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Université Joseph Fourier - Grenoble

MÉMOIRE D'HABILITATION A DIRIGER DES RECHERCHES

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Observation and numerical modeling of snow on the ground : use of existing tools and contribution to ongoing developments

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Abstract

Snow on the ground is an essential medium at the surface of the Earth. For many years, scientists have attempted to decipher its functioning, because it exerts a significant influence on the regional and global climate, and governs environmental phenomena deemed critical for human societies (water resources including hydropower potential, snow avalanches, ski tourism etc.). Numerical models with various levels of complexity have been developed to integrate existing knowledge and predict the emerging behavior of the snowpack under given meteorological conditions from the large number of intertwined processes operating inside or at its boundary. Basic and advanced observation tools have been imagined and built to probe the physical properties of snow and contribute to better document the physical state of the snowpack and its time evolution.

This document summarizes my own contribution to the use and development of various tools used to observe and model the time evolution of snow on the ground. Special emphasis is placed on detailed snowpack modeling using the multilayer snowpack model Crocus, which serves as a knowledge integrator and allows to project the role of physical processes within the snowpack into various other scientific fields covering not only numerical weather prediction, climate or avalanche sciences but also mountain ecology, snow hydrology and glaciology and even the socio-economics of the ski tourism industry.

My impact on intrinsic developments in Crocus has mainly concerned the representation of snow microstructure and its time evolution (termed snow metamorphism) through the reformulation of the time evolution of the specific surface area of snow in a prognostic manner. Upstream research was also carried out with a medium-range goal of improving the way physical properties of snow such as effective thermal conductivity and intrinsic permeability can be parameterized in Crocus but this does not constitute fundamental changes to the model structure. In many cases, the current version of the model already provides relevant results and their applications to more or less original contexts can lead to scientific advances. Examples of such developments include several studies on the impact of the physical properties of snow on the thermal regime of the underlying ground, or recent advances in the way snow management techniques can be represented in Crocus leading to novel ways to assess the impact of snow management practices on snowpack properties in ski resorts, in relationship to environmental, social and technical constraints.

Many perspectives are offered in this field, with increased computational capabilities and increasing integration of the tools used to observe and simulate space and time variations of meteorological conditions together with a physically-sound representation of snow on the ground.

Résumé

Le manteau neigeux est un milieu d'importance capitale à la surface de la Terre. Depuis longtemps, la communauté scientifique s'efforce de décrypter son fonctionnement et son rôle dans le système climatique régional et mondial. En outre, le manteau neigeux joue un rôle clef pour de nombreux enjeux concernant les sociétés humaines (ressources en eau et en énergie, avalanches de neige, industrie touristique etc.). Des modèles numériques de complexité variable ont été développés en intégrant les connaissances existantes et permettent ainsi de prédire le comportement global du manteau neigeux à partir des conditions météorologiques et de l'interaction croisée de multiples processus internes ou ayant lieu à ses interfaces. En outre, des outils d'observations, des plus simples au plus avancés, ont été imaginés pour sonder les propriétés physiques de la neige et contribuent ainsi à mieux appréhender l'état physique du manteau neigeux et son évolution.

Le présent document synthétise ma propre contribution à l'utilisation et au développement de plusieurs outils utilisés pour observer ou modéliser l'évolution de la neige au sol. En l'occurrence, une attention spéciale est apportée à la modélisation détaillée du manteau neigeux à l'aide du modèle multi-couches Crocus, qui sert d'"intégrateur de connaissance" et permet de projeter dans des domaines scientifiques plus ou moins connexes une représentation adéquate des processus physiques du manteau neigeux. Ceci concerne non seulement la prévision numérique du temps, l'étude du système climatique ou des avalanches, mais aussi l'écologie de montagne, l'hydrologie nivale, la glaciologie et même les aspects socio-économiques de l'industrie des sports d'hiver.

Mon apport direct aux développements au sein de Crocus a porté essentiellement sur la façon de représenter la microstructure de la neige et son évolution dans le temps en fonction des conditions thermiques à l'échelle macroscopique (métamorphisme de la neige), au travers de la reformulation des lois d'évolution de la surface spécifique de la neige de manière pronostique. En parallèle, des recherches plus fondamentales ont été menées avec pour objectif de moyen terme d'améliorer les paramétrisations employées pour représenter certaines propriétés physiques de la neige dans Crocus, telles que la conductivité thermique effective ou la perméabilité intrinsèque. Cependant, ces actions ne constituent pas des avancées fondamentales pour l'évolution de la structure du modèle. Néanmoins, dans bien des cas, le comportement actuel du modèle est déjà satisfaisant et permet des applications dans des domaines plus ou moins exotiques. Ceci concerne, par exemple, l'étude de l'impact des propriétés thermiques du manteau neigeux sur le régime thermique du sol sous-jacent, ou, plus éloigné des considérations purement géophysiques, des avancées récentes sur la compréhension et la modélisation de la façon dont la neige est travaillée dans les stations de sports d'hiver en relation avec des

contraintes environnementales, sociétales et techniques.

De nombreuses perspectives sont ouvertes dans les domaines liés à la physique de la neige, grâce aux avancées offertes par l'augmentation des capacités de calcul, mais surtout grâce à l'amélioration et à la meilleure intégration des techniques et outils d'observation et de simulation de l'évolution des conditions météorologiques, associés à une prise en compte solide de la neige au sol et des processus physiques associés.

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1 Introduction

1.1 Scientific knowledge : tools vs. results

The current state of global scientific knowledge is a perplexedly vast accumulation of atomic elements, following millenia of technical, cultural and scientific developments undertaken by presumably millions of human beings motivated by a large diversity of challenges to address. Some of the elemental bits of knowledge belong to the general scientific corpus taught at basic high-school or specialized university levels, while a large number of them are at best reported in dedicated reports or technical procedures (peer-reviewed articles, conference proceedings, technical documentation, websites ...) or embedded in hardware or software elements. The ability to draw from existing knowledge the appropriate tools and identify knowledge gaps and missing elements are critical to address current scientific, technical and societal challenges.

For a given general topic, scientific knowledge has been built upon a diversity of perspectives, to each of which corresponds at least one community of institutions, researchers and practitioners featuring several schools of thoughts and cultural backgrounds, with various degrees of communication between all the levels involved. In many cases, progress is not only achieved by incremental advances within a given isolated group, but rather through the identification of homologous challenges addressed by another scientific community, potentially distant in time, space or scientific area. Modern methods of scientific communication and in particular the skyrocketing number of research articles published every day within a given scientific community may pose severe threats to the scientific world through unidentified duplication of work (due to the difficulty to monitor the breadth of contributions describing specific developments) thereby potentially reducing the efficiency of the scientific process. Efforts are needed both at the individual and community levels to contribute and communicate advances of the scientific knowledge without impairing the long-term sustainability of the scientific process. In the meantime, the systematic use of publication metrics (e.g. number of peer-reviewed articles and citation counts) by funding and evaluation agencies, although heavily criticized, has become a norm from which individual researchers cannot easily escape. While scientific articles, which are increasingly used to report incremental advances in highly specialized areas of research, serve the purpose of both favoring scientific exchanges between research groups and communities and providing long-term archives of the time evolution of scientific knowledge, focussing on scientific *tools* offers an alternative option to foster sustainable scientific development at the community level. The sense of the term *tools* used here is very large, and covers for example (not exhaustively)

instrumentation, software, algorithms – along with their documentation. A large fraction of scientific research, including fundamental research, is actually based on the development of such tools and their applications, the latter providing motivation, hence resources, to carry out the research work. However, it is often the case that in the long term only the scientific results, i.e. the more or less general statements reached through the use of the tools in a particular case, remain available to the scientific community. This situation leads to frequent re-implementations or even re-inventions of the same tools which is not only detrimental pragmatically (costs, resources, etc.) but also slows down the pace of scientific development. Scientific developments specifically aimed at creating tools which are used regularly (e.g., numerical weather prediction models) and not for the sole purpose of research projects, suffer less from this issue, although in such cases the issue of the portability of the tools from one technical environment to the other is often encountered.

1.2 A (very) short introduction to snow science

Snow science is no exception to all of the statements expressed above and has been built upon a variety of scientific motivations spanning avalanche hazard forecasting, water resources and hydrology, meteorology and climate, mountain ecosystems, mountain tourism etc. Abundant literature describes the significant role exerted by snow on the ground on many aspects of the functioning of the Earth's surface and shall not be repeated here in detail (see Armstrong and Brun (2008) for a recent overview). In short, the peculiar physical properties of snow on the ground, consisting of a thin layer of a porous mixture of water ice, liquid water and air, often only intermittently covering land surfaces (and sea ice), induce drastic changes of the energy and mass fluxes at the atmosphere/surface interface with respect to a snow-free situation. Of particular relevance here are the optical (high albedo, i.e., the fraction of solar radiation reflected by the surface), thermal (low effective thermal conductivity), thermodynamic (high latent heat of fusion for ice) properties of snow. A number of specific tools have been designed over the past decades to address scientific challenges involving snow on the ground, especially in terms of observation capabilities allowing in-situ and remotely sensed monitoring in the field and in the laboratory, and in terms of numerical modeling of snow physical processes allowing numerical simulations of the time and space evolution of the physical state of snow on the ground for various applications. Because snow is one of the many facets that land surfaces can show, land surface components of Earth surface models within climate or numerical weather prediction (NWP) models generally include a snowpack model (also called a scheme). In what follows, a snowpack model is thus considered one specific component of a more general land surface model. This defi-

dition is consistent with the context of use of several existing snowpack models (e.g. Douville et al., 1995; Lehning et al., 2006; Oleson et al., 2010; Best et al., 2011; Balsamo, 2012; Masson et al., 2013; Endrizzi et al., 2013; Wang et al., 2013), and accounts for the need to include the interactions of the snowpack with its surrounding environment (atmosphere, ground, vegetation).

1.3 Personal context of the research work

This document intends to summarize my own contribution to the use and development of snow-relevant tools, with special emphasis on snow observing capabilities and numerical modeling of the physical state of snow on the ground, since 2008 which corresponds (1) to the date when my PhD work was defended (Morin, 2008) and (2) the date when my primary research field shifted from probing boundary layer atmospheric chemistry through isotopic investigation methods to snow physics research, first at LGGE until September 2009 then at Météo-France - CNRS, CNRM-GAME/Snow Research Center (CEN). Due to its natural ties to the operational activities carried out by Météo-France, working at CEN induces thematic constraints in that the research must ultimately contribute to address issues related to avalanche hazard forecasting, mountain hydrology and the climatological features of snow on the ground (including contributing to projections of the impact of climate change on snow conditions). Conversely, the current working environment at CEN, and in a broader sense at CNRM-GAME, makes it possible to carry out developments with a medium- to long-term perspective, which is only possible due to an adequate balance in the missions of the permanently hired scientific staff members (researchers, engineers and technicians) between upstream research, applied research and transfer of research results to operational services. Such developments are fostered by interactions with the scientific community at the local (Grenoble geophysics laboratories mainly belonging to the Grenoble laboratories geosciences federation – OSUG), national and international levels, especially when tools are shared and developed through collaborative work.

In contrast to many research positions in academic institutions, which strongly depend on the scientific background and personal research project of the person holding them following a competitive recruitment procedure, Météo-France positions at CEN are primarily meant to be held to sustain long-term research and development activities, with significant emphasis placed on tools rather than on scientific results *per se*. My own position, left vacant for six years prior to my arrival, covers the management of the research team “Snowpack” (*Manteau neigeux*) and the scientific management of the Crocus model and other long-term scientific duties. These concern most the scientific management of the Col de Porte experimental site and technology watch relevant for methods for observing

the physical properties of snow, and potentially contribution to their development. In terms of Crocus development, my main duty has been to foster and develop the links between the representation of snow metamorphism in Crocus and advances in the characterization and modeling of processes operating at the microstructure scale. This document is thus deliberately organized around the perspective of snowpack modeling.

However, prior to any further description and discussion of snowpack model development, it is worth reminding that even with the best possible snowpack model, inaccurate meteorological data used to drive (or force) the model will inevitably lead to bad model performance. Consequently, developments in snowpack modeling must always be balanced with an assessment of the availability of appropriate meteorological forcing data - which otherwise makes advanced snowpack modeling completely useless unless from a purely academic point of view. This explains that part of my time is devoted to meteorological issues. Regarding meteorological observations, I am coordinating the participation of France to the WMO-SPICE¹ (Solid Precipitation InterComparison Experiment) initiative through measurements carried out at Col de Porte, gathering CEN personnel (in particular Y. Lejeune and J.-M. Panel) and local partners (LTHE, LGGE, EDF-DTG, SPC AN - regional flood forecasting authority). In terms of meteorological modeling and forecast, I follow developments in this field to try to foster exchanges between snow modeling and developments of meteorological tools (analysis, forecast) to optimize snow modeling developments especially in French mountain regions. These aspects of my work are, however, not described in detail in what follows, for the sake of consistency.

Also left aside from the current document is my contribution to the field of atmospheric chemistry, in particular through the use of isotopic methods, since the end of my PhD. Besides work that had been carried out during my PhD but was published several years after, I have spent some time at the beginning of my work at CEN to finalize some ongoing work, contribute to the PhD work of J. Erbland, co-supervised with J. Savarino at LGGE, who was my former PhD advisor, and carry out specific research activities, which I feared otherwise no one would take care of. This concerns in particular a study on the numerical modeling of the diurnal variations of the isotopic composition of short-lived atmospheric compounds (Morin et al., 2011), a report and analysis of isotopic measurements carried out on daily samples of atmospheric nitrate collected at Barrow, Alaska during the Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) field campaign in the spring 2009 (Morin et al., 2012a), and a contribution to the analysis of diurnal variations and daily averages of the isotopic composition of atmospheric nitrate collected on a ship off the California Coast during the CalNEX

¹<http://www.wmo.int/pages/prog/www/IMOP/intercomparisons/SPICE/SPICE.html>

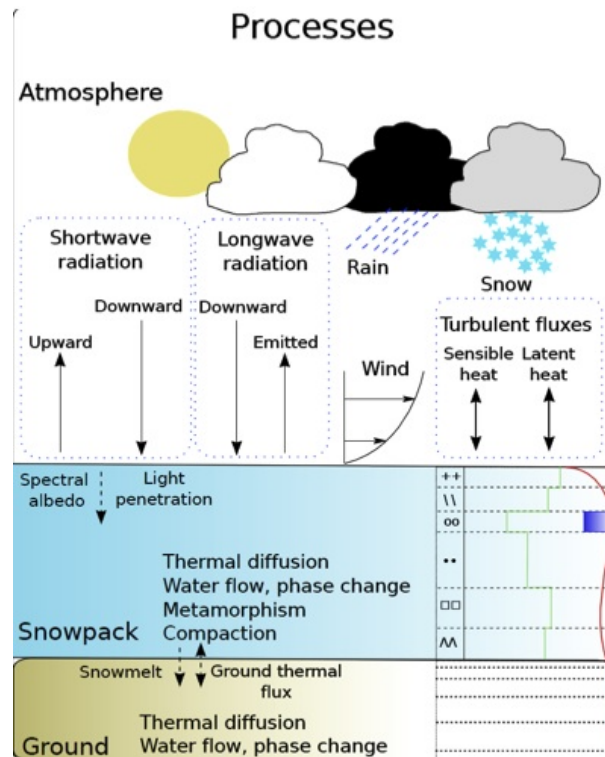


Figure 1: Overview of the main physical processes and boundary conditions which can currently be represented in one-dimensional snowpack schemes within land surface models (from Vionnet et al., 2012).

2010 campaign, for which I had contributed to establish initial contacts with North-American scientific partners and provided guidance to PhD student W. C. Vicars (LGGE), supervised by J. Savarino, for the interpretation of the results (Vicars et al., 2013). Of course, it is never possible to fully close research activities on a given topic, but I feel that the time spent on the above-mentioned studies since 2008 has allowed me to provide a consistent contribution to this field.

1.4 General considerations for detailed snowpack modeling

The basic task of a numerical model is to compute the time and/or space evolution of prognostic state variables characterizing the snow conditions and their interactions with the environment (atmosphere, ground, vegetation etc.), based on the time integration of physical laws expressed in tractable mathematic equations. The model needs to account for the following items:

- Physical processes operating within the snowpack : processes are represented by a set of equations responsible for the time evolution of the physical properties of snow under the influence of boundary conditions and of the intrinsic snow properties.

- **Boundary conditions** : this concerns mostly the energy and mass balance at the interface between the snowpack and the overlying atmosphere and underlying ground, which depends on atmospheric and ground characteristics but also on processes taking place within the snowpack.
- **Initial conditions**: this general concept for geophysical modeling concerns the prognostic variables used to represent the physical properties of snow in the model, and the estimate of their value at the beginning of each time step of integration, that the model evolves until the next time step.

In the case of snowpack scheme within a land surface model, only time derivatives are considered because the simulation points are considered fixed in space and only vertically resolved processes are dealt with. Figure 1 summarizes the main physical processes and boundary conditions which can currently be represented in one-dimensional snowpack schemes within land surface models. The physical knowledge at the basis of snowpack modeling generally draws from well established first principles (heat diffusion, phase change, basic mechanics, etc.) and macroscopically does not involve advanced physics considerations (e.g. Domine et al., 2008).

1.4.1 Boundary conditions

Interactions with underlying ground The main source of interaction between the snowpack and the underlying ground proceeds through heat diffusion at the snow/ground boundary. A proper representation of this process requires that the heat diffusion equation is solved consistently through this boundary. In addition, water mass can be exchanged between the snowpack downwards through liquid water (either originating from snowmelt or rain on snow episodes) infiltration and runoff at the snow/ground interface, and upwards through capillary liquid water motion (see example in Figure 2 reported by Mitterer and Schweizer, 2012). Because energy transfer follows mass transfer (through the latent and sensible heat held by water in various physical states), a consistent handling of energy and mass transfer through the snow/ground interface requires that the heat diffusion equation is solved accounting for both phase change and water mass transport.

Surface energy and mass balance The main surface mass balance terms of the snowpack proceed through liquid (rain) rain and solid (snow) precipitation. Additional surface mass balance terms arise from processes related to phase change occurring at the surface of the snowpack, in particular mass loss through ice sublimation from dry surface snow, liquid water evaporation (also termed vaporization) from wet surface snow, and mass gain by transition from atmospheric water vapor into liquid

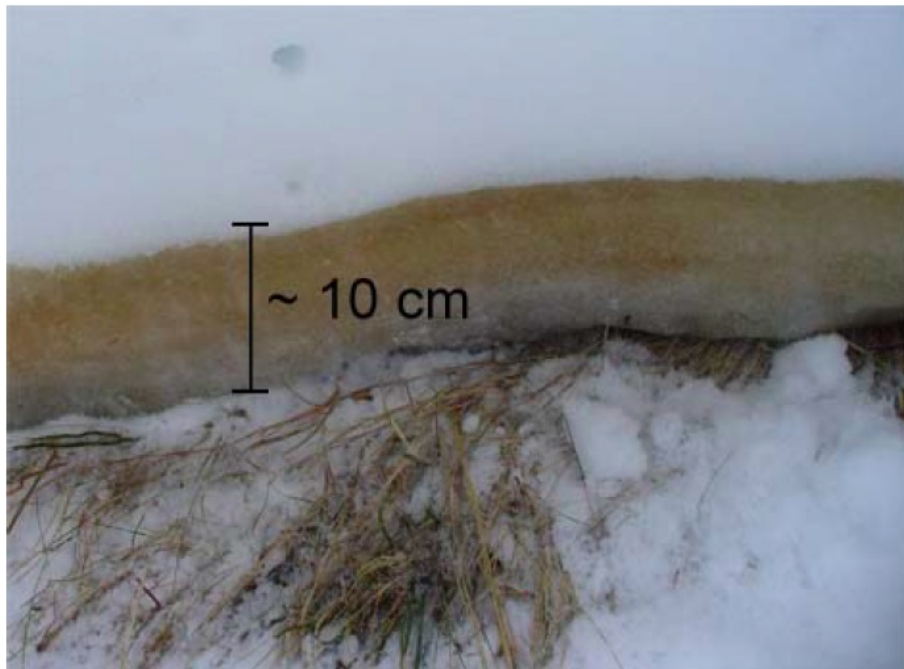


Figure 2: Photo taken at the base of an open glide crack in Switzerland. Basal snow layers show high water saturation. Brownish color hints to soil solutes transported into the snowpack through upwards water flow (from Mitterer and Schweizer, 2012).

water through condensation and to ice through deposition. Last, wind induced erosion and accumulation contribute to the surface mass balance of the snowpack independent from the occurrence of precipitation episodes. Each of these processes is accompanied by energy transfers between the snowpack and the atmosphere. Those associated with phase change occurring at the surface of the snowpack are termed latent heat turbulent fluxes, because they strongly depend on the vertical stability of the atmosphere above the snowpack and are favored by unstable (turbulent) conditions (Andreas, 2002).

Purely energetic terms also contribute to the surface energy balance. The atmosphere emits downwards thermal radiation to the surface depending mostly on the vertical profile of temperature and water vapor. The Earth surface emits upwards thermal radiation depending on the infra-red emissivity of the surface and its skin temperature. Due to its highly dispersed microstructure, the snow surface behaves like an almost perfect black body, i.e. its thermal radiation almost reaches the maximal physically possible amount for a given skin temperature (Warren, 1982; Hori et al., 2006). Conversely, snow absorbs nearly all incoming thermal radiation at its surface. The surface energy balance in the solar part of the incoming radiation is a complex blend of the properties of the incoming radiation (illumination angle of the direct beam, partitioning between the direct and diffuse incoming radia-

tion) and of the near surface snow properties (see e.g. Warren and Wiscombe, 1980; Aoki et al., 2003). In the visible part of the solar spectrum, where ice scattering dominates over ice absorption, the fraction of solar light reflected by the surface (also termed spectral reflectance or albedo) strongly depends on the amount of light absorbing impurities and their vertical profile, and to a lesser extent to the microstructure of snow. In the near-infrared part of the solar spectrum, where ice absorption dominates over scattering, the spectral albedo depends only on microstructure-related variables (Giddings and LaChapelle, 1961; Warren and Wiscombe, 1980). Solar light penetration depends on the previously mentioned properties but also on the degree of anisotropy of the microstructure of snow (Meirolid-Mautner and Lehning, 2004; Libois et al., 2013). In this sense, it is not strictly speaking a snow surface process, because it may contribute to the deposition of energy several cm below the snow surface. Last, sensible turbulent heat flux also contributes to the surface energy balance of snow. This process corresponds to the transfer of energy associated with the advection of heat along with the motion of air masses at the snow/atmosphere boundary, and, similarly to the latent heat turbulent flux, it depends on the vertical stability of the atmosphere.

Figure 3 shows an overview of the main macroscopic physical properties of the snowpack and its interfaces (surface temperature, ground temperature). More similar plots can be found in the supplementary online material of Morin et al. (2012b).

1.4.2 Internal physical processes

The snowpack hosts a diversity of processes which altogether contribute to making snow a unique physical and chemical interface at the Earth surface. Although this is regularly challenged by field observations, it is generally considered that the snowpack can be considered as a layered medium, so that only vertically-resolved processes need to be accounted for in snowpack models embedded in land surface models, all of which assume planar geometries for the stack of layers constituting the vertical structure of the snowpack, which is sometimes encountered in nature (see Figure 4). Lateral transport of heat and mass occur and related processes operate on the snowpack, including wind-related processes (erosion, drift etc.) and processes associated with lateral heat diffusion and liquid water flow within the snowpack. Such processes are deliberately ignored in this document, because my work has so far focussed on point scale mostly vertically resolved processes operating in the snowpack and I have not contributed much to addressing horizontal energy and mass fluxes, below, within or above the snowpack.

Thermal diffusion in snow is a major physical process acting on key internal snow properties

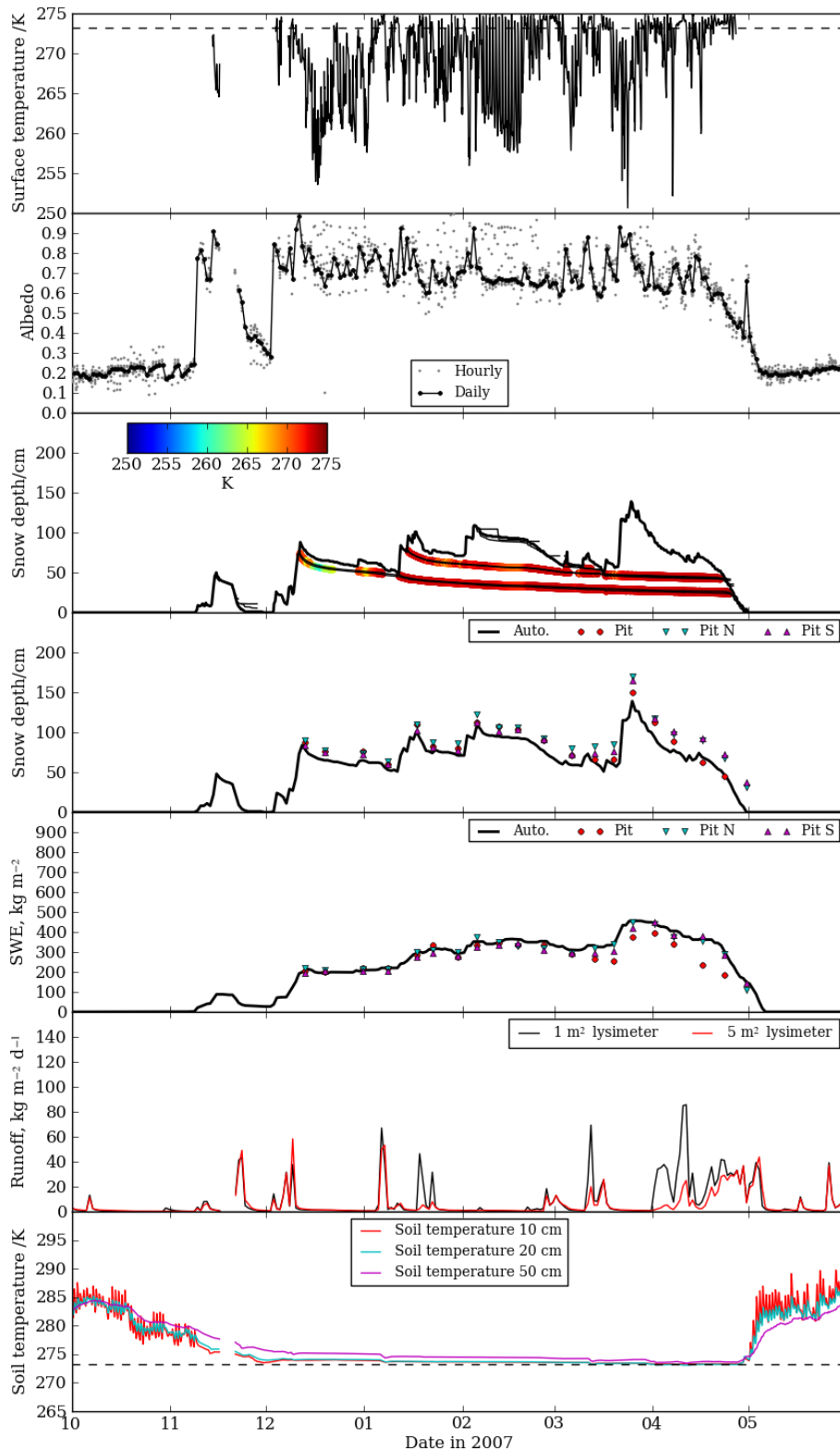


Figure 3: Summary of the physical properties of snow at Col de Porte for the snow season 2007 - 2008 (from Morin et al., 2012b). From top to bottom : snow surface temperature, snow albedo (hourly “instantaneous” values and daily integrated values), automated daily snow height and internal temperature, daily snow height along with weekly manual snow height measurements, automated daily snow water equivalent along with weekly manual measurements, snowmelt flux and ground temperature.

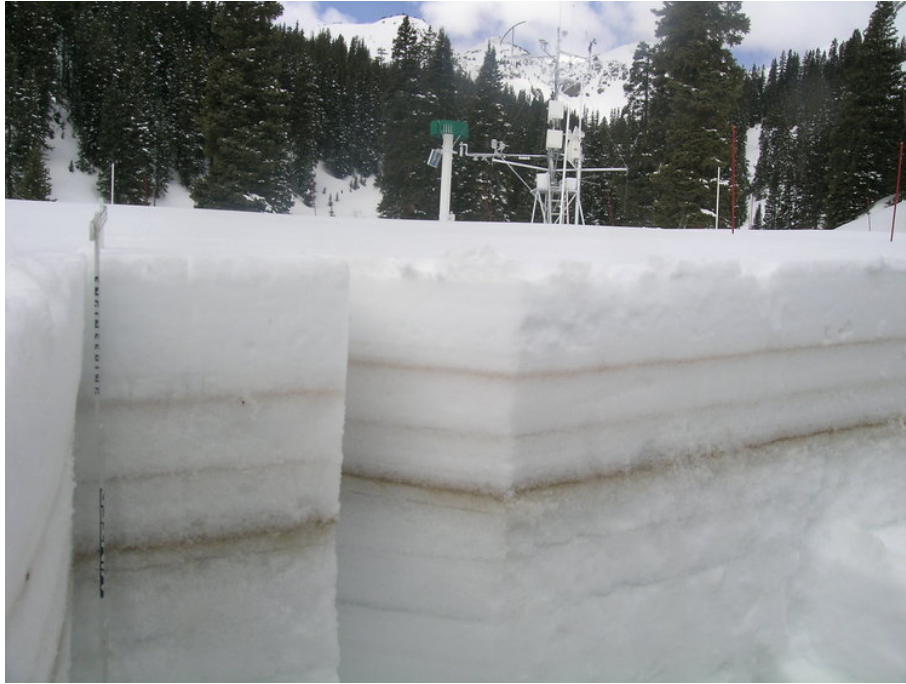


Figure 4: Example of the layering of the physical properties of snow, including variations of impurity content. Original picture taken at Swamp Angel Study Plot in Colorado on 22 April 2013 (retrieved from <http://www.codos.org/>).

such as the vertical profile of temperature, vertical temperature gradient, and liquid water content, but also governing the pace of heat transfer through snow with major implications for the thermal budget of the underlying ground. Snow compaction, induced by the weight of overlying layers and by microstructural transformations of snow, is a key process leading to snow densification hence a modification of its physical behavior. More generally, microstructure transformations are grouped under the term snow metamorphism, which underlines the link between snow science and in a more general geophysical sense phase change and recrystallization processes (e.g. Winter, 2009). While microscopic drivers of snow metamorphism are pore-level heterogeneities of water vapor fields in turn influenced by microscopic temperature gradients and curvature patterns of the microstructure (e.g. Colbeck, 1982, 1983; Flin et al., 2003; Flin and Brzoska, 2008; Kaempfer and Plapp, 2009), snow metamorphism is macroscopically driven by temperature, temperature gradient and liquid water content (Domine et al., 2008). Here again, because snow is found at the Earth surface under thermal conditions very close to its melt point, phase change processes within the snowpack are of critical importance. Under circumstances where liquid water can be found within the snowpack (either due to rain-on-snow or surface or basal melt), water percolation takes place, driven by gravity and very often

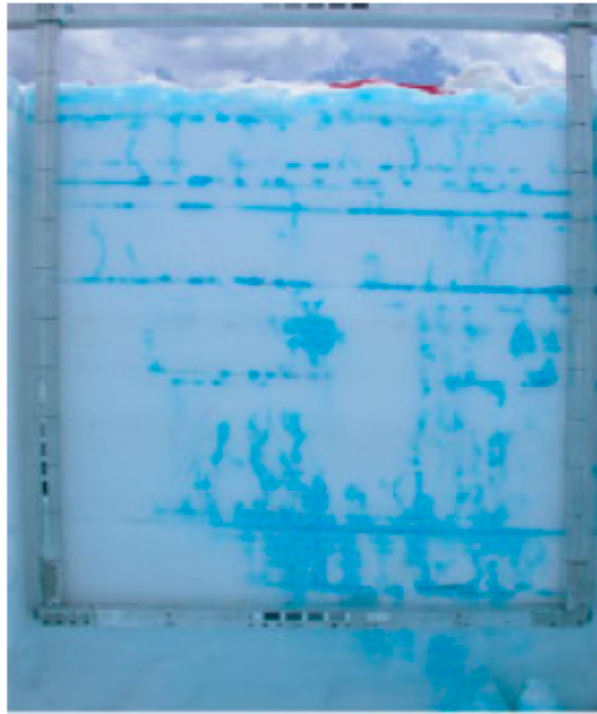


Figure 5: Illustration of the heterogeneous nature of downwards liquid water movement in snow (from Williams et al., 2010).

preferential flow is found to occur (see Figure 5). Such a process is inherently three-dimensional and is currently handled in 1D snowpack schemes in a very rough manner.

1.4.3 State variables for snow

The main difficulties of 1D snowpack modeling arise from the fact that physical processes observed -and modeled- at the macroscopic scale stem from processes occurring at the microscopic scale, i.e. they involve recrystallization, heat exchange and phase change operating at the microstructure level, where snow is a complex tridimensional assemblage of ice, air, liquid water and impurities. The estimation of macroscopically-relevant physical properties which can be dealt with in snowpack schemes in land surface models requires a minimum level of understanding of how the microstructure of snow influences its physical behavior. Major advances in this regard have occurred since the inception of novel methods to probe the microstructure of snow with a resolution of a few micrometers. In particular, X-ray tomography of snow, developed in the late 1990s with a contribution from CEN (Brzoska et al., 1999; Coléou et al., 2001) and later largely popularized and used in many laboratories worldwide (e.g. Schneebeli and Sokratov, 2004; Freitag et al., 2004; Chen and Baker, 2010), has offered new ways to tackle the links between microscopic properties of snow and emerging macroscopic

properties, in addition to providing the basic ingredients to test hypotheses regarding snow metamorphism itself (see section 1.4.2). Similarly to other porous or granular materials, the very definition of macroscopic emerging properties from the microstructure requires that a representative elementary volume (REV) can be defined, within which the emerging property can be considered homogeneous. In some cases, this step is already challenging, especially for properties involving "long"-range interactions (against microstructural characteristic scales), such as mechanical properties for instance (Schneebeli, 2004; Hagenmuller et al., 2014).

Depending on the task that numerical modeling is meant to achieve, the level of complexity of the representation of snow microstructure and its evolution varies. Several state variables, from the most simple to the most complicated, directly emerge from the microstructure of snow. Here we review the key physical properties which are needed for detailed snowpack modeling, and their relationship to variables emerging from the microstructure. By definition, a single value for each variable is assigned to each numerical layer used within the snowpack model to discretize the vertical profile of the physical properties of snow.

The basic state variables used to describe the physical state of a snow layer follow:

- Mass and thickness

A given snow layer needs to be assigned a total mass of condensed water (i.e. ice and liquid water; the mass of air filling up the porosity is generally neglected) per unit horizontal surface area, also referred to as the snow water equivalent, and thickness (Δz). The link between the two is the density (ρ , snow mass per unit snow volume), which corresponds to the mass of condensed water per unit snow volume and is the primary variable emerging from the microstructure (Torquato, 2002).

- Liquid water content

The amount of liquid water (ξ) in a given snow layer is referred to as the liquid water content. It can be reported using various dimensionalities (mass ratio, volume ratio, etc.). Because the water mass is kept unchanged through phase change (in contrast to water volume), I personally prefer to express liquid water content in terms of liquid water mass per unit snow volume. In this case, the liquid water content has the same unit as snow density, reducing risks of errors arising from unit conversions, and making it easy to compute the "dry snow density" (i.e., ice mass per unit snow volume) as $\rho - \xi$, and the mass ratio between liquid water mass and total condensed water mass as ξ/ρ .

- Temperature

The temperature of a given snow layer is a critical variable to characterize its physical state.

Along with snow density and layer thickness, thermal and thermodynamic properties are needed to compute the dry snow internal thermal diffusion equation, provided that boundary conditions (top and bottom energy fluxes) and potential source terms (e.g. solar radiation absorption in each layer) are known:

- The effective thermal conductivity (k_{eff}) describes the heat diffusion efficiency through a given snow layer. The terms “effective” stems from the fact that a value relevant at the macroscopic level corresponding to an homogeneous medium can be estimated from the microstructure level snow properties accounting for both air and ice thermal properties and including only purely diffusive processes.
- The heat capacity (C_p) describes the amount of energy that is needed to raise the temperature of a snow sample of unit mass. It is defined only for dry snow (heat capacity is not relevant for wet snow, i.e. containing liquid water, because its temperature is then fixed to the ice melt temperature). This variable is generally computed for each numerical snow layer by multiplying the specific heat capacity of ice to snow mass in the layer.

For obvious reasons of computing cost especially in terms of memory use, the number of prognostic variables, i.e. the variables that need to be stored for each layer between each iteration of the numerical model, must be considered cautiously. Indeed, each prognostic variable must be defined for every snow layer. In the case of a detailed snowpack model like Crocus featuring typically up to 50 layers, each of the 50 values of each prognostic variable needs to be internally stored at each time step, which becomes quickly intractable if the number of prognostic variables becomes too large, especially for simulations covering a large number of simulation points. Numerical tricks were developed to try to keep the number of prognostic variables as low as possible:

- Thermal state : because snow temperature different from the melt point cannot coexist with a nonzero liquid water content (and vice-versa), snow enthalpy was introduced in snow models several decades ago (Lynch-Stieglitz, 1994; Boone and Etchevers, 2001) as a variable handling both snow temperature and liquid water content in a energetically continuous way across the melt-point physical discontinuity, and is used as such in SURFEX/ISBA-Crocus.
- Layer density/mass/thickness : these three variables are not independent, so that only two need

to be defined (in the case of SURFEX/ISBA-Crocus and SURFEX/ISBA-ES, the mass and density of snow layers are the prognostic variables used).

Additional state variables can be used to characterize snow layers, including variables representing the microstructure of snow (various surrogates for “grain size”, indications of the degree of faceting, bonds characteristics etc.) and properties needed to compute snow compaction (e.g. newtonian viscosity) and other processes operating within the snowpack (Armstrong and Brun, 2008). However, a specific analysis has to be carried out to identify the cost/benefit of adding an additional prognostic variable into the model. In some cases, the relationship between the physical property needed and density is deemed sufficiently robust that a prognostic equation of the considered variable is not used, but rather the variable is computed from density at each time step of the model for each model. This situation may also stem from the fact that prognostic equations (i.e., rate equations for the time evolution of a given variable as a function of the state variable) often do not exist. For example, there does not currently exist a prognostic representation of the intrinsic time evolution of the effective thermal conductivity of snow. Instead, this variable is computed from snow density using a parametric equation (that of Yen, 1981 in the case of Crocus). The number of prognostic variables thus results from a compromise between the number of variables that can be afforded, and the added-value of explicitly evolving a variable independently from other variables. Figure 6 shows an example of the simulated time evolution of some of the physical properties of snow at the Col de Porte field site during a given snow season using the detailed snowpack model SURFEX/ISBA-Crocus (Vionnet et al., 2012).

1.4.4 Degrees of model complexity

Land surface schemes for NWP and climate models were primarily designed to represent energy and mass fluxes at the interface between the atmosphere and the surrounding surface, which implies that emphasis was placed on a realistic representation of the albedo and surface temperature and their time evolution, in particular the diurnal cycle of the latter, while correctly representing the internal processes (heat diffusion, phase change and percolation) was only a secondary objective. Such targets can reasonably be reached using well tuned single layer bulk snow schemes (Douville et al., 1995; Balsamo, 2012). In the SURFEX/ISBA-D95 single layer snow scheme, snow is thus represented with only three prognostic variables which are bulk density, snow water equivalent, and snow albedo (Douville et al., 1995; Masson et al., 2013). Climate and hydrological applications require that not only the fluxes but also the water reservoirs at the Earth surface (not only snow but also ground and lake water masses) are correctly represented. Essery et al. (2013) have provided an in-depth analysis

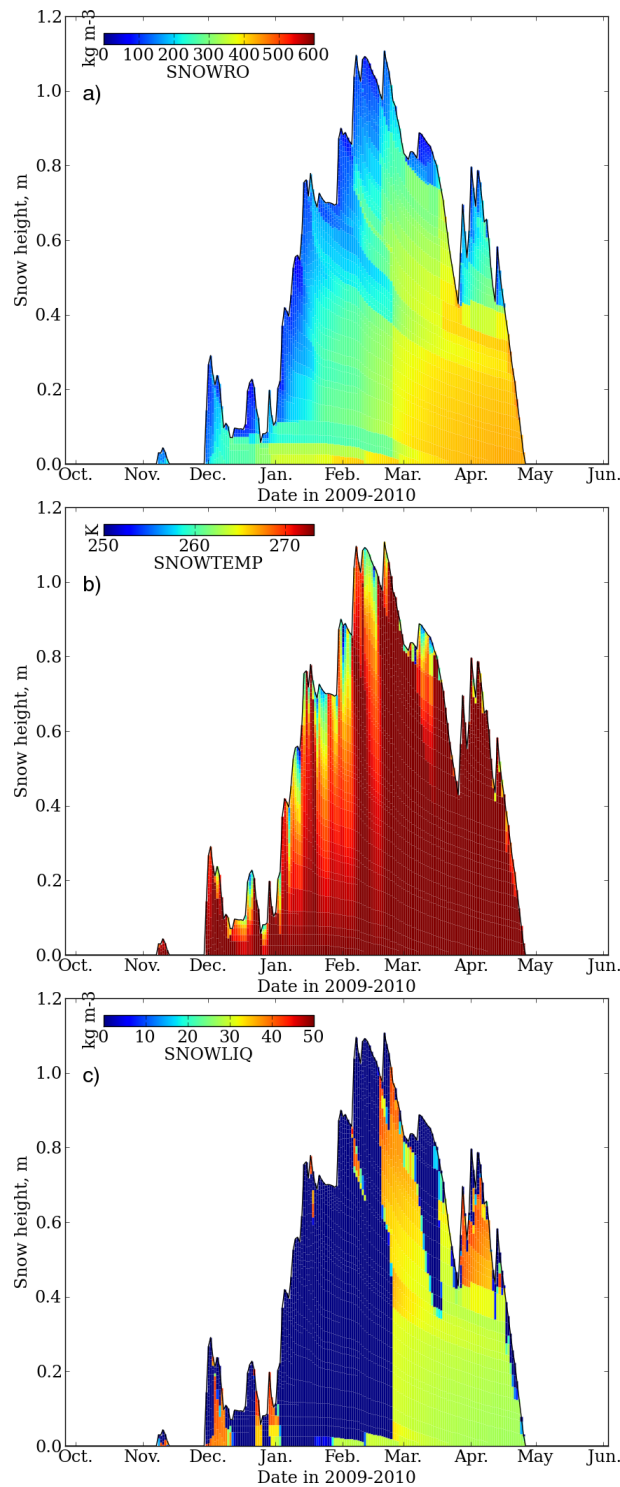


Figure 6: Example of visualization of the time series of snowpack profile properties simulated by the snowpack scheme Crocus in SURFEX. The simulation used is the last year (2009-2010) of simulation from the model run carried out at Col de Porte. The data represented here are **a)** snow density (kg m^{-3}), **b)** snow temperature (K), **c)** snow liquid water content (kg m^{-3}). From Vionnet et al. (2012).

of the key ingredients needed to appropriately represent snow processes in intermediate complexity snow schemes, which are snow compaction, phase change and a water percolation scheme allowing liquid water retention in snow, thermal conduction through snow, and a prognostic albedo evolution. This requires that the snowpack is represented by several layers. SURFEX/ISBA-ES features a sufficiently detailed degree of complexity in this respect (Boone and Etchevers, 2001), and includes three prognostic variables per snow layer (snow water equivalent, enthalpy and density) plus an additional prognostic albedo. For typical conditions of use of the model with 3 layers, 10 prognostic variables must be saved and used for the next time iteration of the model (Masson et al., 2013).

There are at least three scientific areas where a higher degree of complexity is needed to represent snow properties and processes in numerical models of the snowpack. Avalanche hazard forecasting is the first one, due to the need to represent the detailed layering of mechanical properties of snow in order to predict potential snowpack instability conditions, in particular for accidentally triggered avalanches (e.g. Schweizer et al., 2003). This is the main reason why snow microstructure was initially represented in the detailed snowpack model Crocus (Brun et al., 1992). The second domain of applications of higher level of complexity is related to remotely-sensed properties of snow. Indeed, regardless the wavelength considered (microwave to visible and near-infrared) and the observation mode (active or passive observations), the interactions between electromagnetic radiation and snow strongly depends on the vertical profile of the physical properties of snow including snow microstructure variables (e.g. Grenfell and Warren, 1999, see below). While the level of complexity needed for a given application (i.e., NWP or hydrology) does not intrinsically require a detailed representation of snow microstructure, the possibility to assimilate remotely-sensed variables crucially depends on the ability to represent the electromagnetic behavior of the snowpack and thus implies the use of a snowpack model of higher complexity. Last, detailed studies of the physical and chemical processes in the snowpack require a higher level of complexity of the representation of snow processes than in intermediate complexity models. The choice of the state variables relevant to represent physical processes in snow and variables describing the behavior of interest for the selected application is not trivial and needs to account for pragmatic considerations, i.e. in the case of a prognostic variable, whether prognostic evolution laws exist, either physically-based or parameterized.

The SURFEX/ISBA-Crocus scheme belongs to the category of the detailed snowpack models, together with a few other ones (e.g. Jordan, 1991; Lehning et al., 2002; Niwano et al., 2012). The model governs the evolution of 7 prognostic variables in each layer (density, snow water equivalent, enthalpy, grain1, grain2, hist and age - see details below), with 35 prognostic variable in a 5 layers

configuration and up to 350 prognostic variables in the full 50 layers configuration, which is generally employed for offline Crocus applications. Of course, prognostic variables must also be considered for other components of the land surface scheme (ground thermal and hydrological state, vegetation, etc.). It is worth comparing this number with the number of prognostic variables in the atmospheric component of a climate or NWP model. For example, the ARPEGE global NWP model used at Météo-France features 70 atmospheric levels, with 9 prognostic variables, totaling 630 prognostic variables. Cases may thus be encountered where more variables are used to describe the 2D surface fields than the 3D motion and physical properties of the atmosphere.

The land surface scheme ISBA in SURFEX (Masson et al., 2013) features snowpack schemes of these three levels of complexity (D95 - Douville et al., 1995 and EBA - Bazile et al., 2002, Explicit Snow - Boone and Etchevers, 2001 and Crocus - Vionnet et al., 2012) making it a very efficient tool to investigate the impact of model complexity on the performance of the representation of snow processes in the land surface model (and its impact/feedback on other model components in offline and coupled modes), and allowing progressive increase of model complexity and physical representation of processes regarding snow for the various applications for which simpler approaches have been employed so far (in particular, NWP and climate modeling).

1.5 Features and use of the stand-alone version of Crocus

In contrast to the situation encountered in the 1970s when numerical modeling of the time evolution of the physical properties of snow, even the most basic ones (e.g. snow water equivalent, i.e. the total snow mass per unit horizontal surface area), was in its infancy with promising ongoing developments, physically-based numerical models for the time evolution of the physical properties of snow on the ground were largely developed upon my inception in this field in 2008. In particular, extensive developments took place in the 1980s and early 1990s at CEN leading to the development of the detailed snowpack model Crocus (Brun et al., 1989, 1992). Due to the fact that avalanche hazard forecast does not only depend on the total snow mass or height but also on the internal structure of the snowpack, it was needed to develop a modeling framework allowing the representation of the time evolution of a vertically stratified snowpack within which snow layers could evolve independently, as a function of external (meteorological conditions, ground thermal state) and internal (thermal diffusion, phase change, compaction) driving forces. Over tools existing at the time of its creation, Crocus had the peculiarity to track snow layers in a time-evolving finite element grid (lagrangian tracking of layers) including dynamic re-meshing algorithms to secure sufficient vertical resolution near the surface of

the snowpack while respecting a given maximum number of numerical snow layers. This allows to represent the sharp contrast of physical properties of snow which can be encountered from layer to layer in the natural snowpack as can be seen on Figure 4 ; indeed, a more eulerian framework featuring a fixed vertical grid would lead to numerical diffusion of physical properties of snow from contiguous layers smoothing out the vertical profile of snow properties. The other main originality of Crocus was a quantitative representation of snow metamorphism, through the implementation of semi-empirical prognostic equations for the time evolution of ad-hoc variables named snow dendricity, sphericity, size and “hist”. Dendricity characterizes freshly fallen snow and varies from 0 to 1; it roughly represents the remaining initial geometry of snow crystals in the layer, and systematically decreases over time in a given layer. Sphericity varies between 0 and 1 and describes the ratio of rounded versus angular shapes. Both variables can be deduced from 2D image analysis (Lesaffre et al., 1998; Bartlett et al., 2008). Grain size attempts to represent the size of snow grains which can be measured through visual means (Fierz et al., 2009). An additional variable referred to as “hist” indicates whether there once was liquid water or faceted crystals in the layer. These four variables are generally termed the “grain” variables, and are used to diagnose the snow type (Brun et al., 1992). Even if this framework bears its own limits hampering further development (as will be seen below), it has to be recognized that efforts were made to identify state variables relevant to characterize snow microstructure the evolution of which could be inferred based on laboratory experiments. Some of them pre-existed the development of Crocus itself (Marbouty, 1980) and some were specifically designed to fill gaps in the range of conditions occurring in snow and that the model should be able to describe (Brunot, 1986). It must also be mentioned here that the development of Crocus was made possible through high-resolution monitoring of meteorological and snow conditions at the Col de Porte experimental site providing high-quality driving and evaluation data (Brun et al., 1989, 1992), and that further use of Crocus for French mountainous applications was fostered by the development of the meteorological analysis tool SAFRAN (Durand et al., 1993, 1999), which provides hourly records of meteorological variables needed to run Crocus within mountain ranges (massifs) assumed to be meteorologically homogeneous with an altitudinal variation represented by 300m-spaced elevation bands. Operational applications of Crocus for avalanche hazard warning were made possible through the parallel development of the MEPRA model providing a mechanically-based assessment of snowpack stability on a given slope with respect to natural and accidental avalanche release (Giraud, 1992; Durand et al., 1999).

It is not the purpose of the current document to describe in detail the breadth of scientific and operational applications that were permitted by the initial developments of Crocus (see Brun, 2011

and Brun, 2013 for such information). Briefly, the original version of Crocus was used for several studies lead by CEN researchers for snow hydrology (Braun et al., 1994), impact of climate change on snow conditions (Martin et al., 1997; Rousselot et al., 2012), glacier mass balance (Martin et al., 1996; Gerbaux et al., 2005), snow-wind interactions (Durand et al., 2001) and reanalysis of snow conditions in French mountain ranges (Durand et al., 2009a) using SAFRAN driven by the large-scale meteorological reanalysis ERA-40 (Uppala et al., 2005; Durand et al., 2009b). The Crocus model was shared with partner research institutions leading to applications in polar regions (Dang et al., 1997, 1998), coupling with microwave emission models (Wiesmann et al., 2000; Genthon et al., 2001; Brucker et al., 2011), the development of alternative models partly drawing on modeling principles specific to Crocus (Gallée et al., 2001; Bartelt and Lehning, 2002; Lehning et al., 2002), and use of Crocus for avalanche hazard forecasting applications in foreign countries (e.g. Iceland, Haraldsdóttir et al., 2001). An extensive list of known applications of Crocus is maintained and available on the internet².

1.6 From the stand-alone Crocus to SURFEX/ISBA-Crocus

Two facts need to be described that explain the current status of the Crocus snowpack model and its evolution in the recent years. Firstly, in the Spring 2008, V. Vionnet undertook a master internship under the supervision of E. Martin at CNRM-GAME/GMME (Toulouse) having as a mid-term goal the perspective of carrying out model runs with the mesoscale non-hydrostatic model Meso-NH (Vionnet, 2012; Vionnet et al., 2013, 2014) to explicitly simulate the coupling between the snow surface and atmospheric conditions in a mountainous environment accounting for snow-wind interactions. Such applications require that the physical properties of near-surface snow are explicitly simulated, because the susceptibility of snow to be eroded by the wind depends on its intrinsic physical properties (Guyomarc'h and Merindol, 1998). The land surface scheme used by Meso-NH is shared with other atmospheric models developed at CNRM-GAME through the SURFace EXternalisée (SURFEX) Earth surface scheme, which was specifically developed since the early 2000s as a voluntary effort to mutualize development related to surface processes for all Météo-France (and partners) atmospheric models used for coupled NWP, climate, large eddy simulations (LES) modeling and offline applications such as hydrology and climate change impact studies. SURFEX has become a shared surface processes modeling platform within CNRM-GAME with many fruitful interactions and perspectives (Masson et al., 2013). At the time of V. Vionnet master internship, only single-layer (Douville et al.,

²<http://www.cnrm-game.fr/spip.php?article268>

1995; Bazile et al., 2002) and intermediate complexity multi-layer (Explicit Snow; Boone, 2002) snowpack schemes were available in the land surface model Interactions-Soil-Biosphere-Atmosphere (ISBA Noilhan and Planton, 1989) integrated in SURFEX. V. Vionnet thus integrated key Crocus elements in ES, in particular the snow metamorphism routines and the ability to include more than the usual 3 to 5 snow layers in ES. Secondly, the first step of the integration of Crocus features in ES was complemented in the Spring 2009 when E. Brun, returning to basic research activities after about 10 years dedicated to more operational or management tasks, completed the integration of all Crocus-specific features in ES within the SURFEX/ISBA environment.

Upon my arrival at CEN in the Fall 2009 with a mission to pursue scientific developments of the Crocus model, it was straightforward to realize that carrying out scientific and technical developments in Crocus independently from ongoing SURFEX/ISBA-Crocus developments in Toulouse was not a viable option, for scientific and technical reasons. Scientifically, the integration of Crocus features within the ES multi-layer snowpack scheme (soon clearly separated as two independent snow modeling options in SURFEX/ISBA to not hamper the simplicity and cost-effectiveness of the ES scheme) induced several scientific advances to Crocus such as: the coupling with the multi-layer soil scheme ISBA-DIF handling thermal diffusion, water movement and phase change (Decharme et al., 2011, 2013), an improved and more robust numerical scheme allowing internal time steps up to 1 hour while running the stand-alone Crocus required using a time step of 15 min, and large potential for improvement through scientific developments not specific to Crocus but that Crocus could benefit from (e.g. snow vegetation interactions, data assimilation). Technically, including all Crocus developments within the SURFEX framework induced constraints linked to the need to share and phase technical and scientific developments with multiple teams, initially mostly within CNRM-GAME, while preserving the capabilities of the model across its various applications, ranging from operational NWP to climate modeling through detailed snow physics modeling in mountain regions. However, in the meantime and in the longer-term, this allows to benefit from shared technical and scientific expertise of the staff involved in SURFEX development and maintenance for improved model robustness and extended model testing. In this regard, I am indebted to J.-M. Willemet and M. Lafaysse (CEN) and P. Le Moigne and S. Faroux (CNRM-GAME/GMME) for sustained dedication in contributing to stabilize (from 2009 to roughly 2012) and develop (roughly from 2012 on) the Crocus implementation in SURFEX/ISBA, which was still needed after the early (but major) steps of its integration carried out by V. Vionnet and E. Brun in 2008 and 2009. The decision to use adequate version control software (*svn*) for the whole SURFEX code since 2012, the user-friendly input/output file formats (netCDF

based, Rew and Davis, 1990) and scientific and technical meetings organized by the SURFEX coordination team lead by E. Martin (GMME) have been strong assets for the sustainability of the code and the further expansion of Crocus development. My somewhat limited responsibility regarding such developments was to readily make the decision to carry out technical developments and use of Crocus at CEN within the SURFEX environment and actively contribute to scientific and technical discussions related to the code development as well as promoting the capabilities offered by this new implementation in the local, national and international scientific communities. A few specific developments were carried out under my direct action and supervision, and are described in section 2. In what follows, unless otherwise noted, Crocus is used to refer to SURFEX/ISBA-Crocus, i.e. the implementation of Crocus as a snow scheme of the land surface ISBA in the SURFEX environment.

2 Implementations of prognostic equations for the optical diameter of snow

2.1 A bit of terminology

Besides density, the basic geometrical characteristics of porous media can be represented by the ratio between the surface area of the interface between phases and the volume of one phase (typically the “most condensed one”), and higher order terms related to the curvature fields of the interfaces (Torquato, 2002). The surface area/volume ratio of snow, also referred to as the specific surface area (SSA), not only characterizes one of its key microstructural property but is also driving its radiative behavior. Although this has actually seldom been used in practice beyond stating its potential (Domine and Shepson, 2002; Domine et al., 2007; Barret et al., 2011), it is relevant to quantify physical and chemical processes occurring in snow at the ice surface. From snow SSA one can define the equivalent spheres diameter, d_{es} , which corresponds to the diameter of disconnected ice spheres having the same surface area/volume ratio in a given representative elementary volume (REV). Early work on the optical properties of snow (Giddings and LaChapelle, 1961) had already set the idea that in the near infrared (NIR - 0.75 to 1.4 μm) and short-wavelength infrared (SWIR - 1.4 to 3 μm) portions of the solar spectrum, where ice is significantly absorptive, the partitioning between scattering and absorption should depend on the surface area/volume ratio. Because radiative transfer schemes were developed accounting for simple geometry for the individual structural elements, and because in some cases individual elements of the snow microstructure can be geometrically viewed as ice spheres, initial snow radiative transfer modeling was carried out representing snow as a collection of disconnected ice spheres (Warren and Wiscombe, 1980; Sargent et al., 1987; Grenfell and Warren, 1999). It was found that using a given value of the diameter of these spheres in the calculations lead to match observed hemispherical albedo data in the NIR and SWIR (using independently measured spectrally resolved optical index of ice), and this value was termed the optical diameter of snow d_{opt} . Note that d_{opt} is sometimes also referred to as the optical grain diameter, although there is no need to invoke the concept of a grain to define this “diameter”, which has rather to be seen as an optically-relevant snow length scale (Grenfell and Warren, 1999). A formal equivalency between d_{es} and d_{opt} is theoretically not expected but there are hints from field and laboratory measurements where d_{es} and d_{opt} were measured independently (Domine et al., 2006; Gallet et al., 2009) that the values of the two variables can in many cases be considered equal. However, one has to keep in mind that these two terms are not strictly equivalent which may explain cases of discrepancies between different methods

seeking to measure d_{es} (hence SSA) through optical techniques using reflectance features of snow at selected wavelengths in the NIR and SWIR (Domine et al., 2006; Matzl and Schneebeli, 2006; Painter et al., 2006; Gallet et al., 2009; Arnaud et al., 2011). International collaborative work is needed and ongoing to improve the situation in this regard.

2.2 Situation at the beginning of the work

Since the early stages of its development, Crocus has included a representation of the optical diameter of snow, because its albedo scheme with one band in the visible, one in the NIR and one in the SWIR part of the solar spectrum, required an estimate of snow optical diameter to compute snow albedo (Brun et al., 1992). However, in the standard Crocus version, the optical diameter is not a prognostic variable but it is computed at each time step from the three variables used to describe snow microstructure besides snow density, namely dendricity (d), sphericity (s) and size (g_s). The time evolution of these variables depends on temperature, temperature gradient and liquid water content (Brun, 1989; Brun et al., 1992; Vionnet et al., 2012). Empirical formula were set up to compute the optical diameter d_{opt} from these three variables, most probably from laboratory observations lead by C. Sergent in the 1980s:

$$d_{\text{opt}} = \begin{cases} d + (1 - d)(4 - s) & \text{dendritic case} \\ g_s \times s + (1 - s) \times \max\left(4 \cdot 10^{-4}, \frac{g_s}{2}\right) & \text{non-dendritic case} \end{cases} \quad (1)$$

At the time of Crocus development, the estimate of the optical diameter from dendricity, sphericity and size was found sufficiently accurate to be implemented in the model and since then has been used to compute the NIR and SWIR albedo of snow (and a contribution to the visible albedo as well) taking into account the evolution of snow microstructure computed by the model. This intrinsic computation of d_{es} was used in several studies linking Crocus output to remotely-sensed observations, through various operation operators, in the solar visible and near infrared (Fily et al., 2000; Dumont et al., 2012; Mary et al., 2013) and passive (Wiesmann et al., 2000; Genthon et al., 2001; Toure et al., 2011; Brucker et al., 2011) and active (Longepe et al., 2009; Phan et al., 2014) microwave wavelengths ranges. There was a need, however, to better quantify how well Crocus predicts d_{es} . This has been made possible owing to technical development targeting the measurement of d_{es} (methane adsorption techniques at 77K, stereology, X-ray microtomography, optical methods (e.g. Domine et al., 2008)). A dedicated field campaign was organized in the winter 2009-2010 (shortly after my arrival at CEN) to document for the first time the time evolution of the vertical profile of d_{es} in alpine snow through a snow season at the experimental station Col de Porte (1325 m altitude, near Grenoble). Vertical

profiles of d_{es} were measured using the DUFISSS instrument, consisting of a integrating sphere to measure the hemispherical albedo of a given snow sample at 1310 nm, where it is most sensitive to d_{opt} - assumed to represent a measurement of d_{es} (Gallet et al., 2009). Following the measurement campaign and the generation of a quality-controlled in-situ meteorological data driving file carried out by Y. Lejeune, a Crocus run was performed. The output in terms of d_{es} , either calculated internally by Crocus using equation (1), or estimated from snow type and density following Domine et al. (2007), was compared to the field observations and demonstrated that the existing representation of d_{es} in Crocus was performing rather well with room for improvements (Morin et al., 2013a). However, I stated at the time that direct improvement of the model in this respect would be challenging if not impossible - or useless, because to improve the estimate of d_{es} in the model it would be needed to improve the time evolution of the microstructural variables of Crocus and/or the empirical relationship linking them to d_{es} . Instead, I had already in mind to renovate the snow metamorphism module of Crocus to incorporate a prognostic representation of d_{es} thereby removing the empirical variables dendricity and size, which was planned within the projet QUASPPER (“Quantitative Assessment and modeling of Snow Physical PropERTies”) that I submitted to CNRS INSU/LEFE in september 2009 and was funded from 2010 to 2012. This project associated CEN and LGGE scientists with the goal of improving d_{es} measurement capabilities - lead by LGGE scientists G. Picard and L. Arnaud, and improving Crocus d_{es} representation and evaluation against newly observed d_{es} data - lead by us. The snow observation programme and modifications and evaluations of Crocus formed the body of the PhD work of Carlo M. Carmagnola (Fall 2010 - Fall 2013, co-supervised with F. Dominé - LGGE, Grenoble then UMI Takuvik, Université Laval, Québec, Canada since summer 2011).

2.3 Implementation, evaluation and perspectives

A detailed description of the modifications that were performed in Crocus and their evaluation is reported in Carmagnola et al. (2014). Only the main facts and results are summarized here. As indicated above, the main technical development was to replace dendricity and size by d_{es} in the model code wherever these variables were invoked. Because dendricity and size were never simultaneously defined in Crocus (dendritic vs. non-dendritic regimes), a quasi bijective relationship was obtained by “inverting” equation (1). Once d_{es} had become a prognostic variable of the model, intrinsic prognostic equations could be seeked. First of all, in an attempt to perform only a technical update to the model structure, the dry and wet snow metamorphism laws were reformulated in terms of d_{es} , with almost similar results (one of the laws, actually, had a recursive dependency on grain size which could not

be translated in terms of d_{es}). The modification of the code also allowed to test alternative (dry) snow metamorphism prognostic equations already expressed in terms of d_{es} . We tested two of them, one derived from the Taillandier et al. (2007) empirical fits to observation data, although the functional form of the equation used is not easy to convert into a prognostic equation, as already recognized by Lehning (2009) and Morin et al. (2013a), and the other one from the SNICAR (Snow, Ice, and Aerosol Radiation) parameterization produced and provided by Flanner and Zender (2006). Model runs were evaluated against field observations at Col de Porte (2009-2010 and 2011-2012 season - the latter using a newly developed d_{es} profiler built through the QUASPPER project) and Summit, Greenland, where C. Carmagnola and F. Dominé had the opportunity to carry out measurements for a period of 2 months in May-June 2011 (Carmagnola et al., 2013). The model runs revealed that the results obtained using the three prognostic rate equations for snow generally differed less from each other than from between any of them and the observations, with various specific behaviors: for example the results obtained using the Flanner and Zender (2006) parameterization showed quicker d_{es} increase in near surface snow. In contrast, in seasonal snow the results obtained using the parameterization derived from Taillandier et al. (2007) lead to lower d_{es} values than the other d_{es} rate equations. This latter option leads to unrealistic results in the Greenland case, because the mathematical formalism of this equation is not adapted to handle long time periods (exceeding several months). This evolution of the code did not bring significant intrinsic scientific improvements to the model, because the work did not generate new knowledge with respect to the drivers of d_{es} variations in snow layers. It is however a significant technical advance allowing further progress in the understanding of factors governing initial d_{es} values in freshly fallen snow and their time evolution to be readily implemented and tested in the model. Moreover, while the standard Crocus made the task of data assimilation of d_{es} extremely cumbersome (Toure et al., 2011; Dumont et al., 2012; Phan et al., 2014), the fact that d_{es} is now a prognostic variable greatly simplifies assimilation methods operating on this variable. Assimilation schemes can now use d_{es} directly as a control variable, rather than developing assimilating schemes requiring to invert the relationship between d_{es} and dendricity (d), sphericity (s) and size (g_s).

3 Other developments targeting model evaluation and improvements in terms of physical properties

Long-term developments of a detailed snowpack model require a diagnostic of its capabilities in a given state, which can only be performed through a comparison of key physical variables with observations. Such studies are needed to assess the performance of the “base” (or initial) version of the model from which future developments may occur. Motivated by the need to assess the critical shortcomings of Crocus that needed to be addressed first when I started working on/with the model, I performed or contributed to several studies using the base version of the model in various contexts. Note here that by “base” version I refer here in general to the SURFEX version of Crocus which is actually a quite “new” model in which many aspects need to be carefully checked prior to any decision to carry out “improvements”. Indeed, cases could exist where planned model developments actually lead to performance decrease because of insufficiently documented model performance at the initial steps of the development.

3.1 Snow height and snow water equivalent

The most basic physical properties of snow are its height and water equivalent (SWE). The performance of snow models of various levels of complexity is generally assessed mainly through basic statistics (bias and root mean square deviation - rmsd) of simulation results vs. some local observations of snow height and SWE used as a reference. Although my own scientific contribution is probably not most significant here, I have put energy into evaluating Crocus in terms of basic statistics to ensure that using this version of Crocus did not induce a regression of performance with respect to the standalone version of Crocus used operationally hitherto, fed by the same SAFRAN forcing. This work was mainly lead by M. Lafaysse and I attempted to contribute as much as I could to compare snow height and SWE observations in as many as possible stations spanning the longest possible period of time. 83 observation stations were selected in the French Alps, covering the 1980-2012 period. Because the medium-term objective of this work was to perform model adjustment prior to the operational implementation of SAFRAN - SURFEX/ISBA-Crocus - MEPRA (S2M), it has not lead to a specific peer-reviewed publication, although I believe that it has occurred in only a few cases that a snowpack model was evaluated with such an extensive observational dataset. Indeed, the previous version of Crocus was mainly tested at Col de Porte using driving and evaluation data for a few seasons (Brun et al., 1989, 1992). The Snow Model Intercomparison Project (SnowMIP) (Etchevers

et al., 2004) used data for two snow seasons at Col de Porte, one at Weissfluhjoch (Switzerland), one at Sleepers River (USA) and 15 years from Goose Bay (Canada). In general, snowpack models were primarily evaluated either at only one site or for a very limited number of field stations. The situation improves with the increased availability of high-quality multi-year driving and evaluation datasets from snow-dominated sites or catchments (e.g. Reba et al., 2011; Morin et al., 2012b; Landry et al., 2014). Of course, in the case of the S2M observation sites, due to the fact that almost none feature the full suite of meteorological measurements needed to run Crocus, it is actually really the combination SAFRAN - Crocus that it tested. However, inconsistencies can occur between in-situ meteorological and snow measurements even performed with great care, not only due to instrumental malfunction but mostly because of processes inducing heterogeneity (preferential deposition of precipitation, wind drift, uneven, shadowing etc.) (e.g. Morin et al., 2012b; Wever et al., 2014). It is thus very complicated to evaluate snowpack models only, because of the large amount of potential uncertainty in the driving and evaluation data set.

Thanks to my involvement in the scientific management of the Col de Porte and my will to make this unique data set as widely used as possible as a tribute to field observers and a service to the community (Morin et al., 2012b), I have participated in several studies addressing model evaluation from a multi-year perspective using data from this site. The first example is probably the evaluation of SURFEX/ISBA-Crocus at Col de Porte, which is reported in Vionnet et al. (2012) and used 9 years of quality-controlled driving and evaluation data from Col de Porte (restricting the available 18 years dataset to years with most recent years with daily SWE measurements available). It was readily shown that in terms of snow height and SWE, statistics exhibited a very large year-to-year variability (see Figure 7). A previous intercomparison between Crocus and ES at Col de Porte indicated that SWE and snow depth were significantly better simulated by ES than Crocus at this site for one season (see e.g. Table 2 of Boone and Etchevers, 2001). Results shown on Figure 7 and in Vionnet et al. (2012) indicate that such a significant discrepancy no longer exists with the SURFEX implementation of Crocus and that both schemes perform satisfyingly and with comparable levels of performance. ES tends to perform better in terms of SWE, while Crocus performs slightly better in terms of snow height. This shows that in terms of bulk variables such as snow height and SWE, there is little to gain between an intermediate complexity model (ES here) and a more sophisticated snowpack model (Crocus here).

This analysis was further refined by Essery et al. (2013) showing that depending on the year chosen for the evaluation of a snowpack model of intermediate complexity (using here 4 snow seasons

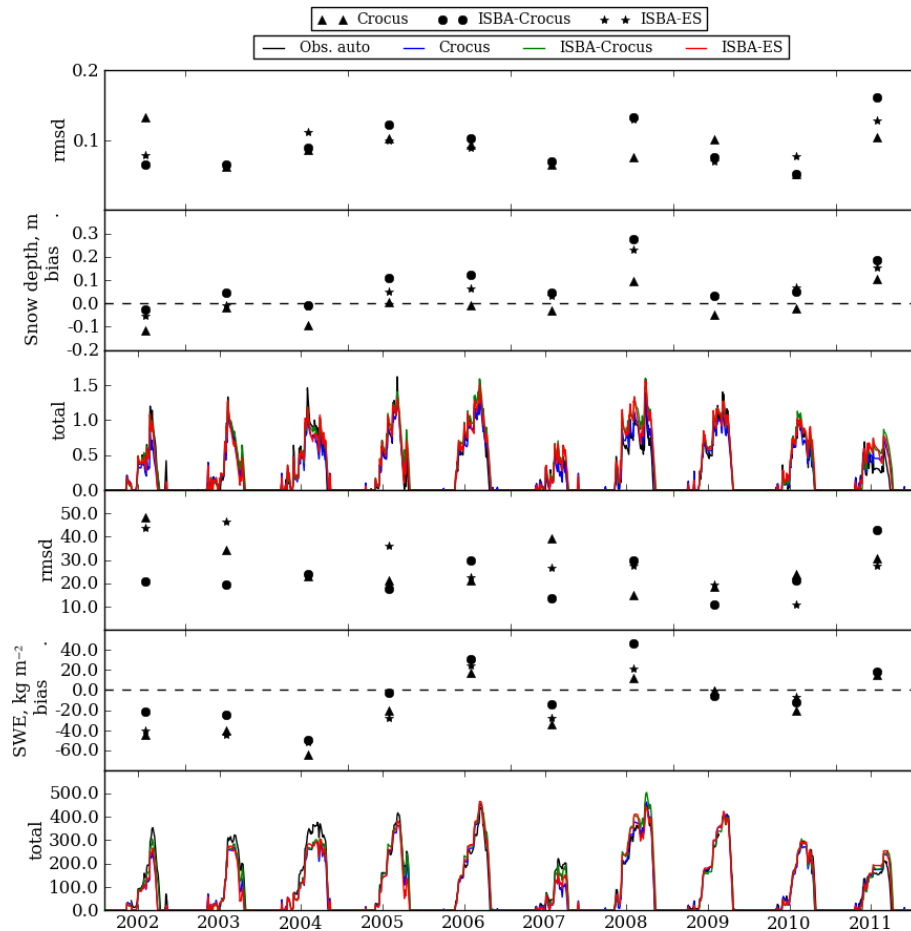


Figure 7: Overview of nine years of simulation at Col de Porte, France. Simulated data for snow depth (top) and SWE (bottom) are provided for two model runs with two snowpack schemes within SURFEX (ES and Crocus), compared to daily in-situ data (from Vionnet et al., 2012).

at Col de Porte from 2005-2006 to 2008-2009), the choice of parameters and even of degree of complexity yielding the best results in terms of scalar variables (snow height, SWE, albedo and surface temperature) could be different, implying that efforts in further developments of model physics may not lead to improvements of the performances in terms of such integrated variables, as long as the degree of complexity is sufficient. Such developments, targeting improvements of the physical consistency of the models, should be aimed at scientific applications requiring better in-depth understanding of physical processes at play, including feedbacks involving snow metamorphism and deposition of impurities, that intermediate complexity models with their mostly density-based parameterizations cannot address. Potential for assimilation of remotely-sensed observation can also drive the need to use detailed snowpack models (see section 1.4.4). This study has also clearly demonstrated the need to carry out multi-year assessments of snowpack model performance, because individual years may

exhibit a peculiar behavior due to specific meteorological conditions but also are more sensitive to inconsistencies between driving and evaluation data, and to the errors they both hold.

In parallel to these developments and applications at alpine sites, I have been involved in large scale experiments using Crocus, in particular through the efforts lead by E. Brun to evaluate the combination ERA-Interim - Crocus against station data from the former USSR in Northern Eurasia, spanning a wide range of snow conditions during several years (especially in the 1980s regarding the overlap with ERA-Interim reanalysis data starting in 1979). It was found that ERA-Interim provides 3-hourly meteorological driving data which, combined with Crocus, lead to generally very robust snow simulations against open field station data (Brun et al., 2013). This driving and evaluation dataset, together with the Col de Porte one, was further used by Wang et al. (2013) to evaluate an intermediate complexity snow model in the IPSL ORCHIDEE land surface model, thereby bridging a gap between the level of complexity of ORCHIDEE in terms of soil processes, and the rather rough snow component of the standard version of ORCHIDEE. As will be shown below, using a snowpack model of at least intermediate complexity is not only critical for snow processes themselves (Essery et al., 2013) but also for the surrounding model components such as the ground thermal regime and the feedback to the atmosphere.

3.2 Effective thermal conductivity

At the time when I started working on snow physics with F. Dominé at LGGE Grenoble from the Fall 2008 to the Summer 2009, he proposed me to focus on the thermal properties of snow on which he had started working a few years before. F. Dominé was then expanding the scope of his research on snow from a reactive chemistry perspective to a broader ranging interest in the role of snow in the climate system. In this context, studying the relationships between the effective thermal conductivity, snow metamorphism and meteorological conditions is a pivotal research area due to the overwhelming role played by the insulating properties of snow in terms of the thermal regime of the underlying ground and associated feedback loops with the environment (permafrost, vegetation, atmospheric conditions, hydrology etc.) (Zhang, 2005). While measuring snow density is relatively straightforward in most snow types as long as a sufficiently large snow volume is sampled (Conger and McClung, 2009), measuring the effective thermal conductivity of snow is more challenging.

The heated needle probe technique, also known as the transient heat probe, is a popular method to measure the thermal conductivity of materials (Blackwell, 1954). It consists in measuring the temperature rise of a straight heated metal wire inserted into the medium, following the intuitive

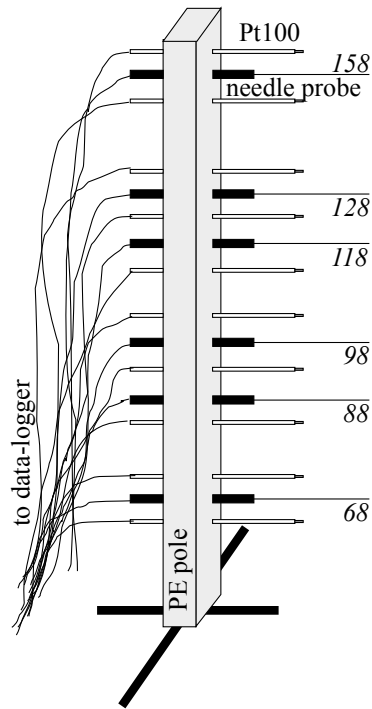


Figure 8: Design of the field experiment carried out to measure the temporal evolution of the thermal conductivity of snow near the Argentière glacier in the winter 2008-2009. 6 needles probes were installed at fixed heights at 68, 88, 98, 118, 128 and 158 cm above ground on a 2 m high white polyethylene pole. Pt100 temperature sensors were installed 5 cm above and below each needle probe (from Morin et al., 2010).

expectation that for a given heating rate, the lower the thermal conductivity the higher the resulting temperature rise. In general, a uniform heating rate is applied to the heated section of the needle for a constant period of time. The heat-diffusion equation can be analytically solved for this geometry under the assumption that the wire has an infinite length, is in perfect thermal contact with the medium, which is further assumed to be isotropic and homogeneous. The heated needle probe technique has long been used in snow for measuring its effective thermal conductivity k_{eff} (see e.g. Sturm et al., 1997, for a review). This requires a careful examination of the probe characteristics (size, heating rate, heating time...) in relationship to the thermal properties of the snow. It has been reported that k_{eff} exhibits a large scatter around the density regression curve according to the widely used compilation of data provided by Sturm et al. (1997).

The most ambitious research project initiated during the rather short post-doctoral period together with F. Dominé was to monitor as continuously as possible the time evolution of k_{eff} in snowpack. This required to embed needle probes in the snowpack and let them operate at regular time intervals throughout the snow season and thus carry out repeated measurements of the “same” snow layer. Such an achievement was made possible thanks to the key contribution of L. Arnaud (LGGE) who provided a method to multiplex needle-probes to a common datalogger, allowing to carry out measurements with up to 10 probes in the same snowpack at various heights above ground (see Figure 8). Temperature probes were also included on the vertical mast hosting the needle probes. The main experimental results of this campaign, carried out near Argentière glacier in the Mont-Blanc area during the winter 2008-2009, were reported in Morin et al. (2010) and are summarized in Figure 9. Under most situations, k_{eff} was found to increase over time. Whenever the probe was in contact with freshly fallen snow, the measured k_{eff} was on the order of 0.04 to 0.06 $\text{W m}^{-1} \text{K}^{-1}$. The values of k_{eff} then progressively increased over time. As shown on Figure 9d, the temporal rate of change of k_{eff} was maximum shortly after snowfall for a given snow layer (rates typically above 0.005 $\text{W m}^{-1} \text{K}^{-1} \text{day}^{-1}$), then decreased over time within the 0.000 – 0.005 $\text{W m}^{-1} \text{K}^{-1} \text{day}^{-1}$ range. Such variations led to k_{eff} values on the order of 0.15 to 0.25 $\text{W m}^{-1} \text{K}^{-1}$ only a few weeks after snowfall, highlighting that thermal properties of snow layers evolve quickly and significantly over time. Although the general trend of increase appears quite similar, it is worth mentioning some differences in the temporal rate of increase of k_{eff} as a function of snow type. For instance, the probe situated at 88 cm above ground had a higher initial k_{eff} , on the order of 0.10 $\text{W m}^{-1} \text{K}^{-1}$. According to the stratigraphic profile carried out a few meters from the vertical array of probes, this probe sampled the temporal evolution of a dense layer with small rounded grains. In contrast, the probes situated

above (> 98 cm above ground) were exposed to a combination of decomposing particles and rounded grains. These layers exhibited lower initial k_{eff} values (on the order of $0.05 \text{ W m}^{-1}\text{K}^{-1}$), but then k_{eff} increased more rapidly than in the denser layer described before, consistent with the laboratory investigations of Satyawali et al. (2008). The two probes situated at 98, 118 cm above ground show parallel k_{eff} time series, illustrating that they were undergoing similar rates of metamorphism under very similar conditions. The probe situated 128 cm above ground show an even faster increase in k_{eff} over time: initially situated in a layer exhibiting a lower density than snow layers below, it underwent quicker metamorphism over time, which eventually led to higher k_{eff} values than other probes. The rate of increase of k_{eff} is therefore highly dependent on the initial microstructure of the snow layers, in addition to obvious other environmental variables such as the temperature gradient.

Although it was deemed too preliminary to be included in the peer-reviewed publication describing these measurements and the main results (Morin et al., 2010), a Crocus (stand-alone version) model run was carried out at the experimental site using in-situ meteorological data and its output was compared to field measurements of k_{eff} (Morin et al., 2009). It was found that Crocus model output were consistent with density measurements and generally similar features in terms of k_{eff} were observed but the analysis remained preliminary (see Figure 10).

The main caveat of the experimental system used at Argentière was to place needle-probes at a fixed height without allowing them to move vertically, which lead to bending the inner end of the needles and made it impossible to position them accurately during the data analysis (although, given that the needles remained straight, it is believed that they continued to operate normally and provided appropriate measurements). The following year, an alternative method was employed to maintain needle-probes in a given snow layer through time. The experiment was carried out at Col de Porte, where the data acquisition from Argentière was relocated, and needle-probes were then attached to "snow gliders", i.e. white plastic horizontal plates (including holes to minimize thermal disturbances in snow) allowed to move vertically and following snow settling. This system did not include a vertical positioning system requiring frequent field visits to manually monitor the vertical position of the sensors. In addition, temperature sensors were fixed 5 cm above and below each needle probe. The results from this season-long experiment have to date not been fully analyzed besides a synthesis of the k_{eff} values obtained vs. time since snowfall, reported by Morin (2010) in the journal of the French snow and avalanche association (ANENA - Neige et Avalanches), summarized in Figure 11.

The main reason why a comprehensive data analysis has not been pursued hitherto stems from the fact that doubts have been cast on needle-probe measurements, especially when they were compared

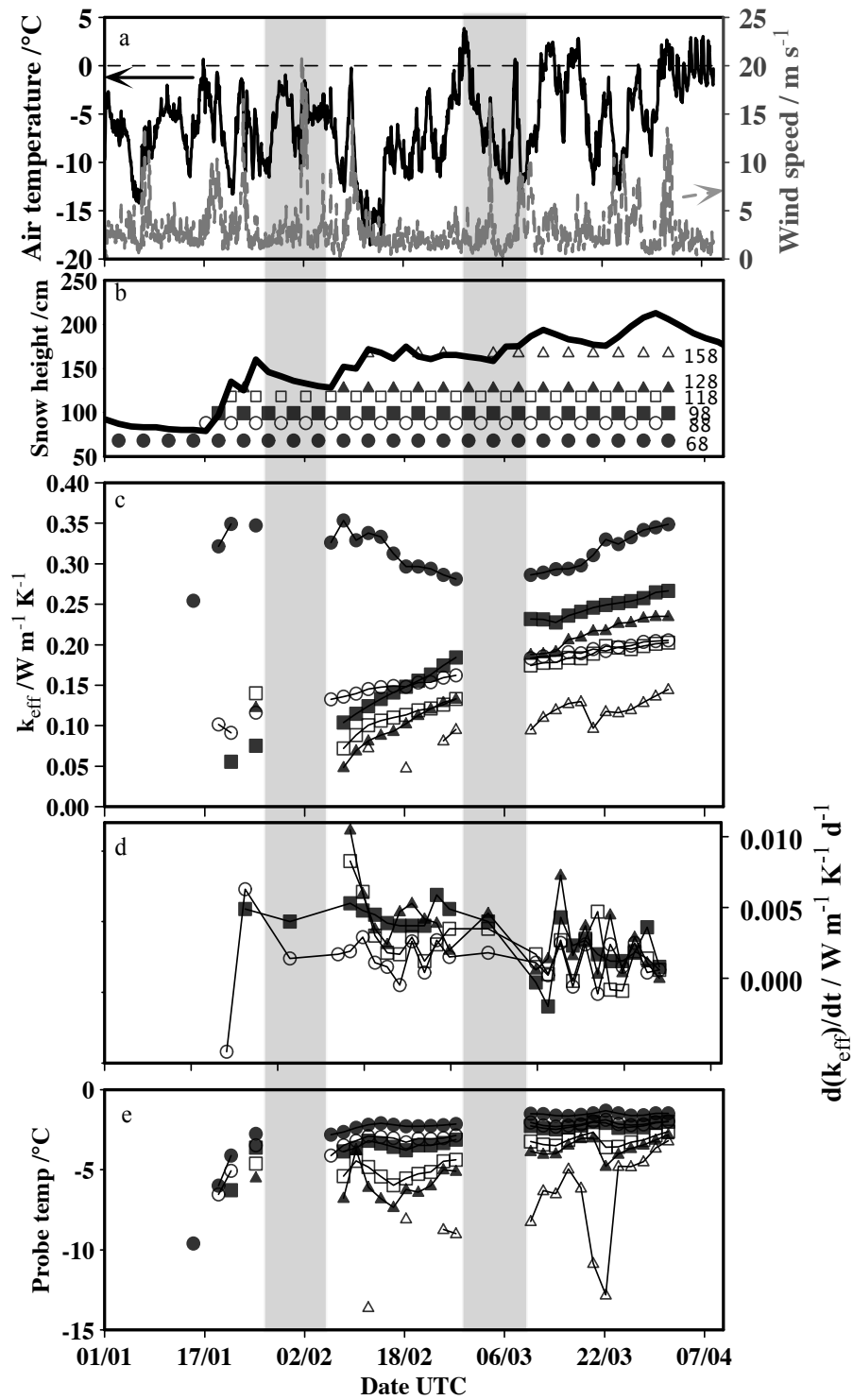


Figure 9: Overview of the meteorological data and of snowpack thermal properties recorded during the field campaign near Argentière glacier in the winter 2008-2009. (a) wind speed and air temperature measured using the automated meteorological station, (b) snow height and the location of the needle probes, (c), (d) and (e) measured k_{eff} values, the temporal rate of change of k_{eff} and the corresponding snow temperature values, respectively, using the same symbols as in (b). The error on the measurements is smaller than the symbols used. Vertical shaded areas represent periods of interruption of the automated measurement protocol due to too high snow temperatures (from Morin et al., 2010).

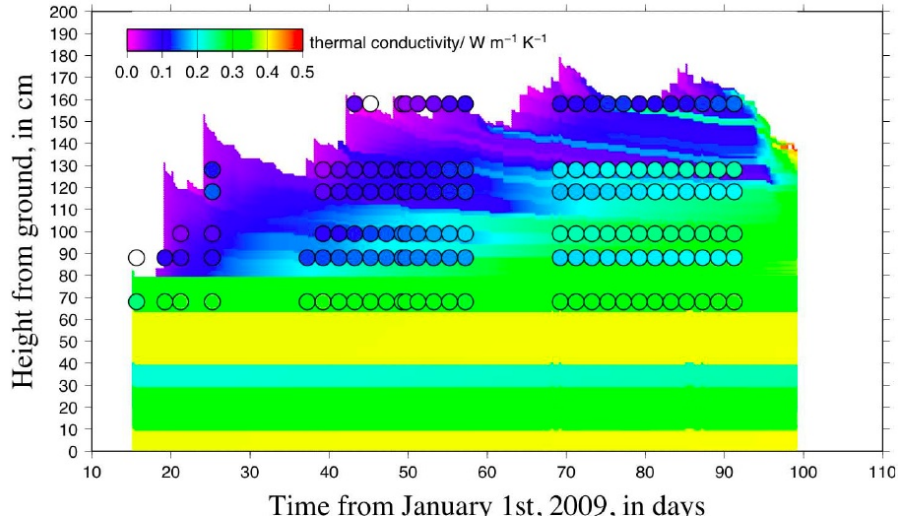


Figure 10: Results of a stand-alone Crocus model run using in-situ meteorological driving data measured close to the experimental site at Argentière in the winter 2008-2009, together with field measurements of the effective thermal conductivity of snow (from Morin et al., 2009).

to estimates of k_{eff} from micro-tomographic images accounting only for purely diffusive processes in ice and air. The feasibility for such computations was demonstrated by Kaempfer et al. (2005) although they focused on heat transfer solely through the ice matrix. New computations from micro-tomographic images were carried out during the Master 2 internship of N. Calonne in the spring 2011, co-supervised with F. Flin (CEN) in collaboration with Ch. Geindreau (3S-R, Grenoble). The goal of the internship was to compute k_{eff} for over 30 3D-images of snow already available in the database produced over the years by the microstructure group within the snowpack team at CEN, using computational tools available at the 3S-R laboratory (in particular the Geodict periodic homogenisation software) which allow to account for heat transfer through ice and air. The main outcomes of this internship, summarized in Calonne et al. (2011), was that (i) k_{eff} estimates from micro-tomographic images exhibit a very strong relationship with snow density ($k_{\text{eff}} = 2.5 \times 10^{-6} \rho^2 - 1.26 \times 10^{-4} \rho + 0.024$), very close to the Yen (1981) regression curve ($k_{\text{eff}} = 2.22 \times (\rho_{\text{snow}}/\rho_{\text{water}})^{1.88}$), (ii) k_{eff} estimates from micro-tomographic images were very different from needle-probe measurements in the same snow sample and (iii) that k_{eff} displays significant anisotropy, related to snow type. Figure 12 summarizes the results of this work. Riche and Schneebeli (2013) have since then confirmed these conclusions using a larger set of samples.

As deliberately stated in Calonne et al. (2011), resolving the discrepancy between needle-probe and microtomography estimates of k_{eff} requires in-depth studies of the physical processes occurring

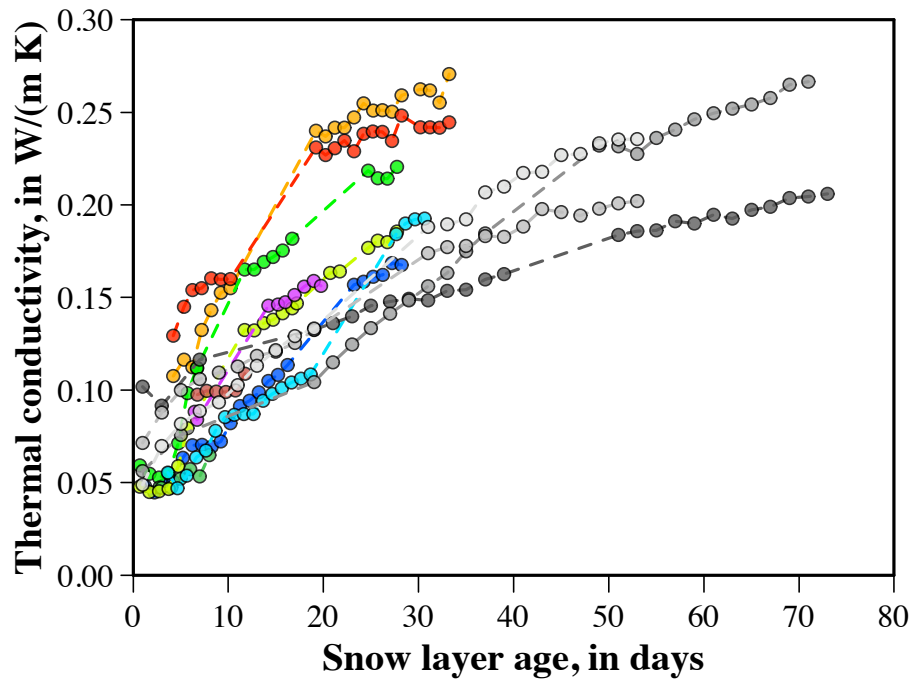


Figure 11: Overview of k_{eff} values obtained vs. time since snowfall in Argentière (2008-2009 ; grey symbols) and at Col de Porte (2009-2010 ; colored symbols) (from Morin, 2010).

around a needle-probe during a measurement, which still needs to be carried out through an explicit numerical simulation of the thermal field around a needle probe in a “true” microtomographic image of the microstructure of a snow sample.

Even if the “final” word on needle probe measurements is probably not to be said within years, it is already tempting to analyze variations between k_{eff} measurements carried out at various places using the same experimental method and compare them with alternative snow measurements. In this regard, I contributed to the data analysis of field measurements of k_{eff} , SSA and snow stratigraphy data from the Arctic campaign OASIS (Ocean - Atmosphere - Sea-Ice - Snowpack interactions) at Barrow, Alaska, in the spring 2009 which were reported by Domine et al. (2012) in the *J. Geophys. Res.* OASIS special issue in support to more advanced reactive chemistry studies requiring description of the physical properties of snow during the measurement campaign. However, there has not been yet a specific snowpack modeling effort to attempt to evaluate whether existing snowpack models driven by in-situ (or reanalysis) meteorological data are able to reproduce the observed features of tundra snow conditions encountered there. The numerous field data acquired in collaboration with F. Dominé in terms of k_{eff} but also density and shear resistance (measured using the CEN shear vane) was used to study the links between these three variables, not surprisingly revealing that k_{eff} was better correlated

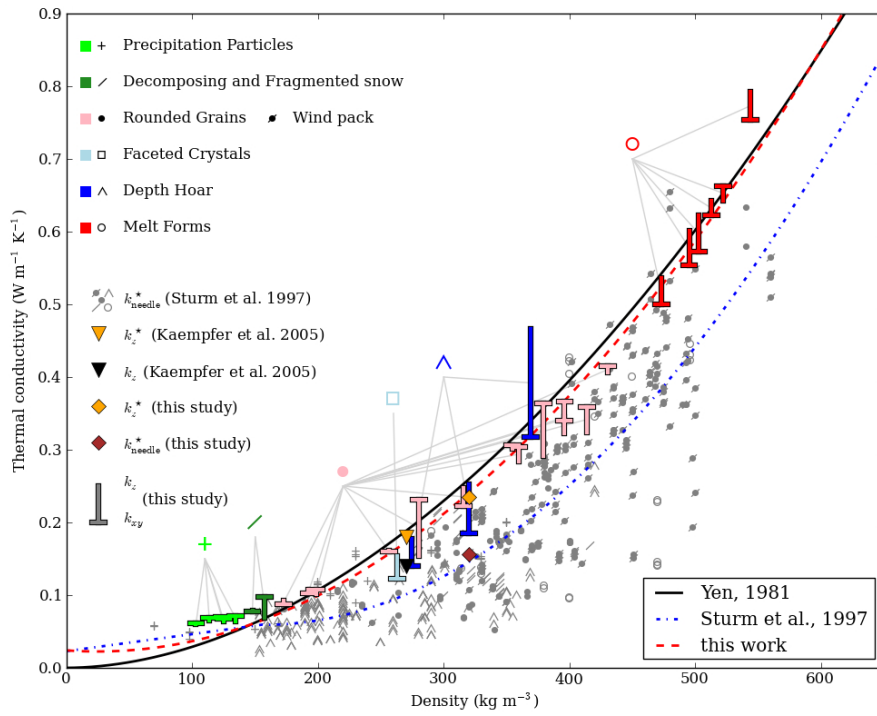


Figure 12: Overview of the results of Calonne et al., 2011 showing the good correlation between the effective thermal conductivity of snow and snow density calculated from microtomographic snow images. The scatter is significantly lower than needle-probes observations by Sturm et al. (1997). See text section 3.2 for details.

to a combination of density and shear resistance than density itself, due to the fact that mechanical bonds in the snow microstructure probably favor both heat transfer and mechanical resistance for the same given density (Domine et al., 2011). This study requires further refinement probably using microtomography images and micro-mechanical modeling, which is beyond my expertise and may only take place through collaborations. Note also that the body of field measurements of k_{eff} measurements compiled by F. Dominé and myself in relationship with environmental conditions (including wind speed) was used in an original way by Lecomte et al. (2013) to study the impact of snow thermal properties on sea-ice growth and thermodynamical behavior, demonstrating that not only snow on the ground, but also snow on sea ice, would benefit from improved representations of heat transfer processes.

3.3 Intrinsic permeability

Accurate predictions of snow permeability values are needed prior to any explicit representations of transport processes in snowpack models. The relationship provided by Shimizu (1970), which relates permeability K (in m^2) to the visually determined grain radius r_{vis} and snow density ρ (in units of m and kg m^{-3} , respectively), has probably been the most widely used:

$$K = 0.308r_{\text{vis}}^2 e^{(-0.0078\rho)} \quad (2)$$

even though it was obtained on a limited number of snow types so that its general validity has been questioned (Jordan et al., 1999). Quite similarly to what has been undertaken for the effective thermal conductivity of snow, snow permeability can be derived from micro-tomographic images (Freitag et al., 2002; Courville et al., 2010; Zermatten et al., 2011, 2014). Using the same samples that were used for the effective thermal conductivity of snow (plus a few additional ones) to compute snow permeability, Calonne et al. (2012) proposed the following regression curve (see Figure 13):

$$K = (3.0 \pm 0.3)r_{\text{es}}^2 \exp((-0.0130 \pm 0.0003)\rho) \quad (3)$$

The QUASPPER project originally included the planned construction of an instrument to measure snow permeability, based on the design introduced by Shimizu (1970) and later replicated by Jordan et al. (1999) and Arakawa et al. (2009). However, limitations of the experimental device in the case of highly layered snow due to the large size of samples which can be measured, and the good quality of the regression curve obtained by Calonne et al. (2012) based on over 30 snow samples spanning most seasonal snow types, has finally lead to the decision not to build a new field permeameter. Focus was rather shifted on the potential applications of the regression curve reported by Calonne et al. (2012) within snowpack models. Since Crocus was found to reasonably predict snow density and the equivalent spheres radius, it was tempting to directly use equation (3) to compute the snow permeability using Crocus output. An original dataset acquired by F. Dominé during a year-long stay in Fairbanks AK (USA) was used to compare the model output with field measurements of density, d_{es} and permeability. The additional originality of this data is that snow samples were collected both in snow on the ground but also from a snowpack which was developed on top of tables, deliberately attempting to suppress the macroscopic temperature gradient in snow which is generally found in Arctic and sub-Arctic seasonal snow. Thus, the same meteorological conditions drove the time evolution of a natural and modified snowpack, exhibiting caricatural temperature gradient and equi-temperature metamorphism patterns, respectively. Because of the fact that density and r_{es} play opposite roles in determining

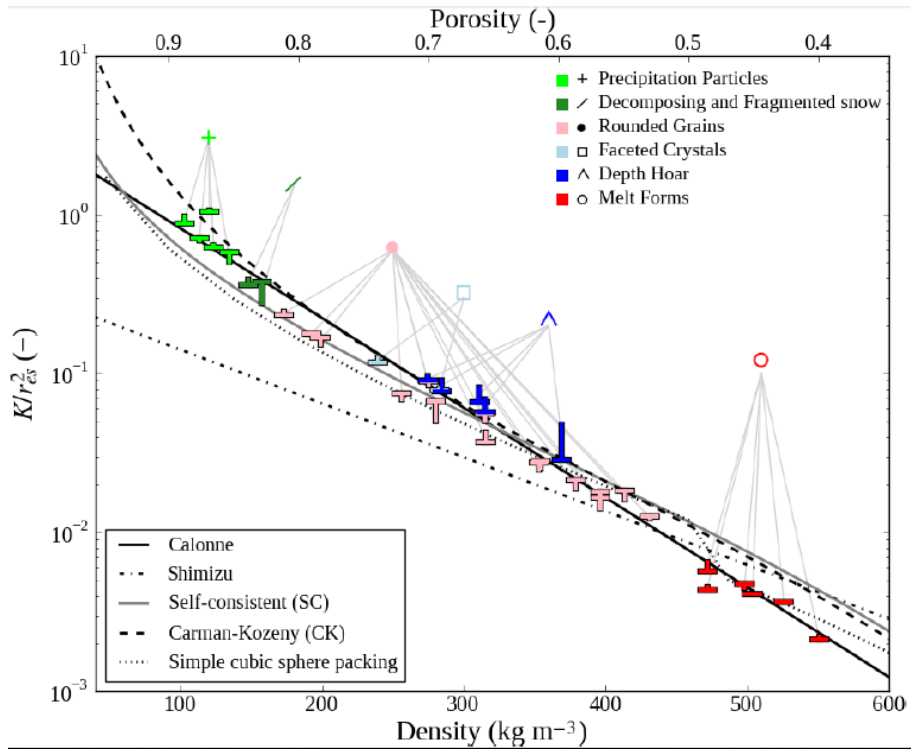


Figure 13: Dimensionless permeability (K/r_{es}^2) vs. snow density. “T” symbols indicate the computation values. Tips and horizontal bars of the “T” shapes represent the vertical and horizontal components of K/r_{es}^2 , as computed in this study, respectively. Colors correspond to the International Classification of Seasonal Snow on the Ground (Fierz et al., 2009). Analytical models, numerical computations and several empirical fits are also plotted (from Calonne et al. (2012)).

snow permeability (see Eq. (3)), and that both are generally found to increase over time through snow metamorphism, predicting the sign of the time variations of K is not trivial. It was experimentally found that in the first case, intense temperature gradient metamorphism lead to an increase over time of the permeability of snow, while in the second case, the permeability of snow tended to decrease over time. Crocus simulations fed by meteorological driving data extracted from the ERA-Interim (Dee et al., 2011) reanalysis (Brun et al., 2013) were found to reproduce the observed behavior, although a quantitative agreement between K estimates was not reached better than a factor of two (especially in the case of depth hoar layers developing at the base of snow on the ground). However, given that K subtly depend on ρ and r_{es} , and that K measurements are not believed to be very accurate for various experimental reasons (including REV issues for highly layered samples), this study gives credence that snow permeability estimates from density and d_{es} could be used to explicitly implement transport processes depending on snow permeability in a snowpack model in a more physically-based manner

(Domine et al., 2013). This concerns in particular air movement in snow (wind-pumping etc.) and liquid water movement (percolation). Note that in the latter case, Wever et al. (2014) have used this approach to compute the permeability of snow layers in the detailed snowpack model SNOWPACK, which is needed to implement the 1D Richards equation for liquid water movement in snow.

3.4 Towards explicit representations of radiative transfer in snow

Improving the representation of physical processes in a detailed snowpack model is one of the main goal of snowpack modeling. Although better predictions are generally sought and form the motivation for such developments, it may not lead to better predictions of the profile of the physical properties of snow, but it should make physically more consistent predictions, allowing further improvements through model adjustment and for which data assimilation frameworks should work better than for less-physically based representations of processes. My work has so far not lead to major improvements of physical processes in Crocus, because of the time invested in the above-mentioned studies attempting to diagnose the performance of the model in a range of environments. The main development that has taken recently place in Crocus in terms of snow processes is the development of a two-stream, spectrally resolved, radiative transfer scheme explicitly accounting for the vertical profile of the physical and chemical properties of snow layers and of the spectral and angular characteristics of incoming solar light. The so-called TARTES (Two-stream Analytical Radiative TransfER in Snow) algorithm was developed by G. Picard, Q. Libois (LGGE) and M. Dumont (CEN) during the ANR JCJC MONISNOW project (lead by G. Picard for the period from 2011 to 2015, in which I am involved), and implemented in Crocus by M. Lafaysse. Scientific details regarding TARTES can be found in Libois et al. (2013). Crocus runs using TARTES are currently tested, mainly by Q. Libois, but are limited to areas where the impurity content of snow play a marginal role - which is the case on the Antarctic plateau. Using TARTES in mid-latitude areas requires in the first place a realistic representation of the impurity content of snow, which is currently only in a prospective stage as of now (see below). Besides better representations of the impact of impurities and snow microstructure on the energy and mass balance of the snowpack, using TARTES opens the way to direct assimilation of spectrally-resolved visible and NIR remotely-sensed data, and is the main focus of work undertaken by M. Dumont at CEN.

4 Scientific applications independent of intrinsic model developments

4.1 Representation of topography

The traditional use of Crocus within the SAFRAN - Crocus - MEPRA model chain (Durand et al., 1999) uses a conceptual representation of topography (massifs, altitude levels, slopes and aspect classes) which features many advantages for large scale applications, including operational activities, and is consistent with both the spatial resolution of global or regional NWP or climate models and the scarcity of ground observations. However, many local applications of the model in mountainous environment require the capability to explicitly represent topography (including slope and aspect of grid points) on 2D grids. In addition, the last generation of NWP and regional climate models now feature horizontal resolution of the order of a few km which is not anymore consistent with the massifs scale used by SAFRAN. The technical part of the development allowing to run Crocus in a fully distributed manner has been almost entirely taken care of by M. Lafaysse, adapting routines developed by several people including Y. Lejeune, V. Masson and V. Vionnet, in a manner that makes it numerically efficient, compatible with the parallel nature of the SURFEX and relatively easy to setup and use allowing a wide range of applications for a variety of users. This development is virtually finished, and will be used from the onset of a research project targeting hydrological forecasting in the Mont-Blanc area, forming the body of the work of PhD student G. Lecourt starting in the Fall 2014 (co-supervised by I. Zin from LTHE, M. Lafaysse and myself).

4.2 Glaciological applications

4.2.1 Context and previous work

Crocus has long been applied to glacier environments, because the latter are frequently snow covered, making Crocus an appropriate tool to study the surface energy and mass balance of glaciers. In addition, ice can be seen as very dense snow to some extent (at least thermodynamically, thermally and optically), so that adapting the surface energy and mass balance of snow to that of firn or bare ice is conceptually rather straightforward. The first known use of the SAFRAN - Crocus combination for glaciological applications in the French Alps was on the Sarennes glacier by Martin et al. (1996). For such applications, the ice/firn/snowpack continuum is modeled as a thick snowpack with very dense layers at the bottom. Gerbaux et al. (2005) have computed the long-term mass balance

of the St Sorlin glacier in the French Alps using a distributed version of SAFRAN - Crocus (i.e., altitude-interpolated SAFRAN meteorological fields on a regular grid of points on which Crocus was run, taking into account the solar masks of each grid point) and found satisfactory agreement with glaciological measurements (pending appropriate scaling of SAFRAN precipitation fields). Lejeune (2009) developed a similar tool to study the mass and energy balance of the Zongo glacier in Bolivia using driving data from in-situ meteorological stations and evaluating the results against in-situ measurements of the glacier mass balance and streamflow of the associated river. Note that for this work, due to the fact that not only glaciated but also moraine parts of the catchment contributed to runoff, it was needed to use a version of Crocus coupled to the ISBA land surface scheme (Lejeune et al., 2007; Wagnon et al., 2009). Unfortunately, these development were not phased with the inclusion of ISBA in SURFEX, and the fact that the Crocus component of SURFEX/ISBA is *not* a direct coupling of the existing stand-alone Crocus with ISBA (which is what was done by Lejeune et al. (2007) based on developments carried out by Bouilloud and Martin (2006), and previously and somewhat independently by Etchevers et al. (2001)) but rather an expansion of ISBA-ES to include Crocus scientific features while preserving ISBA-ES algorithmic and technical superiority. Although this is currently a work in progress, I have initiated the consolidation of the possible use of SURFEX/ISBA-Crocus for glaciological applications taking into account the benefits of the earlier developments of Gerbaux et al. (2005), Lejeune (2009) and Dumont et al. (2012), while using the extended portability of SURFEX and the more convenient handling of input/output of data.

4.2.2 Recent applications and perspectives for glaciological applications

Glaciological applications should directly benefit from the 2D mode described in section 4.1, allowing to take into account specific developments aimed at representing the fact that bare ice has different surface properties (albedo, roughness, etc.) than snow, which is important for year-long simulation where snow in glacier ablation areas completely disappears during the melt period. In addition, many scientific aspects remain to be addressed including mostly : (i) hydrology within the glacier, (ii) water routing and redistribution of ground water in complex topography, and (iii) accounting for glacier flow. The first item may strongly suffer from a flaw of the water percolation scheme of Crocus, because the water retention capacity of snow layers with near-zero porosity (used to represent ice) is negligible, leading to immediate water flow through ice layers which is unrealistic in several cases. Nevertheless, I have contributed to at least two studies attempting to use Crocus to simulate the energy and mass balance of small ice-sheets in Northern Canada (Dupont, 2013; Gascon et al., 2014), where this is-

sue was particularly critical requiring specific model adaptations to circumvent this issue in a case of superimposed ice formation and lateral flow of liquid water due to the (observed) quasi-impermeable nature of the ice layer that Crocus could not handle due to its current design (Dupont, 2013). The second item may be addressed using existing water redistribution schemes based on topography indices (Audard-Vincendon, 2010) but remains to be tested in high mountain environments. The last one is currently not addressed and will require collaboration with ice flow specialists. In the case of Alpine glaciers, this issue becomes critical only for time scales extending over several decades (and would thus be relevant for studies willing to use the scientific features of Crocus in terms of surface energy and mass balance for long-term glaciological reconstructions or climate projections).

4.2.3 Debris covered glaciers

Beside the technical perspectives on glaciological applications of Crocus, it is worth to mention an original development of Crocus in the field of debris-covered glacier, initiated by Y. Lejeune and P. Wagnon that I supported scientifically and technically in particular during the internship of J.-M. Bertrand in the spring 2011. Debris-covered glaciers constitute an important scientific challenge especially in the Himalayas, although some debris-covered glaciers can be found in other regions as well. Rock debris lying on top of glacier ice have opposed effects on the surface energy balance : their lower albedo tend to increase solar absorption, but their effective thermal conductivity lower than that of ice has an insulating effect counteracting the solar radiation impact. Depending on the thickness of the debris layer, either the radiative or thermal effect dominate leading to the so-called Østrem (1959) curve where, in comparison to a bare ice glacier, the melt rate initially tends to increase with increasing debris thickness to a maximum value, and then decreases. The ability for an energy balance model to represent this behavior requires that the heat diffusion equation is explicitly solved in the debris and ice layers, and that the albedo of the surface depends on the cover type. Over alternative existing models (e.g. Reid and Brock, 2010), the main interest of implementing debris layers in Crocus as snow layers with peculiar physical properties is that the model could handle a transient snowpack on top of the debris layer and that the temperature at the base of the debris need not be fixed at the melt temperature (see Figure 14). Both features make it an appealing tool to perform year-round simulations of the surface energy and mass balance of a partially debris-covered glacier (Lejeune et al., 2013). The last step of this development is now to implement it in the SURFEX version of Crocus, allowing its use together with the future consolidated 2D framework for running SURFEX in glacier environments with a complex topography and heterogeneous surface cover (glacier, moraine,

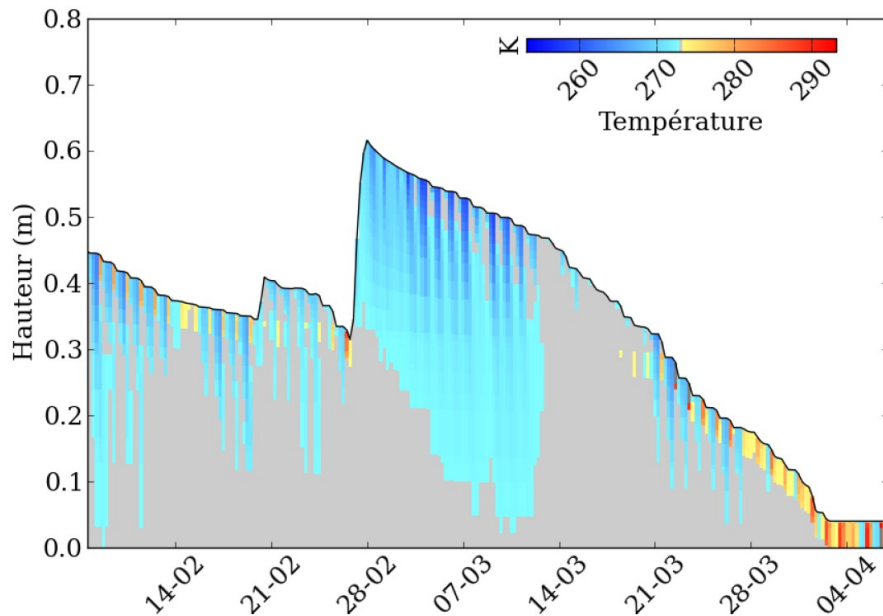


Figure 14: Example of simulation result using Crocus-DEB at Col de Porte during the spring 2011. The plot shows the possibility for debris layers (initially at the surface) to feature a temperature above the ice melting temperature.

rocky outcrops, vegetation etc.). This development will take place within the ANR PRESHINE project which started in January 2014 and in which CEN is a partner.

4.3 Thermal state of the ground

4.3.1 Context and previous work

Developments in the 1990s led by E. Brun have taken place to better represent the thermal interactions between the ground and the snowpack but they were aimed at a better representation of snow processes (in particular the relaxation of the need to impose a fix temperature of 0°C at the base of the snowpack for the stand-alone Crocus version) and they were not fully finalized so that they never entered in the main Crocus branch and were not used after these initial developments. It must also be noted here that a prior coupling of the stand-alone version of Crocus with ISBA in the context of road conditions in snowy conditions (Bouilloud and Martin, 2006) had alluded to this issue but not in a way sufficiently visible to make it appealing to researchers interested in “natural” ground thermal state (permafrost and ecology communities in particular). In addition, the fact that the stand-alone version of Crocus did not include a ground component also did not favor links with people interested in the thermal state

of the ground, at least in Grenoble.

The coupling of Crocus with ISBA within SURFEX allows to address scientific issues related to the impact of snow on the ground on the thermal regime of the underlying ground. This is further favored by the multi-layer ground heat diffusion scheme ISBA-DIF (Decharme et al., 2011, 2013), replacing the force-restore ground thermal scheme which was employed in ISBA and is still common in NWP and climate land surface schemes (Masson et al., 2013). Together with the implicit coupling of the numerical solvers for the heat diffusion equation in the snow and in the ground, the possibility to describe the vertical profile of ground properties with an arbitrary (user-defined) number of ground layers of prescribed thickness and the high level of detail of the representation of physical processes acting on heat diffusion through snow makes the ISBA - Crocus combination a tool of choice to investigate the relationships between meteorological conditions, snowpack processes and properties, and their impact on the thermal regime of the underlying ground.

4.3.2 Ecological impact of snow conditions

I have specifically contributed to one project aimed at studying the impact of snow conditions on soil surface temperature with a focus on the rate of biologically-induced degradation of vegetation debris in the wintertime. It is well accepted in the ecology scientific community that snow conditions induce significant changes in the thermal conditions of near-surface soil hence on the magnitude of biological processes potentially occurring in the wintertime. However, the quantification of such effects is often not addressed and a 30 cm snow height empirical threshold is used to separate snow “insulation” vs. “no insulation” regimes. Due to the large range of snow density and effective thermal conductivity values of snow layers making up the snowpack, such a fixed threshold is obviously an oversimplification, and requires further investigation. This project has been initiated during my post-doctoral time at LGGE at an experimental plot near the Lautaret pass (around 2000 m altitude) during the winter 2008-2009 in collaboration with the Grenoble Ecology laboratory (LECA) where the environmental setting (terrasses) allowed larger amounts to develop on one side of the plot than on the other one allowing a direct comparison of ground processes under various amounts of snow and the same meteorological conditions. In addition to field measurements of snow physical properties, meteorological conditions, and biologically-relevant information at the soil surface (carbon, nitrogen pools, etc.), an ISBA-Crocus model run was performed on each side of the experimental plot using a combination of SAFRAN meteorological data with in-situ meteorological observations. This study demonstrated experimentally that a snowpack with higher thermal resistance created an insulating

layer favouring the decomposition process. Indeed, litter decomposition rates were stable during winter and 3-fold higher under deeper and permanent snowpack with higher thermal resistance. These results suggest that the temporal (permanence vs. intermittency) and physical (depth and thermal resistance) characteristics of the snowpack should be considered when studying the response of winter ecosystems functioning to climate change in mountain regions (Saccone et al., 2013). More generally, this study has shown the significant potential borne by ISBA-Crocus for ground thermal state studies in mountain regions with a wide ranging application spectrum ; the main limit to these developments is the lack of time which can be devoted to such projects, which do not require extensive model developments (i.e., many interesting results could be obtained using the current state of the model) but that resources are allocated to such applications by interested parties. This may hopefully happen more often in the future.

4.3.3 High latitudes thermal regime of the ground

The thermal regime of high latitude permafrost is a scientific topic of prime interest due to its relevance to global climate change in relationship to the carbon pool which permafrost stores and could be destabilized and emitted to the atmosphere upon permafrost warming (e.g. Gouttevin et al., 2012b). Here again, the high level of detail of thermal processes occurring in snow which are included in Crocus makes it appealing to use in this context. Brun et al. (2013) have shown in our study on ISBA-Crocus simulations in Northern Eurasia, driven by ERA-Interim surface meteorological forcing fields, that the performance of the model in terms of 20 cm ground temperature could be considered very satisfactory (bias and rmse of -0.5 K and 2.8 K, respectively). In contrast, Wang et al. (2013) compared the results of the ORCHIDEE LSM driven by the same forcing data and compared to the same observation dataset, and found bias ranging from -9.4 K to -6.3 K, and rmse ranging from 7.9 K to 10.5 K depending on the snowpack scheme used. Note that these results were obtained without the newly developed multilayer soil freezing scheme (Gouttevin et al., 2012a), so that further improvements of model results using the ORCHIDEE LSM are anticipated. The representation of snow processes makes a significant contribution to the model results, as can be seen on Figure 15 which compares bulk snow density, snow height and 20 cm ground temperature using ISBA-Crocus with either 20 or 50 layers maximum, and ISBA-ES, respectively, every thing else being equal. The model run was performed at one randomly chosen site in Northern Eurasia (among the sites used by Brun et al., 2013) using ERA Interim driving data. Similarly to what can be found in general with snowpack schemes with too few layers, ground temperature data exhibit a cold bias when the ES snowpack scheme is

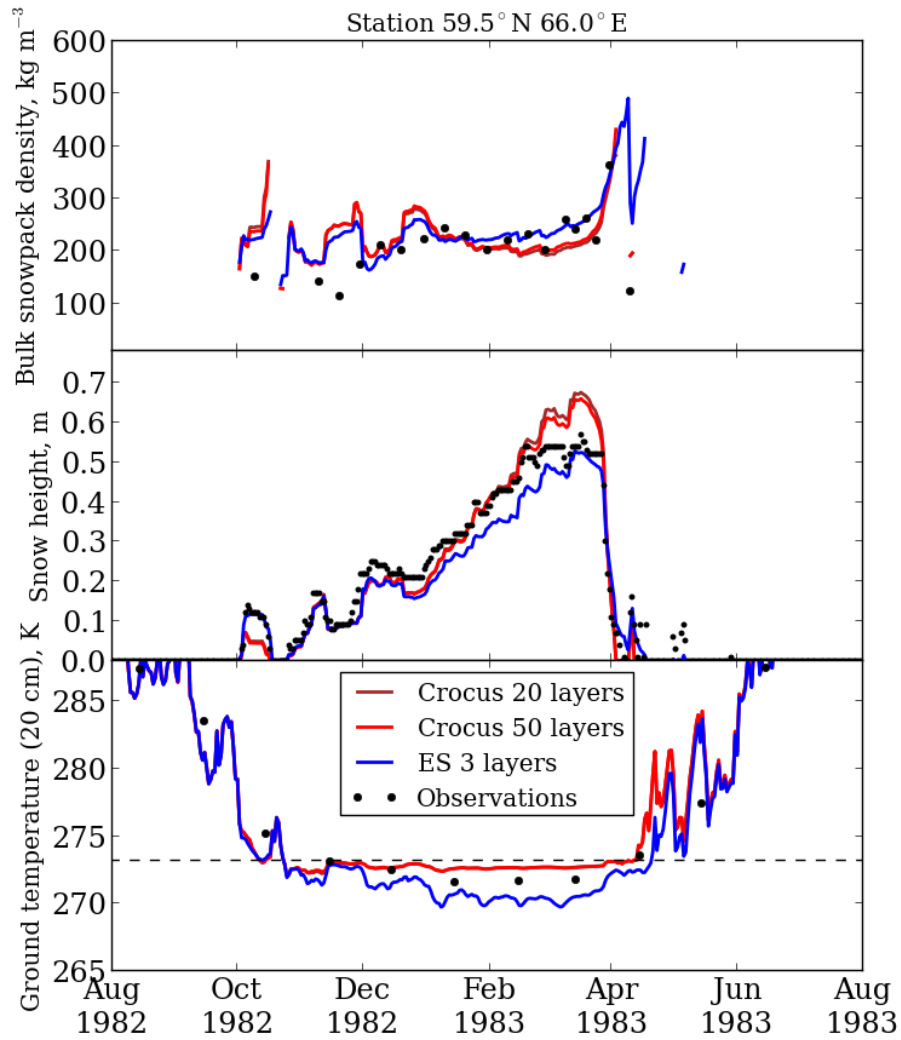


Figure 15: Impact of the choice of the snowpack scheme used within the same land surface model (ISBA) in terms of bulk snow density (top), snow height (middle) and ground temperature (bottom). Model runs were performed at the same Northern Siberian site using ERA-Interim driving data and the ISBA-ES and ISBA-Crocus model combinations (the latter with either 20 or 50 maximum snowpack layers).

used (Wang et al., 2013). In contrast, using Crocus with either 20 or 50 snow layers maximum does not make a huge difference in terms of bulk snow density, snow height or even ground temperature. Simulated ground temperature values are higher than what is obtained using the ES snowpack scheme, and while the agreement with observations is not perfect this model run clearly demonstrates the impact of the way snowpack properties are simulated on ground thermal regime. It is tempting to use the ISBA-Crocus model to explore the sensitivity of physical processes occurring in snow on ground thermal regimes, in order to (i) better understand current observations and improve knowledge and models in this respect and (ii) perform better projections of the impact of climate change on the thermal state of the ground taking into account not only variations of the meteorological conditions and bulk snow variables but also variations of snow properties due to varying meteorological conditions (wind regimes, existence of rain-on-snow events etc.). Colleagues from CNRM-GAME in Toulouse (B. Decharme, E. Brun and P. Le Moigne in particular) have recently developed a new intermediate complexity level between ES and Crocus for use in global climate simulations and potentially NWP. This model uses more than the 3 layers originally implemented in ES, and features some of the properties of Crocus, but without all of what makes Crocus special i.e. snow metamorphism and the semi-lagrangian tracking of layers. Nevertheless, increasing the number of layers to between 10 and 20 significantly increases model performance in terms of ground thermal state and other processes which are critical for global land surface modeling.

4.3.4 Interactions with vegetation

Vegetation exerts significant influence on snow conditions through a reduction of near surface wind speed, incoming shortwave radiation, variations of incoming long-wave radiation, and interception/release of precipitation (Rutter et al., 2009). The current state of the model allows to test the influence of some of these processes on snow properties and ground thermal state. In particular, activating or not the Crocus option allowing to represent the impact of wind on near-surface snow compaction (Brun et al., 1997; Vionnet et al., 2012) is a simple way to test the impact of dense vegetation effectively annihilating wind-induced snow compaction, which is typical for taiga snowpack type as opposed to tundra snowpack type (Sturm et al., 1995). Figure 16 shows the impact of taking into account (or not) wind-induced near-surface compaction in terms of SWE, snow height and 10 cm soil temperature driven by the ERA-Interim grid point close to the Umjuak field site in Northern Quebec while simulated SWE is almost the same. Denser snow in the case where the snow drift scheme is activated leads to more efficient thermal diffusion through the snow and thus much colder ground conditions. This clearly

shows the very large impact of the physical properties of snow, also illustrated with more details on Figure 17, on the thermal state of the underlying ground and confirms using the detailed snowpack model Crocus what previous assessments using simpler snowpack schemes have found (e.g. Gouttevin et al., 2012b). Further refinements of these early sensitivity tests are to be carried out by M. Barrère as part of his PhD study co-supervised by F. Dominé and myself since the Fall 2013. This will include using in-situ meteorological driving data, refining the modifications of Crocus to represent snow/vegetation interactions in a phenomenological way, and using in-situ snow and ground observations to evaluate the relevance of model modifications and assess their impact. These activities should additionally benefit from the development of the ISBA-Multiple Energy Balance (MEB) module aimed at improving the representation of processes involving the vegetation in ISBA, and is led by A. Boone at CNRM-GAME and P. Samuelsson at Swedish Meteorological Service.

4.4 Use of point-scale snow height observations : SWE estimates, data assimilation, medium range predictions

4.4.1 Snow water equivalent estimates

Operational snow observation networks in France and other countries are most often limited to point-scale snow height measurements, because the latter is easier to measure than SWE using automated methods (ultrasound or laser ranging). In many cases however, SWE is the target variable that applications are interested in. SWE can be measured manually through weighting a snow core of a known volume, and several dedicated tools have been developed although there are generally more costly than snow height gauges and some of them are not necessarily reliable (or appropriate) in mountain conditions. Conversely, the output of snowpack models of varying complexity is very often biased in terms of both SWE and height due to errors in meteorological driving data and the fact that many processes driving snow height and mass variations are generally not represented in snowpack models (in particular wind-related effects). Several authors have shown that snowpack bulk density (ρ) values, i.e., total snow mass per unit surface area divided by snow height, are in general more consistent throughout the landscape than snow height and SWE alone (Jonas et al., 2009). This had lead to the inception of parameterizations of bulk density which could be used to convert snow height measurements into SWE estimates. Jonas et al. (2009) provided a method to compute ρ estimates based on snow height, date and altitude which was developed based on measurements carried out in the Swiss Alps. Sturm et al. (2010) proposed an approach using a snow type classification and date to estimate ρ

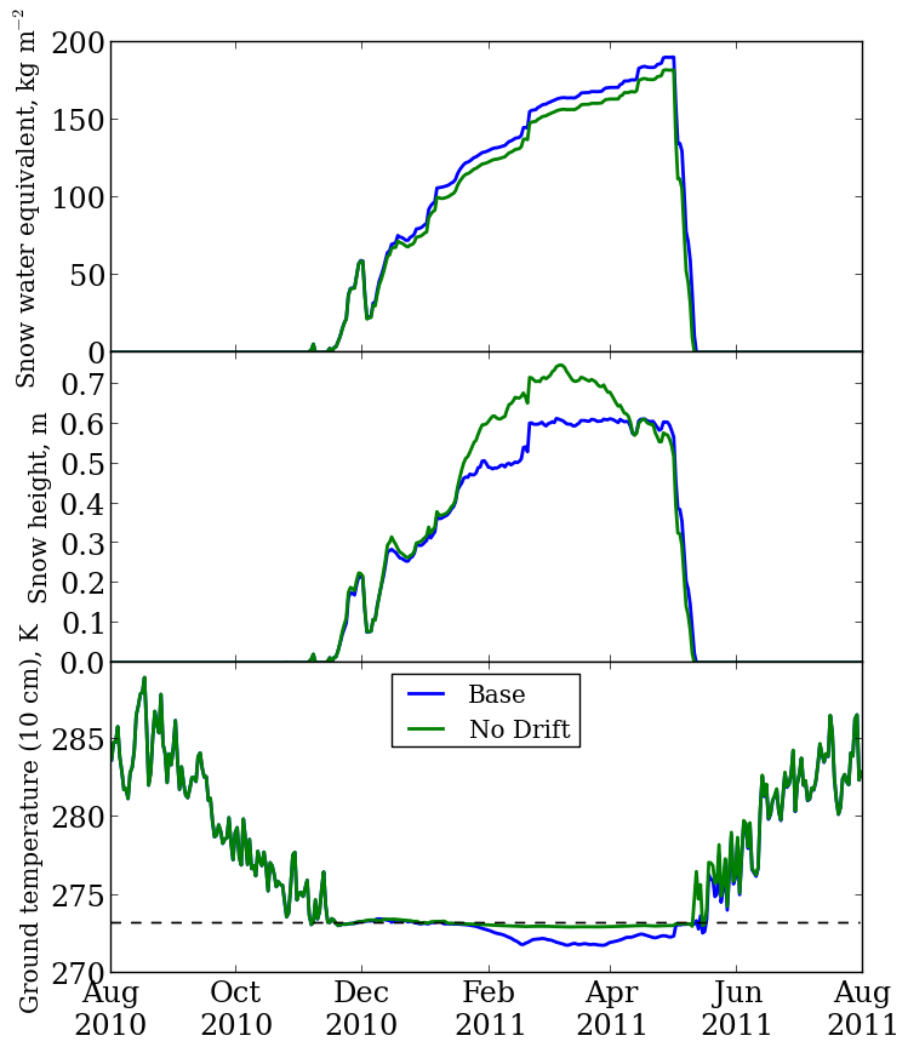


Figure 16: Impact of the representation of wind-induced near surface snow compaction in SURFEX/ISBA-Crocus on snow properties (SWE and height) and ground thermal state (10 cm temperature) at the location of the Umjuak experimental site in the Canadian Arctic.

at the global scale. Bormann et al. (2013) and McCreight and Small (2014) proposed different flavors of analogous methods to infer ρ from observation data. I proposed an extension of these approaches to the use of model estimates of ρ which could be multiplied by local measurements of snow height to infer SWE values. This does not constitute a major development but it appeared to me that this method had not been tried (at least in the French mountains) and could be very powerful in terms of SWE estimates, with a wide range of research and operational applications. Figure 18 shows an example of the application of this method for the snow season 2004-2005 at the Notre Dame d’Août monitoring station operated by EDF-DTG in the Vanoise mountain range in the French Alps, at an altitude of 2500 m altitude. Note that none of the meteorological and snow measurements carried

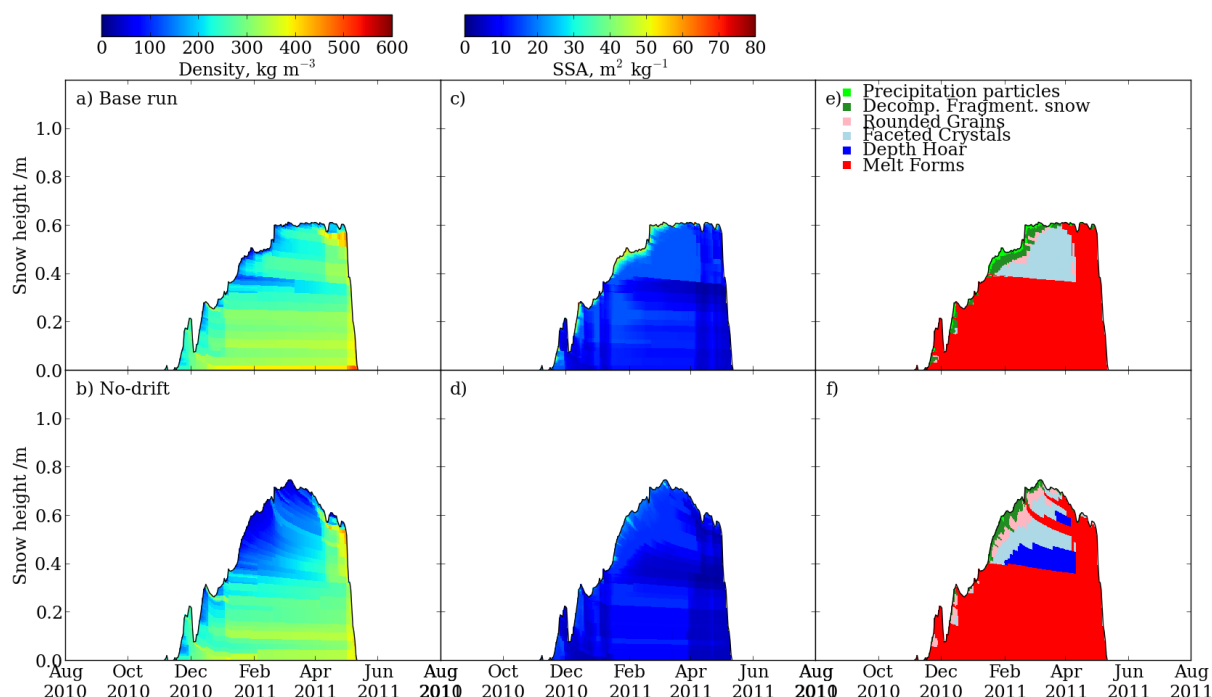


Figure 17: Internal physical properties of the snowpack of the model runs reported in Figure 16

out at this site are used by the SAFRAN meteorological analysis system. For this study, a SAFRAN - SURFEX/ISBA-Crocus model run was performed at the altitude of 2500 m using linearly interpolated meteorological fields from the 2400 m and 2700 m SAFRAN analysis levels. At the site, snow height is measured using an ultrasonic ranger, and SWE is measured using the cosmic rays instrument initially developed by Kodama et al. (1979) and implemented by EDF-DTG in the French mountain ranges (Paquet and Laval, 2006; Gottardi et al., 2013). Figure 18a shows the measured SWE along with model results (in blue referred to as open loop, see below), Figure 18b shows measured snow height along with model results, and Figure 18c shows the computed bulk snow density in the case of measurements and model results. Red dots on figure 18a correspond to the multiplication of measured snow height (when available) with simulated density. The obtained results show that, while simulated SWE seems rather underestimated, most probably due to underestimated precipitation amounts in this case, the simulated bulk density is reasonably well simulated thus the estimated SWE matches observations rather well. However, in this case, due to the SWE underestimation, total melt occurs too early in model results leading to the impossibility to predict SWE with this method at the end of the snow season. At the time of writing, quantification of the performance of the method is underway and will be reported after finalization. However, simulations ran at several sites spanning various environmental and meteorological contexts within the French Alps demonstrate the power of the method.

I believe that such method could prove useful not only at the point scale but also for SWE mapping algorithms (e.g. Bavera et al., 2014), benefiting from the advantage of using bulk density values relevant to current ongoing snow season together with field estimates of snow height, which are easier to measure systematically than SWE. At the catchment scale, this method could be used together with snow height maps derived using terrestrial or airborne laser scanning, to provide accurate estimates of total snow mass in a given geographical area. However, the further step of data assimilation of snow height within SURFEX/ISBA-Crocus could prove even more powerful in this respect (see section 4.4.2).

4.4.2 Data assimilation of point snow height measurements

Context and previous work In its current state, the SAFRAN - Crocus model chain does not make use of snow height measurements to update the simulated snow conditions in order to correct inevitable deviations between simulations and observations. All of the data assimilation that is carried out in this model chain takes place within the meteorological analysis carried out by SAFRAN (Durand et al., 1993), accounting for ground meteorological observations (including daily precipitation observations and amount of fresh snow measured using a snow board), radiosondes altitude observations, and remotely sensed cloudiness maps. Deviations between measured and simulated snow height values are currently not corrected, which is mainly due to the fact that the model chain is not targeted to provide point scale estimates of snow conditions, but rather estimates which are regionally relevant for a given altitude, aspect and slope topographical class. The large variability of snow height around a given observation point, especially in mountain environments, requires that point scale snow height data is used with great caution (e.g. Grünewald et al., 2013; Grünewald and Lehning, 2013). This prevents direct spatial extrapolation of point scale snow height measurements in mountainous areas.

In the field of numerical weather prediction and meteorological reanalysis, snow height observations are sometimes assimilated within the snow scheme of the land surface model used, which is the case in the European Center for Medium range Weather Forecast land data assimilation system (de Rosnay et al., 2012) and is also used in Norway by the HIRLAM consortium within the single layer snow scheme of SURFEX/ISBA. There is currently no assimilation of snow height measurements in the Météo-France NWP surface analysis system.

There are however applications where assimilation of snow height measurements could be useful, including a refinement of the above mentioned technique to infer SWE using snow height measure-

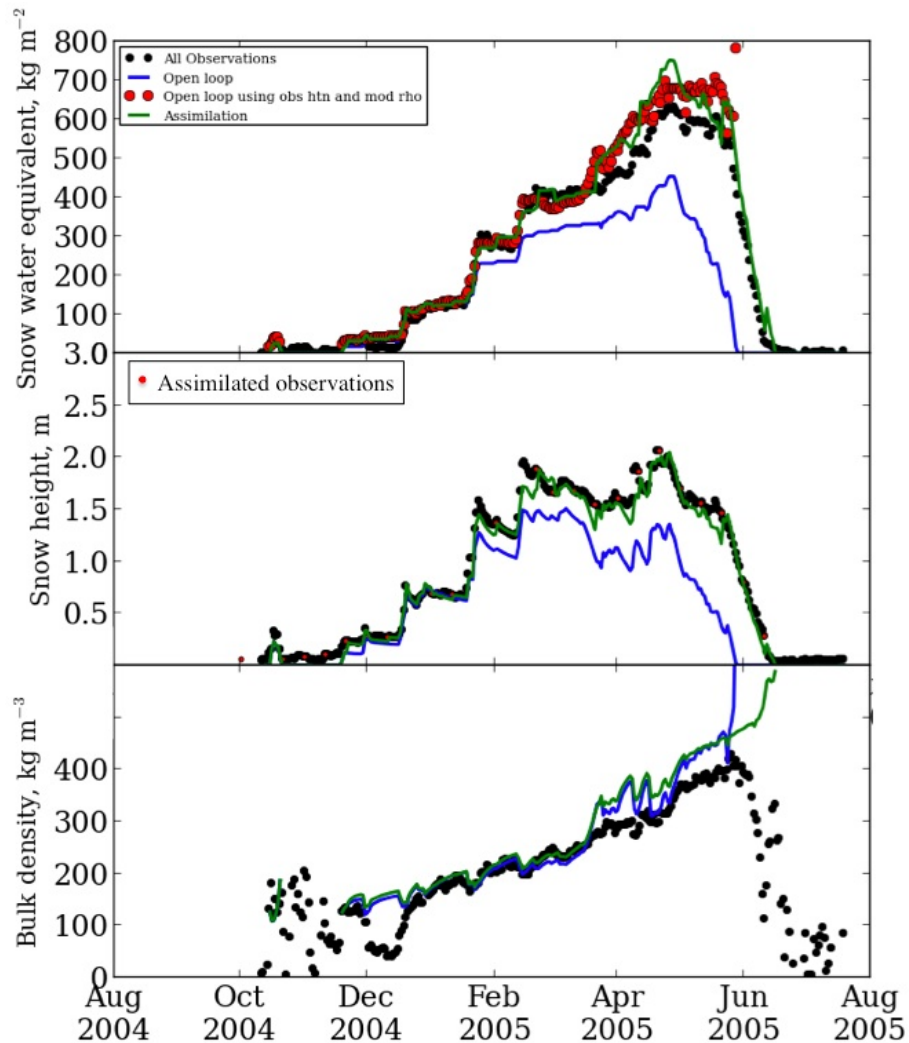


Figure 18: Comparison of observations (black dots) with several ways to simulate snow water equivalent (top), snow height (middle) and bulk density (bottom) at the Notre Dames d’Août monitoring station operated by EDF-DTG in the Vanoise mountain range in the French Alps, at an altitude of 2500 m altitude. Open loop results (i.e., standard SAFRAN - Crocus model run) are shown in blue. Estimates of SWE using open loop snow height and measured bulk density are shown in red on the top panel. Results of the snow height assimilation (assimilated data shown in small red dots on the middle panel) are shown in green.

ments and model estimates of bulk density, and the gap-filling of observation time series. Indeed, climatological studies of snow conditions are mostly based on snow height observations. The French mountain snow observation network, mostly relying on ski resort observers, lacks observations before and after the opening season i.e. before mid-December and after mid-April (with interannual variability in the beginning and end of observation records). During the observation period, two types of observations are reported, either twice daily routine observations including precipitation, snow height and surface snow conditions generally close to the lower altitude of ski resorts (to ensure continuous access to the observation site through the winter), or weekly snowpit observations generally carried out at higher locations in the ski resort. In order to use such data for monitoring current snow conditions and use such data with a climatological aim, there is a need to build continuous, gap free records. Note that the sites of daily observations include daily minimum/maximum temperature record and daily precipitation, and qualitative measures of wind conditions. Such data do not suffice to carry out simulations with Crocus. However, such observation data feed the SAFRAN analysis and allow to carry out Crocus model runs under the conditions (altitude, slope, aspect) of the observation point. Again, inevitable deviations between model results and observations occur, because of intrinsic Crocus deficiencies and also the fact that in the SAFRAN framework, within a given mountain range, two points located at the same altitude under similar aspect and slope characteristics are assumed to encounter similar meteorological conditions, which is often challenged by field observations. Several methods can be employed to carry out data assimilation of snow height into a detailed snowpack model. The SNOWPACK model, when run at the location of automated weather stations stations (Bartelt and Lehning, 2002; Lehning et al., 2002), uses measured snow height increments to infer snow precipitation (automatic snow precipitation measurements would be far too challenging to be used operationally) which allows to adjust measured and simulated snow height (but does not allow to diagnose rain events in terms of occurrence and intensity).

Attempts to develop a simplified extended Kalman filter for snow assimilation During the visit of Richard Essery at CEN in the Fall 2012, with the aim to develop data assimilation into Crocus with the long term goal to assimilate microwave satellite data, a simplified extended Kalman filter (SEKF) assimilation system was developed for Crocus and initial tests were performed to assimilate point scale snow height and SWE data. The principle behind SEKF is to run a series of parallel model runs with the same meteorological forcing, initialized with small variations of the initial values of the targeted prognostic variables, in order to infer the dependency of model results to the variations of its target prognostic variables and then propagate this sensitivity backwards to perform the analysis (i.e.,

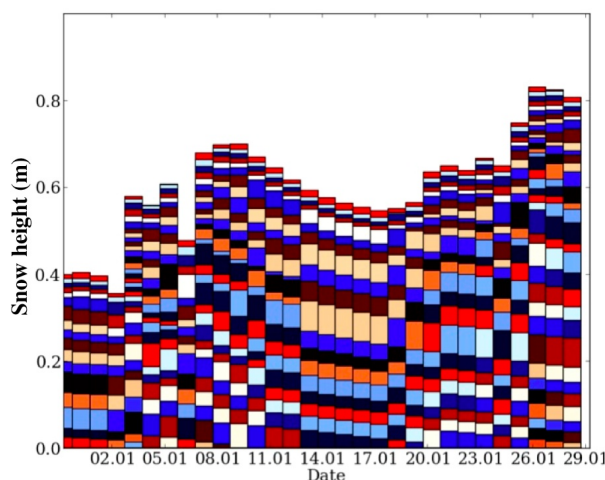


Figure 19: Illustration of the way the numbering of snow layers varies in time (each color corresponds to a given snow layer number). In Crocus, snow layers are numbered starting from the top, so that each precipitation event leads to renumbering of the full vertical profile. However, even without precipitation, layer split/merge and basal melt can lead to modifications of the labeling of snow layers.

adjust the values of the prognostic variables to maximize the performance of the model run for the next model run). SEKF is a popular method for land surface modeling, with applications in terms of soil moisture and temperature (e.g. Parrens et al., 2014). In the case of a snowpack model like Crocus, the challenge lies in the fact that the number and labeling of snow layers varies in time, so that tracing back the change of model forecast to slight variations of the values of the prognostic variables in a given layer becomes elusive as soon as a too large number of snow layers is allowed (difficulties already occur with “only” 5 layers). Figure 19 shows how the numbering of snow layers varies in time and illustrates how difficult it can be to keep track of the numbering from previous model time steps, which is required for SEKF application. In addition, I am increasingly convinced that the initial state of the snowpack plays a significantly lower role than the unfolding of meteorological conditions during a given forecast period, especially in terms of precipitation amount, phase, and timing, so that ensemble-based data assimilation schemes should place more emphasis on the spread of possible meteorological conditions than on the variations of prognostic variables at the beginning of the model run. This is key for studies where the vertical structure of the snowpack plays a major role, such as assimilation of microwave or optical remotely sensed observations.

A simple method to “assimilate” point scale snow height values In the case of snow height and SWE, the robustness of the bulk density predicted by a model with a level of complexity compared to

Crocus opens the way to a very simple data assimilation scheme where snow height and SWE observations can be directly injected into the model at the time of analysis so that the simulated snow height or SWE is adjusted to match corresponding observations. Such a crude analysis method will of course not be able to counteract qualitative errors of the meteorological forcing (such as a wrongly assessed snow/rain altitude limit) leading to errors in the vertical structure of the snowpack, but will be able to correct quite satisfyingly bulk values such as snow height or SWE as long as the meteorological driving data is not too far from “reality”. Obviously, refinements of this simple “snowpack stretching” must be considered to improve the quality of the analysis system, such as taking into account model and observation errors avoiding overfitting of observation data, focussing the modifications of the simulated snowpack on layers which have been created in the model after the former analysis step (to avoid multiple corrections of the same snow layers), or placing more weight on modifications of the snowpack structure towards the top of the snowpack. Still, the core of the method is to conserve the bulk snow density. Figure 18 shows an example of a simple analysis system where the mass of each layer is simply scaled to match the observed snow height at each analysis step (in this case, snow height is assimilated on the 1, 11 and 21 of each month if the snow height data is available - indicated by a red dot on Figure 18b). By construction, the simulated snow height record matches the observed one even with data assimilation once every at least 10 days, but interestingly the system also increases the agreement between observed and simulated SWE. In a way, this data assimilation scheme can be viewed as a dynamic implementation of the SWE estimate method described in the above section. Figure 18 shows the comparison between SWE estimates using open loop (i.e., no assimilation, in blue) model runs without accounting for snow height observations, open loop accounting for snow height measurements to estimate SWE (method described in section 4.4.1 ; red dots) and results from the simplified data assimilation system (in green). This analysis demonstrates the high potential of this method to estimate SWE at locations where only snow height is available, including the potential to adjust model runs and create point scale SWE forecasts even when snow height measurements are not available in real time. Over the previously described method based on measured snow height and simulated bulk density, the method provides SWE estimates at dates where the open loop simulations indicate no snow on the ground. Similarly to the previous methods, more work is needed to finalize these developments but they already demonstrate the high added-value that can be anticipated to combine numerical models such as SAFRAN and Crocus together with ground observations to improve the real-time monitoring or climatological analysis of snow conditions in mountain regions, even without a dense network of SWE observations. This developments will be used by G. Nicolet,

who started a PhD in the Fall 2013 co-supervised by N. Eckert (Irstea/ETNA, Grenoble), J. Blanchet (LTHE) and myself on extreme value statistics of snow precipitation and snow on the ground amounts in the French Alps.

4.4.3 Climatologically-based prediction of snow conditions

Modern societies increasingly require anticipation capabilities in virtually all aspects of human life, including snow conditions in mountain regions, due to their strong socio-economic impact. Winter meteorological conditions vary significantly from one year to another, which is often worrisome for mountain professionals because natural snow conditions heavily depend on meteorological conditions and their variations through the snow season. Current forecasting tools are of little use for prediction lead times exceeding one week: operational weather forecast cover only time periods on the order of 5 days, and seasonal forecasts are too coarse at the local scale. In order to provide a quantitative answer to frequent requests from mountain professionals to provide bounds for potential future snow conditions several weeks to months in advance, I have contributed to the development of a forecast system using meteorological conditions from past snow seasons to generate an ensemble of the many possible meteorological scenarios within a given snow season. Numerical snowpack modeling, initialized with simulated conditions on a given date, allows to generate an ensemble of possible realizations of the unfolding of the snow season. Figure 20 shows examples of the ensemble of “predictions” which can be generated on 1/12, 1/2 and 1/4 of the snow season 1996-1997 in the Mont Blanc SAFRAN massif at an altitude of 2400 m on flat terrain. The initial stage of this study, presented at the ISSW 2013 in Grenoble (Morin et al., 2013b), relied only on the median of the prediction ensemble which showed poor predictive capacity compared to the “real” unfolding of the snow season in terms of score inspired by the Nash and Sutcliffe (1970) score. An interesting development occurred since ISSW thanks to the collaboration with N. Eckert (Irstea/ETNA), who developed a statistical framework to analyze the simulation results taking into account the whole ensemble of predictions. In addition, not only Nash-like performance but also more probabilistic evaluations based on the odds to exceed a given snow height threshold were investigated. This latter analysis, more relevant to potential users of such predictions (i.e., ski resort managers willing to assess what is the range of physically possible snow conditions several weeks ahead), is still under development but is anticipated to be powerful in assessing physically sound bounds for the mid-term (weeks to months) evolution of snow conditions starting from given snow conditions. Of course, this approach could be combined with the data assimilation and SWE estimate methods presented above, to provide ensemble forecasts of SWE in mountain lo-

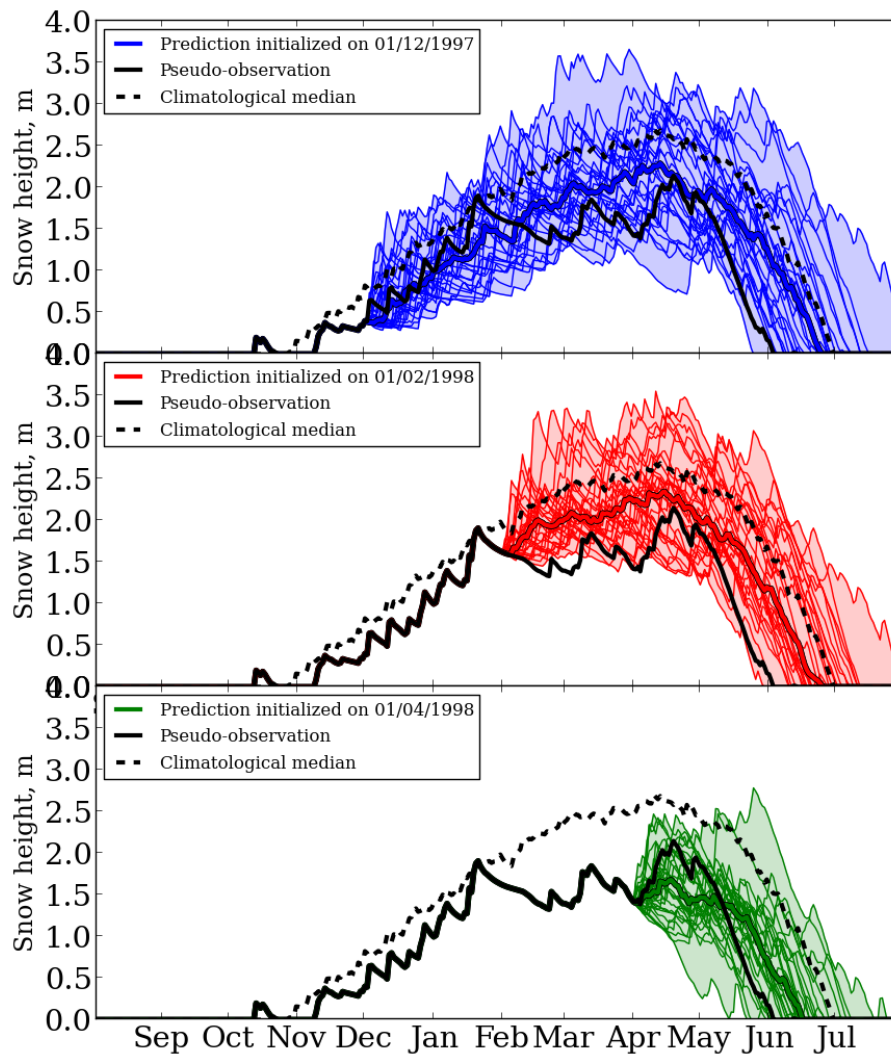


Figure 20: Results for three climatologically-based ensemble predictions of snow height for the snow season 1996-1997 in the Mont-Blanc massif at 2400 m altitude. Predictions were initialized on 1 December, 1 February and 1 April using analyzed meteorological conditions for the current snow season (SAFRAN). Predictions were then built through replacing the unfolding of meteorological conditions from the prediction data into the future by a meteorological time series starting on the same calendar date from an other snow season. The prediction consists of an ensemble of possible unfolding of snow conditions driven by the ensemble of past meteorological scenarios initialized from the same starting point.

cations accounting for current conditions (through the assimilation of snow height observations) to minimize the impact of model errors at the time of forecast. Additional refinements include the possibility to account for snow management techniques (snowmaking, grooming) and could be widely used to support operations of ski resort technical activities (see Conclusions and perspectives).

4.5 Assimilation of remote sensing observations

Another field where existing snowpack models could be used more intensively and benefit from is assimilation of remotely sensed observations. Atmospheric radiative transfer models have long been used to retrieve directly into the core of the numerical weather prediction model remotely sensed observations in a given electromagnetic frequency range (visible, near-infrared, thermal infrared, microwave - active and passive etc.). The situation for land surface schemes is generally not as advanced, in part due to the large heterogeneity of the Earth surface but also, in my view, due to the fact that remotely sensed information is often used towards generating environmentally relevant products (SWE, soil moisture etc.) rather than as a way to improve an a priori estimate from a land surface model. The lack of a priori knowledge about the surface state for the retrieval algorithm used to generate such products, and the lack of direct connection with the physical principles conducive to the observed electromagnetic behavior, are undoubtedly leading to under-use of the capabilities of such observations. Together with colleagues from Grenoble (M. Dumont, G. Picard, F. Karbou), Toulouse (E. Brun) and Edinburgh (R. Essery), I have militated for projects associating explicitly snowpack modeling and forward modeling of the electromagnetic behavior of the simulated snowpack with the ultimate goal to be able to assimilate observations directly into the snowpack model. I am happy to have contributed to a few examples showing the feasibility of this approach, in particular for active X- and C-band microwave behavior of the snowpack (Phan et al., 2014), for passive microwave (interactions with G. Picard group at LGGE and visit of R. Essery to Grenoble in the Fall 2012), and for optical remote sensing of snow (Mary et al., 2013). Figure 21 shows how snow surface SSA inferred from the MODIS sensor can be compared to semi-distributed SAFRAN - Crocus simulation results projected on the same observation grid as MODIS data (500 m horizontal resolution) which demonstrates the technical feasibility of gridded data assimilation techniques in mountain regions. However, it has to be recognized that remote sensing of snow requires much more knowledge and expertise than I currently hold in this domain so that my direct contribution to this field is likely to remain marginal. I am however convinced that energy has to be invested into this perspective to make sure that detailed snowpack models, able to generate a vertical profile of density, liquid water content,

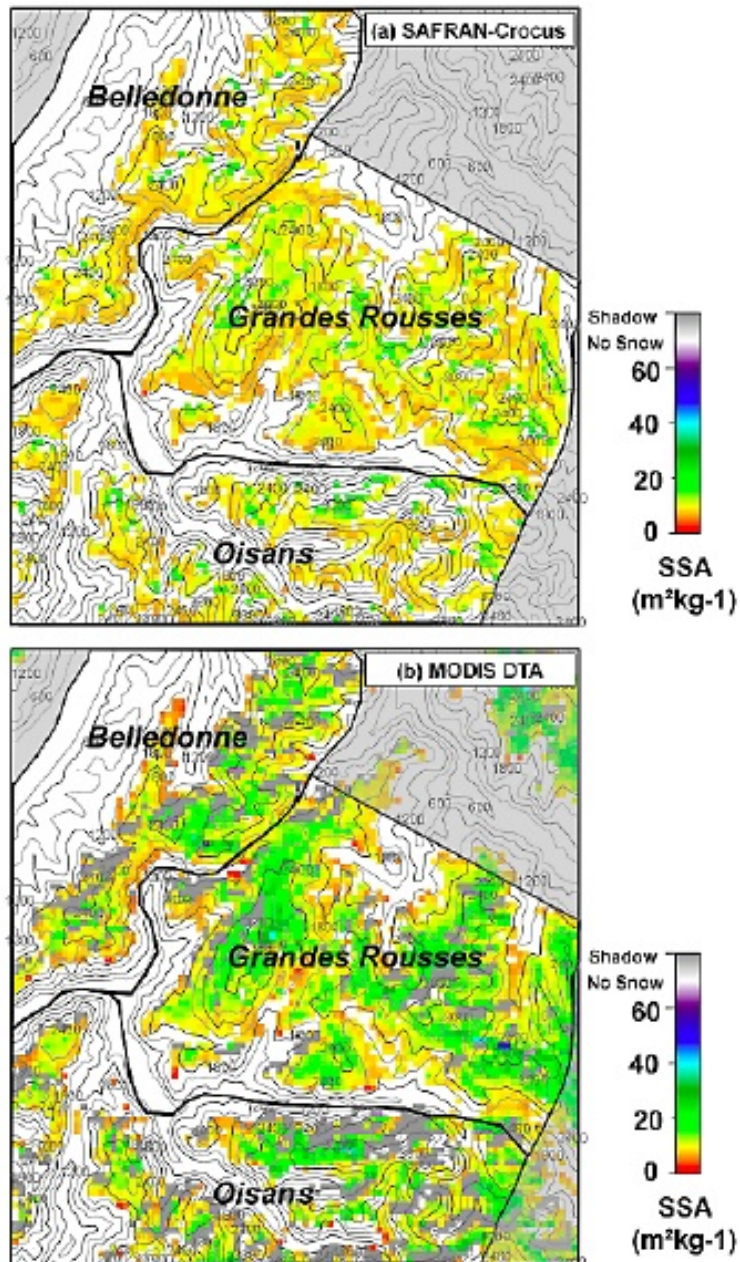


Figure 21: SSA maps obtained from SAFRAN-Crocus (a), and from the processing of MODIS images (b) for 21/03/2009. Elevation lines are 1000 m spaced. Grey pixels are shaded areas. White pixels are not detected as snow. Delimitation of the massifs Belledonne, Grandes-Rousses and Oisans are also drawn (from Mary et al., 2013).

optical radius, temperature etc., are duly considered in further developments in this field. Dedicated efforts are placed on mountain application of snow remote sensing with great potential for avalanche warning, hydrological and snow mapping activities, and should be followed and encouraged³.

³http://www.wsl.ch/fe/warnung/projekte/ESA_AAF/index_EN

5 Conclusions and perspectives

This document attempts to synthesize several years of technical and scientific developments in the field of snow science, with a focus on the modeling and numerical simulation of the physical processes and properties of the macroscopic snowpack to which I have participated. The large number of issues, methods and applications that have been considered over these years is indicative of the fact that snow is at the forefront of many scientific and societal challenges. Prior to the beginning of my research work on this topic roughly around 2008 (my PhD work from 2005 to 2008 did not ignore snow completely although the perspective was rather from a reactive chemistry perspective, which is beyond the scope of my current research activities), I had the feeling -and the fear- that snow research may be confined in a small and endogenic research community. I currently think exactly the opposite: in many cases, environmental sciences require knowledge and tools to address snow related processes, be it for water supply in a large fraction for the World's population, the Earth climate and the strong sensitivity/impact of polar regions linked with physical snow properties and processes (including issues related to permafrost), meteorological forecast which is influenced by snow conditions and thus requires appropriate handling of snow in land surface models and data assimilation schemes etc. Progress in snow science is thus favored by interactions with scientific communities for which snow used to be a marginal concern but now moves forward as a critical element. In addition, the large interest generated by snow for many reasons including esthetic considerations and its "fun" touch sparkles the interest of researchers originating from distinct communities (especially in the field of material sciences and applied physics targeting new snow observation capabilities). The past roughly 6 years have been devoted for me to the development and consolidation of new tools (in particular SURFEX/ISBA-Crocus) and the exploration of various aspects where it could be improved and applied without much censorship on the number and diversity of projects, which possibly explains the flurry of potential perspectives that my work may open. Given that a growing part of my professional time is used for management and administrative activities, time has now come to restrict my personal research to a narrower range of issues, attempting to finalize some ongoing research projects and potentially transfer them to more directly involved scientific communities - the developed tools were designed to be portable to other scientific and technical environments for this purpose.

I intend to specifically contribute to several improvements in the representation of snow processes in Crocus and related application studies, such as:

- Impurities: The radiative impact of snow impurities is critical for regional (e.g., Painter et al., 2010; Ménégoz et al., 2014) and global (e.g., Hansen and Nazarenko, 2004; Krinner et al.,

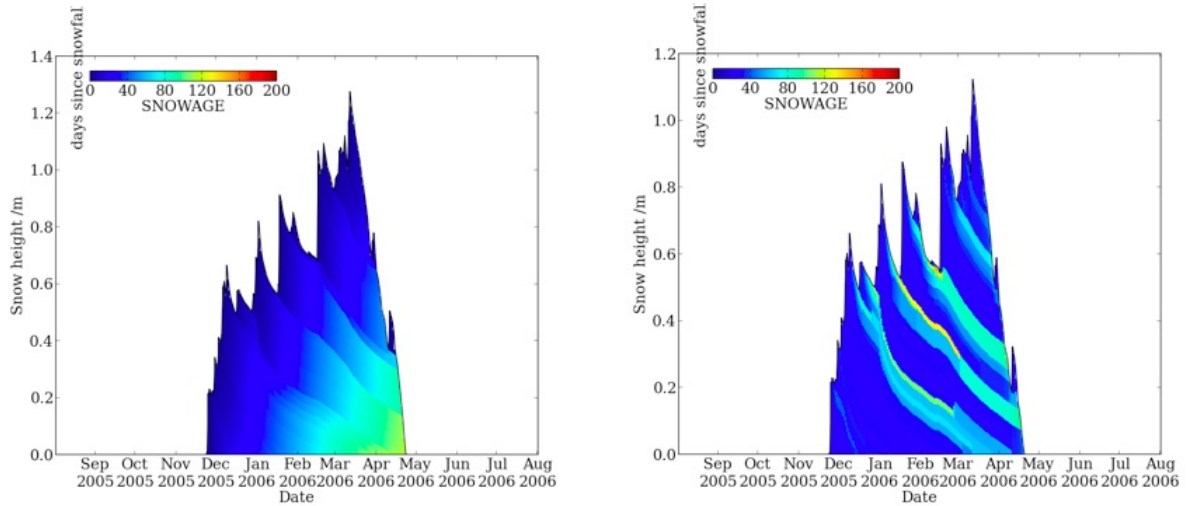


Figure 22: Preliminary result showing how impurities could be implemented in Crocus. Currently, snow albedo in the visible part of the solar spectrum depends only on snow layer age (computed since snowfall date). Snow age using the regular version of Crocus is displayed on the left, for one year of simulation at Col de Porte in 2005-2006. The plot on the right displays the time evolution of snow layer age, whose evolution depends on the exposure time of snow layers in the near surface (values do not anymore correspond to a true age), and attempts to represent more realistically the fact that snow impurities concentrate in snow layers exposed for longer time periods near the surface.

2006) issues and the current representation in Crocus, simply representing visible albedo as a function of snow age, is not satisfying. While several snowpack schemes of land surface models increasingly attempt to account for the role of impurities in snow (e.g. Flanner et al., 2009; Yasunari et al., 2011; Niwano et al., 2012), I intend to contribute to the improvement of the representation of the deposition of snow impurities in Crocus, their impact and their fate after deposition. This work will take place in collaboration with colleagues specializing in snow impurity observations (chemical properties and behavior of snow impurities ; D. Voisin, LGGE Grenoble) and radiative transfer in snow (TARTES and beyond, see above). The technical feasibility of this work is obvious given that Crocus already features the relevant framework to handle the time evolution of state properties of snow layers. I have carried out a first attempt to represent the time evolution of a mass conservative tracer in snow layers. In this case, the initial impurity level of fresh snow is fixed, and is evolved in time as a function of the vertical distance of the snow surface (representing that dry deposition is stronger near the snow surface) and accounting for densification of snow layers so that the total amount of impurities in a given snow layer is unaffected by densification and water percolation. In case a snow layer disappears due to complete melt, its impurity content is transferred to the next snow layer below. Developing this work further requires to define in detail the number and nature of tracers which should be handled (so that the technical infrastructure in SURFEX can be established and consolidated). Taking explicitly into account the interactions between impurities and phase change (in particular, liquid water percolation) will require to better understand them and to better handle water percolation in Crocus. Figure 22 shows an example of a model run where the impurities were evolved according to the simple rules given above. The layering can be clearly observed, which is due to the fact that layers exposed to the atmosphere for a longer time period incorporate more impurities.

- Vertical transfer of water vapor and liquid water: Crocus currently does not account for vertical water vapor transfer which is an issue in environmental contexts exhibiting large and/or sustained temperature gradients conducive to water mass redistribution between snow layers (e.g. Domine et al., 2013). The current percolation scheme (bucket approach) is also not satisfying in that it does not treat unsaturated flow and capillary barriers and uptake, with potentially major implications for internal snow processes likely affecting the assessment of slope stability. Both issues need to be addressed, at least in part drawing from developments carried out in other models (e.g. Wever et al., 2014). Potential for a fruitful local collaboration on the matter has

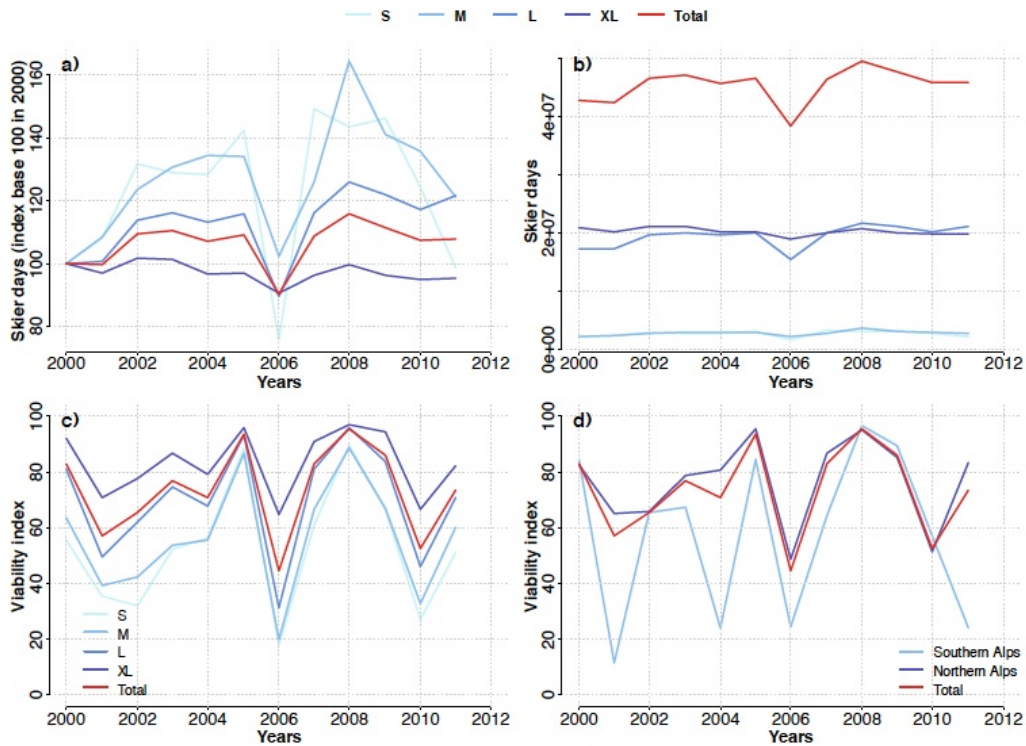


Figure 23: Time evolution from the seasons 2000-2001 to 2011-2012 of the (a) relative and (b) absolute with respect to 2000-2001 snow season skier days values as a function of ski resort size class (S, M, L and XL), and viability index (based on natural snow conditions) (c) as a function of ski resort class and (d) separating Southern and Northern French Alps domains. For each year, the label corresponds to the first half of the winter season (i.e., 2000 corresponds to 2000-2001) (from François et al. (2014)).

recently emerged (L. Oxarango, LTHE, Grenoble) and should be further explored.

- Snow in ski resorts : up to now, much emphasis has been placed on natural snow processes, and climate projections of snow conditions in future years have focussed on observations and numerical modeling of natural snow conditions (e.g Martin et al., 1997; Rousselot et al., 2012), which is likely to be very different from snow on ski slopes due to the major influence of snow management strategies (grooming, snowmaking etc.). My current work on this topic focuses on two directions. The first one results from interactions with the Mountain Economy group of Irstea (DTM) and in particular E. George-Marcelpoil and H. François. We have initiated work aimed at crossing physical conditions of snow in ski resorts (obtained through numerical modeling using SAFRAN and Crocus) with socio-economic data including the setting of ski lifts (altitude range, theoretical skier flow etc.) and actual skier days values. As an example, Figure

23 shows a time series of absolute and relative skier days values for the period from 2000 to 2012 for almost all ski resorts in the French Alps (split according to size classes), and a viability index computed using a resort-level aggregation of the 100-days rule. This rule states that a ski resort is viable at a given altitude if it features 30 cm of continuous snow cover for at least 100 days. It is questionable in many respects but it is widely used, and we decided to use it as it is for our first study together with H. François and E. George-Marcelpoil aimed at checking the feasibility of crossing physical and socio-economic information, which is often challenging. This preliminary study provides ways to assess quantitatively the links between meteorological and socio-economic data relevant for ski resorts. As Figure 23 shows, this is particularly well illustrated by the fact that the 2006-2007 season was both unfavorable in terms of natural snow conditions and skier days, while the 2010-2011 season was unfavourable in terms of natural snow conditions but did not show the same drop of skier days than 2006-2007, most probably because meteorological conditions and/or snowmaking strategies were more appropriate for good snow conditions on ski slopes. Moving further from this study requires to include snow management practices in Crocus. This second research direction is currently undertaken through the work of PhD student P. Spandre since the Fall 2013, co-supervised by E. George-Marcelpoil (Irstea/DTM ; specialist of socio-economic aspects of mountain regions). Figure 24 shows a preliminary result from the PhD work of P. Spandre, where a snowmaking module was implemented in Crocus to artificially add snow precipitation depending on meteorological conditions but also on the snowmaking strategy of a given ski resort. The main originality of this work, with respect to existing snow models handling snowmaking, is that “fresh” layers of machine-made snow are attributed specific physical properties (in particular density and specific surface area) so that the physical behavior of machine-made snow layers is explicitly accounted for. Results from Figure 24 do not account for grooming, although a simplified grooming module has also been incorporated in Crocus. Merging the two approaches outlined before will be initiated during the PhD work of P. Spandre and could be amplified through a dedicated research project.

- Evaluation of modeling tools : the temptation is high to continuously move forward and increase the time, space, physical resolution of models used in the context of snow science. However, it is critical to better assess the quality of existing tools to be able to document the current deficiencies of the modeling tools and document the added-value of specific developments, including their impact on forecasting activities. This concerns the assessment of the quality of

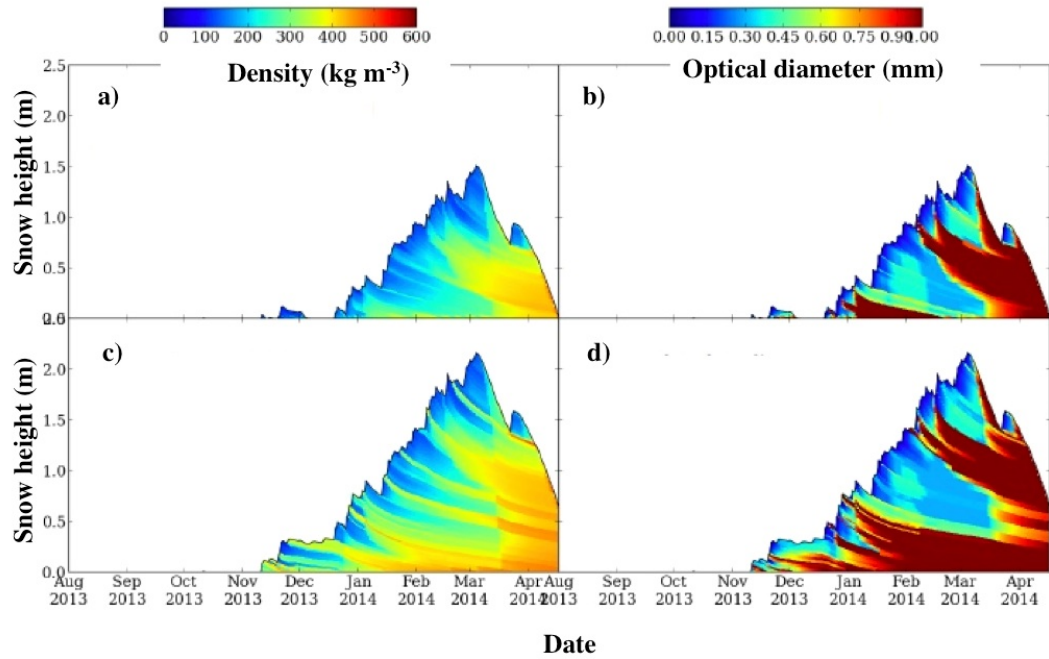


Figure 24: Time evolution for the season 2013-2014 of the vertical profile of the physical properties of snow (density a) and c) and optical diameter b) and d)) at an altitude representative of a ski resort (1800 m altitude near Grenoble) in case of a natural snowpack (a) and b)) and for a snowpack including snowmaking (c) and d)). Grooming is not taken into account in this example (from Spandre et al. (2014)).

the numerical simulation of the vertical profile of the physical properties of snow against field observations (e.g. Lehning et al., 2001), but a wider extent also the resulting assessment of snow cover extent or avalanche hazard predicted by the chain of models. The degree of complexity of the latter will also surely increase, with the planned transition from a deterministic use of SAFRAN forecast to (i) the use of ensemble predictions with SAFRAN (Vernay et al., 2014) leading to increased complexity of time variations of the simulated properties and (ii) the use of higher space resolution NWP models in mountainous environments leading to increased complexity of spatial and time variations of the simulated properties. Although this may not seem a purely research-grade objective, the complexity and heterogeneity of snow on the ground makes such a goal extremely challenging and will require collective work at the local, national and international level to improve the situation.

Besides the list of perspectives given above which provide a workplan for the next 5 years at least, emphasis should also be placed on the mechanical properties of snow beyond the approach developed in MEPRA, which are critical for avalanche research and its applications for avalanche hazard warning activities to which almost none of the developments in terms of snowpack modeling described above have made a significant direct contribution. Progress in the prediction of the snow conditions potentially conducive to a given avalanche hazard level is certainly even more challenging than all the issues addressed by my research up to now and tackling such issues will require collaboration between various institutions and individuals, in which I will attempt to play the most proactive and positive role that I possibly can.

All the past, present and future developments to which I have contributed and are listed above share as a common characteristic the ambition to integrate new or existing knowledge into the snowpack model Crocus, or develop additional tools building upon or at least consistent with its scientific and technical framework. Here again, I remain convinced that a significant fraction of the scientific community needs to maintain emphasis on the development and consolidation of long-lasting *tools* which can then be used as widely as possible to address scientific bottlenecks. The developments listed above will contribute to improved tools which will be applied to tackle a potentially large number of scientific issues, either by the local community to which I belong or by other members of the scientific community. Managing such tools is in my opinion at least as important as producing new scientific results. Even if this appears less rewarding in the short term, the diversity of applications and the interactions it offers with a wide range of contributors and users makes it genuinely gratifying and shows large promise in the longer term.

List of acronyms

3S-R	Laboratoire Sols, Solides, Structures - Risques
ANENA	Association Nationale pour l'Étude de la Neige et des Avalanches
ANR	Agence Nationale de la Recherche
CalNEX	California Research at the Nexus of Air Quality and Climate Change project
CEN	CNRM-GAME Centre d'Études de la Neige unit
CNRM	Centre National de Recherches Météorologiques
CNRS	Centre National de la Recherche Scientifique
Crocus	Crocus is not an acronym !
Crocus-DEB	Crocus-DEBris covered glaciers module
DUFISSS	DUal Frequency Integrating Sphere for SSA measurements in Snow
ECMWF	European Center for Medium-range Weather Forecast
EDF-DTG	Électricité de France - Division Technique Générale
ERA-40	European ReAnalysis 40
ERA-Interim	European ReAnalysis Interim
GAME	Groupe d'étude de l'Atmosphère Météorologique
GMGEC	CNRM-GAME Groupe de Météorologie de Grande Échelle et Climat unit
GMME	CNRM-GAME Groupe de Météorologie de Moyenne Échelle unit
HIRLAM	High Resolution Limited Area Model consortium
ICSSG	International Classification for Seasonal Snow on the Ground
INSU	Institut National des Sciences de l'Univers
Irstea	Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture
Irstea/DTM	Irstea Développement des territoires montagnards unit
Irstea/ETNA	Irstea Écoulement Torrentiels, Neige et Avalanches unit
ISBA	Interactions Soil-Biosphere-Atmosphere
ISBA-DIF	ISBA DIFfusion multilayer ground scheme
ISBA-ES	ISBA Explicit-Snow snowpack scheme
ISBA-MEB	ISBA Multiple Energy Balance scheme
ISSW	International Snow Science Workshop
LECA	Laboratoire d'Écologie Alpine
LEFE	Les Enveloppes Fluides et l'Environnement

LES	Large Eddy Simulation
LGGE	Laboratoire de Glaciologie et Géophysique de l'Environnement
LSM	Land Surface Model
LTHE	Laboratoire d'étude des Transferts en Hydrologie et Environnement
MEPRA	Modèle Expert pour la Prévision du Risque d'Avalanches
MesoNH	Mesoscale Non Hydrostatic model
MODIS	MODerate resolution Imaging Spectroradiometer
MONISNOW	MONItoring SNOW in a changing climate ANR project
NetCDF	Network Common Data Form
NIR	Near InfraRed
NWP	Numerical Weather Prediction
OASIS	Ocean Atmosphere Sea-Ice Snowpack project
ORCHIDEE	Organizing Carbon and Hydrology in Dynamic Ecosystems land surface model
OSUG	Observatoire des Sciences de l'Univers de Grenoble
PRESHINE	Pressions sur les Ressources en Eau et en Sols de l'Himalaya Népalais ANR project
QUASPPER	Quantitative Assessment and modeling of Snow Physical PropERTies project
REV	Representative Elementary Volume
S2M	SAFRAN - SURFEX/ISBA-Crocus - MEPRA
SAFRAN	Système d'Analyse Fournissant des Renseignements Atmosphériques pour la Nivologie
SEKF	Simplified Extended Kalman Filter
SnowMIP	Snowpack Model Intercomparison Project
SPC-AN	Service de Prévision des Crues - Alpes du Nord
SPICE	Solid Precipitation InterComparison Experiment
SSA	Specific Surface Area
SURFEX	SURFace EXternalisée
svn	subversion (version control software)
SWE	Snow water equivalent
SWIR	Short-Wavelength InfraRed
TARTES	Two-stream Analytical Radiative TransfEr in Snow
UMI	Unité Mixte Internationale
WMO	World Meteorological Organization

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