity:

$$C_T^{*}=\left(1-\phi\right)C_{soil}+\theta_l C_{water}+\theta_g C_{ice} \tag{4}$$

Effective volumetric latent heat of fusion of soil water:

$$L_T^{*}=L_{fusion,ice}\,\theta_l\big/\left(1-\phi\right) \tag{5}$$

Here, T stands for the soil temperature [K], T_f is the temperature of the fusion of ice [K], θ_i is the icy water volumetric content in the soil [m^3.m^{-3}], θ_l is the liquid water volumetric content in the soil [m^3.m^{-3}], θ_{tot} is the total water volumetric content in the soil [m^3.m^{-3}], $\mathbf{K}_{\mathbf{T}}^{*}$ is the effective thermal conductivity of the soil [J.s^{-1}.K^{-1}.m^{-1}] (i.e. the thermal conductivity of the porous medium constituted by soild grains, air, the liquid water and icy water), C_T^{*} is the effective volumetric calorific capacity of the soil [J.m^{-3}.K^{-1}], L_T^{*} is the effective volumetric latent heat of fusion of soil ice [J.m^{-3}], $\mathbf{K}_{\mathbf{T},i}$ is the thermal conductivity of the component *i* of the soil [J.s^{-1}.K^{-1}.m^{-1}], C_i is the volumetric calorific capacity of the component *i* of the soil [J.m^{-3}.K^{-1}] (*i* may stand for solid, water or ice), ϕ is the porosity of the soil [m^3.m^{-3}], and $L_{fusion,ice}$ is the volumetric latent heat of free ice [J.m^{-3}]. Several remarks may be made here. First, one can see that the evaluation of the effective thermal conductivity and the effective calorific capacity of the soil are based on a local thermal equilibrium assumption, following for instance Guymon and Luthin (1974). Second, the evaluation of the effective latent heat of fusion of the soil ice, which is influenced by interfacial processes, interaction with the solid skeleton, etc., is done with the simple empirical formulae of Kersten (1949) – Eq. (5). Finally, one can note that we use a linear interpolation for the ice content around the temperature of the fusion of ice T_f, with a small (i.e. T_f >>) parameter ΔT [K] for the interval of linearisation. Figure 5 presents the table of the classical order of magnitude considered for the various physical parameters of the model.

	Soil	Solid grains	Liquid water	Ice
Thermal conductivity [MJ.s^{-1}.K^{-1}.m^{-1}]		7.5*10^{-7}	6*10^{-7}	2.1*10^{-6}
Volumetric calorific capacity [MJ.m^{-3}.K^{-1}]		1.53	4.18	1.89
Latent heat of fusion [MJ.m^{-3}]				305.36
Porosity [-]	0.43			
Total water content [-]	0.33			

Figure 5: Typical values of model parameters discussed in this study.

Then, Figure 6 shows a summary of the obtained results, with the considered climatic input signal and the evolutions of the active layer, water state and temperature within the soil column over a year.

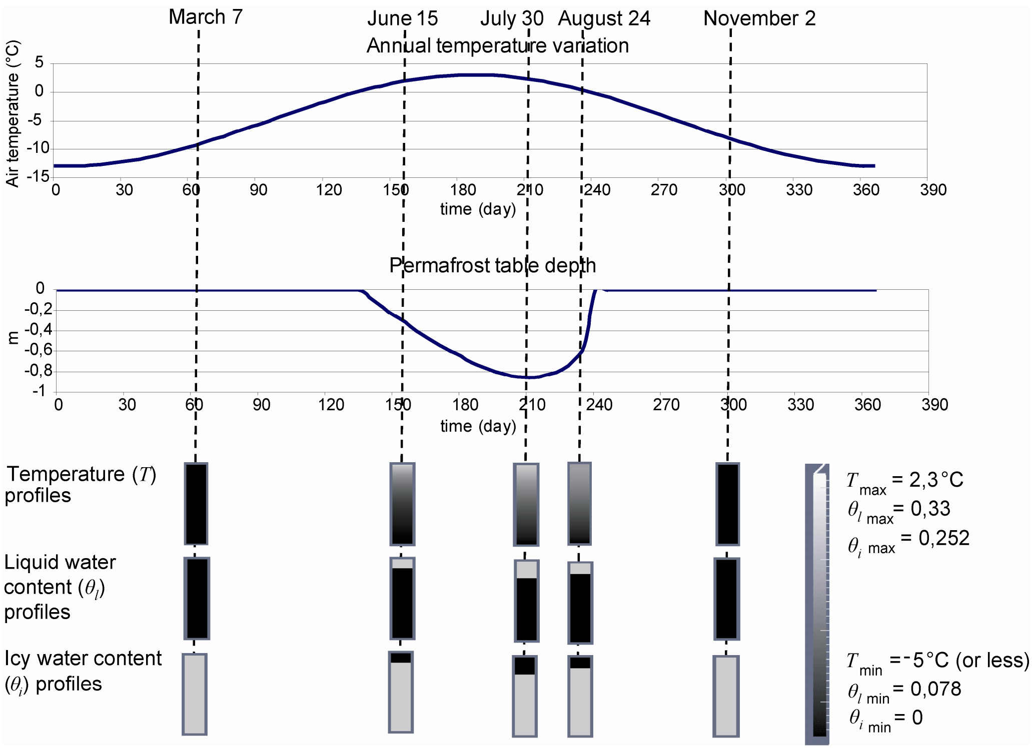

Figure 6: Permafrost table depth, and some temperature, liquid water content and icy water content profiles within a 4 m thick loess soil column submitted to a sinusoidal annual variation in temperature at its surface (mean : -5 °C, amplitude: 16 °C). Values obtain by numerical resolution of equations (1) to (5) using a homemade OpenFOAM® solver.

One can see that we obtain a maximum active layer thickness of slightly less than one metre with a surface temperature signal far smoother than the one for the region of the Putorana Plateau with a mean annual surface temperature at Tura station in the Putorana Plateau: -9°C, and rough amplitude : 53 °C. Thus we can see that neglecting the organic layer and the snow pack insulation effect leads to strong discrepancies between the theoretical behaviour obtained by modelling and that observed. It is numerical evidence of the importance of the organic layer and of the snow pack in the thermo-hydrological behaviour of the Putorana Plateau catchment. Also note the temporal asymmetry of the active layer's thickness variation, due to the thermal inertia of the soil column. It shows that the phenomena are more complicated than a simple linear dependency of active layer thickness on surface temperature, and thus justifies the need to use mechanistic approaches. The computation shown here is one-dimensional, but the solvers developed in the framework of OpenFOAM® are by default 3D solvers, which can be applied to 1D or 2D modelling by using peculiar empty boundary conditions,.

CONCLUSION

As shown by the study of weathering fluxes in the Putorana Plateau, the thermo-hydrological behaviour of a boreal catchment in a permafrost dominated area is a key parameter in the export of matter from the catchment. It is then an important stake for the study of the impact of climate change on the export of matter from boreal areas and on the associated potential feedback. The complexity of the physics involved here (coupling between heat and water fluxes, highly contrasted regimes both seasonally and spatially – north aspected slope/south aspected slope, antagonistic effects of climate change expected ...) requires a quantitative and predictive modelling approach, if one wants to infer the reaction of these systems to global changes. Mechanistic modelling is recognised as the "golden standard" in the study of hydrosystems dynamics (Miller et al., 2013), and many efforts have been made in the past to build efficient tools to study the physical behaviour of freezing soil-water systems. Nevertheless these works were limited in applicability due to a lack of computation power. The generalisation of the use of massively parallel computing may allow the community of modellers of thermo-hydrological behaviour of permafrost to overcome this difficulty, and to move towards the predictive modelling of the response of these complex systems to climate changes.

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