Lac Blanc Pass: a natural wind-tunnel for studying drifting snow at 2700ma.s.l

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ABSTRACT: The investigation of the spatial variability of snow depth in high alpine areas is an important topic in snow hydrology, glacier and avalanche research and the transport of snow by wind is an important process for the distribution of snow in mountainous regions. That's why, for 25 years IRSTEA (previously Cemagref) and Météo France (Centre for the Study of Snow) have joined together in studying drifting snow at Col du Lac Blanc 2700 m a.s.l. near the Alpe d'Huez ski resort in the French Alps. Initially, the site was mainly equipped with conventional meteorological stations and a network of snow poles, in order to test numerical models of drifting snow Sytron (CEN) and NEMO (Cemagref). These models are complementary in terms of spatial and temporal scales: outputs of Sytron model will form the inputs of NEMO model. Then new sensors and technologies appeared which allow to develop new knowledge dealing with thresholds velocity according to morphological features of snow grains, snow flux profiles including parameters such as fall velocity and Schmidt number, histograms of particle widths, aerodynamic roughness, gust factors. More recently, the coupled snowpack/atmosphere model Meso-NH/Crocus has been evaluated at the experimental site. At the same time, some tested sensors have been deployed in Adelie Land in Antarctica, where blowing snow accounts for a major component of the surface mass balance. Japanese and Austrian research teams have been accomodated at Lac Blanc Pass and new foreign teams are welcome. Initial observations continue. That's why Lac Blanc Pass is also a climatological reference for 25 years at 2700 m. Data are available.

KEYWORDS: Snow, wind, drifting snow, blowing snow, model, sensor.

1 INTRODUCTION

Wind-transported snow is a common phenomenon in cold windy areas such as mountainous and polar regions. The wind erodes snow from high-wind speed areas and deposits it in low-wind speed areas. The resulting snowdrifts often cause problems for infrastructure and road maintenance and contribute significantly to the loading of the avalanche release area. In Antarctica, blowing snow accounts for a significant component of the surface mass balance near the coast.

For 25 years IRSTEA (previously Cemagref) and Météo France (Centre for the Study of Snow) have joined together in studying drifting snow at Col du Lac Blanc 2700 m a.s.l. near the Alpe d'Huez ski resort in the French Alps. This paper aims at giving an overview of research and results obtained thank to this experimental site.

It is organized as follows. Section 2 describes the experimental site, the numerical models and the meteorological data acquired to test models performance in the 1990s. Section 3 focus on new sensors which appeared at the beginning of the 2000s, results obtained thanks to this new technology and correlatively improvements of numerical models.

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2 LAC BLANC PASS EXPERIMENTAL TEST SITE 1999-2000 : FROM MODELLING TO OBSERVATIONS

2.1 *Description of the site, first available instrumentation and drifting snow studies*

The experimental site (Figure 1) is located at the Alpe d'Huez ski resort near Grenoble, France. The large north–south-oriented pass (Col du Lac Blanc) has been dedicated to the study of blowing snow in high mountainous regions for approximately 20 years by IRSTEA –

previously Cemagref (Snow Avalanche Engineering and Torrent Control Research Unit) and Météo France (Snow Study Centre). Due to the surrounding topography, the pass may be considered as a natural wind-tunnel (Naaim-Bouvet et al., 2000). Wind direction measurements indicate that North-East or South stand for 80% of the wind directions. Besides snow transport is observed during 10.5% of the time in winter (Vionnet et al., 2013a). For 25 years, three automatic weather stations (AWS) (Figure 2) are located around the pass and record meteorological data every 15 min in wintertime: wind speed (mean, maximum, minimum), wind direction, air temperature, snow depth and amount of precipitation (it must be noticed that precipitation data suffer from high uncertainty due to strong winds). These meteorological sensors have been completed by six acoustic drifting snow sensors (Figure 2) developed by IRSTEA in collaboration with Hydroemac (Font et al., 1998). This is basically a miniature microphone located at the base of a 2 m long aluminium pole during snowdrift: the pole is exposed to the snow-particle flux and the sound produced by impact is recorded as an electronic signal. Calibration tests were not conclusive and such sensors have been used to detect beginning and duration of drifting snow events. These automatically recorded data were completed by manual measurements (stratigraphic profile of the snowpack, ram test, estimation of snow fluxes thanks to mechanical snow traps called « butterfly nets », snow depth measurements thanks to a network of snow poles).

All these measurements allow to perform analysis of drifting snow situations and of their effects on the snow distribution (Guyomarc'h et al., 2010). One of the most important contribution was the determination of the threshold velocity for snow particles erosion according to the snow surface features (Guyomarc'h and Merindol, 1998), (Merindol et al., 2000).

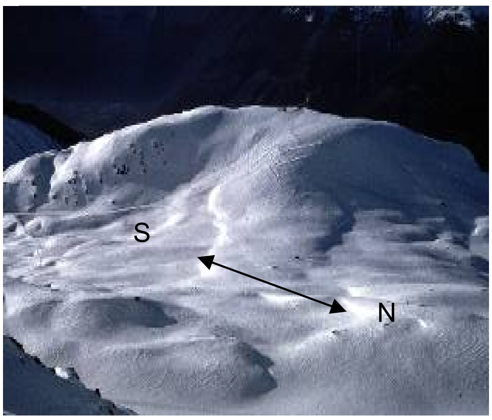

Figure 1. Lac Blanc Pass

Figure 2. Automatic weather station, accoustic drifting snow sensor and network of snow poles in the background

So, a drifting snow occurrence index has been defined taking into account the wind velocity and the characteristics of the snow surface grains (Figure 3).

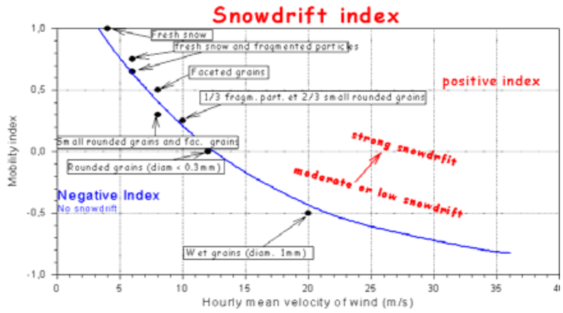

Figure 3. Snowdrift occurrence index according to wind velocity (x axis) and the potential mobility of the snow surface particles (y axis) depending of the grain cohesion.

But the experimental device was also specified for allowing the validation of numerical models developed by IRSTEA (NEMO) and Météo-France (SYTRON). The modeling developed by these laboratories are complementary and permit to describe the phenomena at different scales: outputs of Sytron model (45 m mesh, time step: 1 hour) will form the inputs of NEMO model (mesh: 1 m, time step: 10 minutes).

2.2 Description of NEMO model

The numerical model developed by IRSTEA under the name NEMO (Naaim et al., 1998) is an Eulerian multiphase model. It is based on continuum mechanics and it includes a description of physical processes included in the diffusion and saltation layers. The resolution is about one meter (or less) and its domain of application is about a hundred meters (typically an avalanche path). This paper does not aim at introducing the model in details but only at specifying its principal characteristics (Figure 4). In such way, input parameters can be identified. NEMO takes into account inertia of snow erosion and snow deposition. The saltation layer is described by its height, its concentration and two turbulent friction velocities, one for the solid phase and one for the gaseous phase. Expression of these friction velocities depend on particles concentration. The saltation layer is considered as the lower boundary of the suspension layer. The suspension layer is described by mass- and momentum-conservation equations for both the solid and gaseous phases. The interaction between these two phases was taken into account by an equation based on the drag force of a particle in a turbulent flow. Turbulence is modelled by the k-ε model, in which a reduction of turbulence with the concentration is introduced. Turbulent diffusion of the solid phase is considered higher than the turbulent diffusion of the gaseous phase thanks to a Schmidt number < 1. The exchange between the saltation layer and the snow cover is described by an erosion and a deposition model. The mesh is adapted to the time evolution of deposit.

The model needs a set of input parameters including fall velocity, threshold shear velocity, shear velocity, aerodynamic roughness. NEMO has been tested by comparing leeward and windward saw-dust drift equilibrium obtained in a wind-tunnel near a small-scale solid snow-fence with a bottom gap (Naaim et al., 1998) with all these input parameter known and constant throughout the experiment. The obtained numerical results are close to experimental results (Figure 5). But the results were less conclusive when comparing numerical data with field experiments carried out at Lac Blanc pass (Michaux J-L et al., 2001). In this case, input parameters came from automatic weather station (duration of the event, wind speed, threshold wind speed) or are estimated from semi-empirical relationships (maximum particle concentration in the saltation layer, height of the saltation layer, Schmidt number, snow particle terminal velocity, aerodynamic roughness modified by the presence of snow particles) obtained with data collected under different conditions than those encountered in the Alps. The numerical model was a little bit modified in order to reduce calculation time and additional hypothesis have been done. Nevertheless, it is likely that an important source of uncertainty may be due to inaccuracies in estimating input parameters.

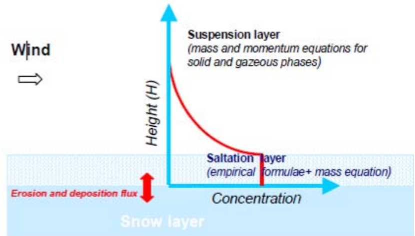

Figure 4. Characteristics of the numerical model

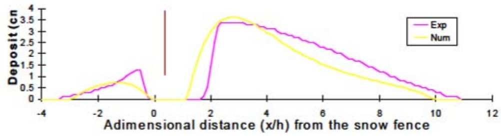

Figure 5. Comparison between numerical and experimental results in wind-tunnel (u_*=0.23 m.s^{-1}, u_{*t}=0,21 m.s^{-1})

2.3 Description of SYTRON 1 model

The SCM chain (Durand et al., 1999) composed of the software SAFRAN, Crocus and Mepra is an automatic suite of snow cover numerical simulation including a detailed stratigraphy and the potential avalanche risks at the spatial scale of a mountainous massif (~400 km^2), but at various altitudes, aspects and slopes. The snowdrift index (Figure 3) automatically calculated, is used both operationally by Météo-France forecasters and it is also integrated into higher-level numerical models in order to provide initial conditions for the computation of blowing snow fluxes. (Sytron 1 and 2, see the following paragraphs (Gallée et al., 2001)). Sytron1 (Durand et al., 2001) is a raw parameterization in pre-operational testing, integrated into the SCM chain (Durand et al., 1999) which aims at simulating the effects of transported snow at this massif scale without really modeling the underlying fine-scale phenomena. Practically Sytron 1 removes an estimated amount of snow on windward slopes and redeposits it on the leeward side at all the altitudes simulated by SCM (by 300 m vertical steps) inside each massif (Figure 6). The different steps of the process are:

- Estimation of speed and direction of wind transport using SAFRAN and determination of the occurrence of transport using the transport index.

- Determination of the amount of snow transported on the two opposite aspects (creep + saltation + turbulent diffusion) and loss by sublimation.

- Modification of Crocus profiles in order to take dynamically into account the perturbations induced by snow transport phenomena (modification of the grains, densification, aggregation, loss or addition of mass).

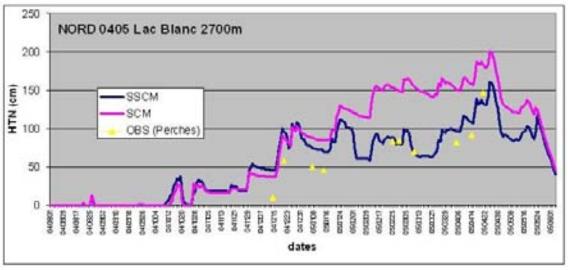

Figure 6. Snow depths (2004-2005 winter season) modeled with use of Sytron1 (SSCM) and without (SCM) at the Lac Blanc site. Modeled data are compared to pole measurements.

3 LAC BLANC PASS EXPERIMENTAL TEST SITE 2000-2013 : FROM OBSERVATIONS TO MODELLING

Then developments in the field of instrumentation and the increasing investment on the site allowed to test assumptions used in the models. The physical processes involved in drifting snow have been studied more deeply to be better taken into account in the models (Naaim-Bouvet et al., 2008). At the same time, the instrumentation also allowed an estimate of the output parameters (snow depth) with higher spatial resolution.

3.1 Improving sensors set up at Lac Blanc Pass

<u>Anemometers</u>

In 2004 the site was fitted with a three-dimensional ultrasonic anemometer (Metek USA-1) set up at 3.3 meter high. Then in 2007, six anemometers and three temperature sensors were mounted on a 10-m vertical mast with logarithm vertical spacing. The mast aimed at better investigating the friction velocity and the aerodynamic roughness (Figure 7b).

<u>Drifting snow sensors</u>

Measurements of drifting snow flux is one of the key challenges (Bellot et al., 2010). Although sensors for wind measurements may be reliable and accurate, this is still not the case for all blowing snow sensors and one of the goals of this site was the comparison of different blowing snow sensors.

The first sensors used to estimate the flux where snow traps consisted of butterfly nets, i.e., a metallic frame with a nylon mesh bag attached. The mixture of air and snow grains goes through the traps and while the snow is collected in the bag, the air escapes through the pores. They need presence of operators on-site. But they are still the best reference and are used when calibrating other automatic sensors based on acoustic or optic principles (Figure 7a).

In the late 1990s, a Swiss company (IAV Engineering) placed on the market a snowdrift sensor named FlowCapt, based on a acoustic principle, similar to the one developed by Cemagref and AUTEG. A flowcapt sensor consisting in 6 independent vertical Teflon coated tubes with microphone inside was set up in 2004. The device was delivered with complete calibration performed with a controlled flux of PVC particles at a constant velocity (1 m/s^{-1}) and give an estimation of mass flux of snow ($g.m^{-2}.s^{-1}$). Nevertheless, experiment carried out in wind tunnel and at Lac Blanc Pass (Cierco et al., 2007) showed that estimated flux depended on the grain types but also on particle velocity: it varied with the inverse of the particle velocity to the fourth power so that the acoustic sensor appeared to be insufficiently accurate whatever the calibration may.

That's why we turned to another sensor, the snow particle counter (SPC-S7, Niigata electric), which is an optical device (Figure 8). The diameter and the number of blowing snow particles are detected by their shadows on photosensitive semiconductors. It detects particles between 50 and 500 µm in size, divided into 32 classes and allows to calculate the horizontal snow mass flux assuming spherical snow particles. SPC and snow traps showed a good agreement (Naaim-Bouvet et al., 2010). At the present time, 4 SPC are mounted on a 3 m vertical mast which aims at better investigate drifting snow flux profiles. Output signals from SPC acquired at high frequency also allow to determine particle speeds (Nishimura et al., 2013).

However, the SPC requires a large power supply and data are stored on computer. Deployment of an SPC is therefore not always practical for unmanned observations, particularly under the severe conditions in Antarctica. That's why a Japanese team (Nishimura and Ishimaru, 2012) developed a simpler device – the automatic blowing-snow station (ABS) – that measures the attenuation of light intensity, which is strongly influenced by the blowing snow flux. This device is currently tested at Lac Blanc pass. At the same time we also tested at Lac Blanc pass the sensor Wenglor YH08PCT8, a simple and cheap commercial counter which allows the recognition of extremely small parts, holes, slots and notches in industry. It was already tested for 5 years as a sensor for Aeolian sand and snow transport.

a) b)

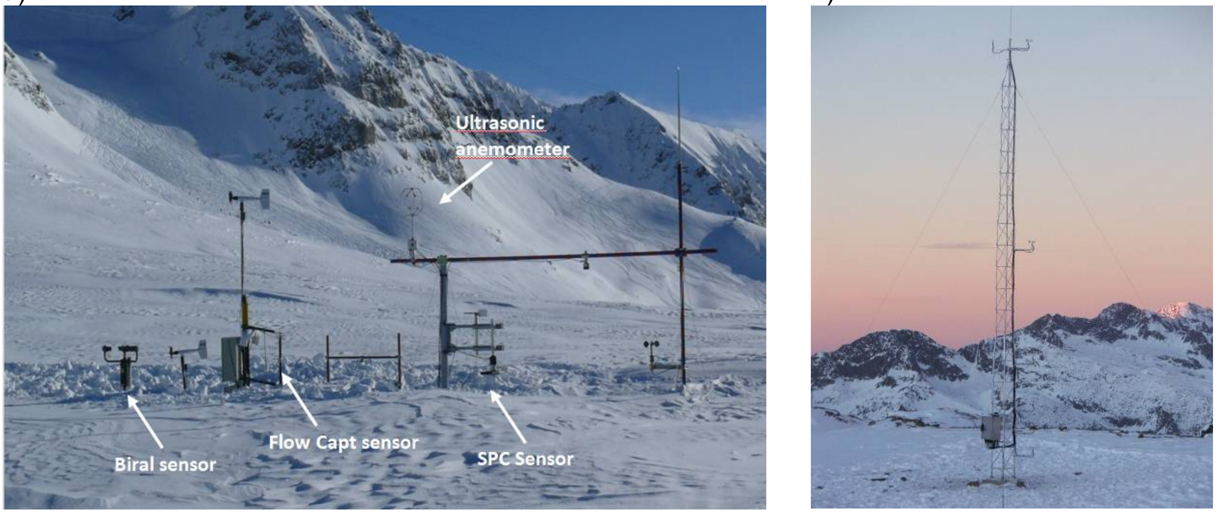

Figure 7. a) Drifting snow measuring station including different sensors and b) A tower 10 m high with 6 anemometers including snow depth and temperature measurements

The Wenglor sensor's performance and limitations in the framework of blowing snow measurements are presented within this proceeding (Bellot et al., 2003).

Finally a present weather station (PWS), Biral VPF730, was set up in Antarctica and then at Lac Blanc Pass in order to estimate the drifting snow fluxes, even if it was not designed for such purposes (Bellot et al., 2011). Results were not conclusive. First, it was necessary to treat the raw data contained in the size/velocity matrix because the software rejected some drifting snow particles considered as nonhydrometeoric particles. Secondly, the Biral VPF730 detected one larger particle instead of several smaller particles.

Figure 8. A Snow Particle Counter

Spatial distribution of snow

Estimation of snow albedo allowed to monitor the spatial distribution of snow with higher spatial resolution than those obtained by network of snow poles. This experiment (Corripio et al., 2004) is based on the retrieval from terrestrial photographs of the spatial variations of the snow reflectivity and the snow texture in order to detect and localize the blowing snow phenomena that modifies the surface grains and therefore changes the radiative characteristics. This identification of erosion and accumulation areas is crucial for the validation of the used models (Sytron NEMO ...). This estimation is made using a radiative transfer model to calculate the energy by spectral bands, visible and very near infrared, of the solar radiation in taking into account the uncertainties due to the response curve of the camera. The obtained result is an albedo map (ratio of solar energy reflected on the incident energy) that is directly comparable to the outputs of the model.

a) b)

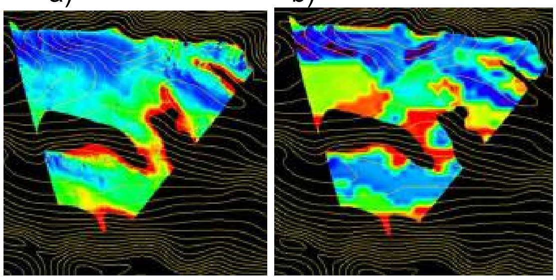

Figure 9. Comparison between relative albedo maps estimated (a) from photography and (b) deduced from the snow surface grains of Sytron2 on the February 18th 2003. Colors are enhanced in to order to highlight the differences (in red the highest values). North is on the right and the photography is taken from «Pic Blanc».

In parallel, the terrestrial laser scan (Figure 10) has shown its ability to directly retrieve the spatial repartition of snow depth in including the steep slopes (Prokop, 2008). This technology has presently been used since the measurement campaigns 2010-2011 and 2011-2012.

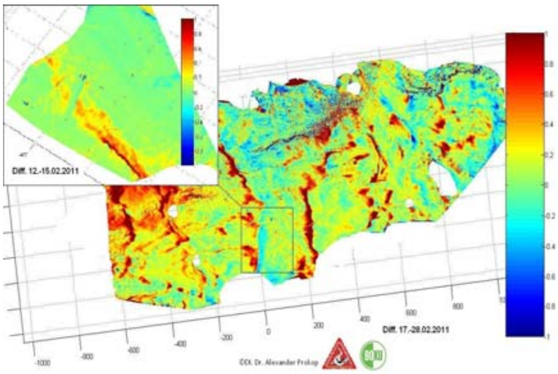

Figure 10. Snow height maps obtained by terrestrial laser scan.

3.2 Towards a better knowledge of the physical processes

The first results obtained thanks to these new sensors have shown that for the studied drifting snow events (Naaim-Bouvet et al., 2008), (Naaim-Bouvet et al., 2010), (Naaim-Bouvet et al., 2011) :

- the proportionality of the aerodynamic roughness to the square of the friction velocity seems to be confirmed but with a constant depending on the snow drift event and with a rather low coefficient correlation (Figure 11).
- Values of $\sigma_s U_F$ (σ_s is the Schmidt number and U_F the snow particle terminal velocity) are relatively well approximated by empirical formulae obtained thanks to Antarctica data (Naaim-Bouvet et al., 1996)
- Snowdrift concentration profiles obtained by Pomeroy's semi-empirical formulae (Pomeroy and Gray, 1986) for the saltation layer coupled with theoretical approach for the diffusion layer leads to an overestimation of the concentration profiles

$$C(z)=\frac{2*0.68}{2.8*1.6}\frac{\rho}{u_*}\left(1-\frac{u_{*t}^2}{u_*^2}\right)\left(\frac{z}{0.08436u_*^{1.27}}\right)^{-\frac{\sigma_s U_F}{\kappa u_*}}$$

- In the Alps, as already observed in Antarctica, the size distribution of the snow particles fits well with a gamma density function both for the 1-s peak and 10-min drifting snow events.
- High drifting snow gust factors (i.e. drifting snow gust much higher than wind gust) were observed

Recent experiments also showed that the snow particle speed and the wind speed increase with height, but the former is always smaller than the latter one at less than 1 m high (Nishimura et al., 2013)

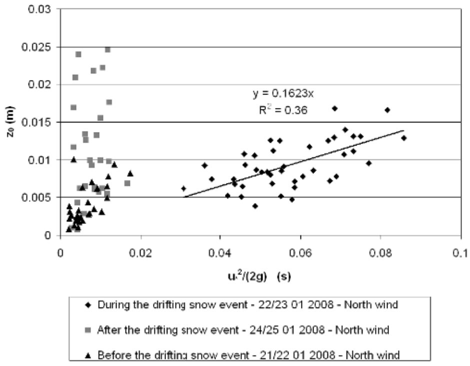

Figure 11. Aerodynamic roughness height plotted against for the 15–16 February 2008 period now height maps obtained by terrestrial laser scan.

3.3 … for better modeling

Thanks to measurements collected at Col du Lac Blanc on a weekly basis and during specific blowing events, distributed versions of Sytron 1 have been developed (Sytron 2 et 3, Durand et al., 2004, 2005). They allow the realistic simulation of horizontal and vertical snow mass transfer over a limited domain (horizontal resolution 50 m) included in a massif where results from the SCM chain are available.

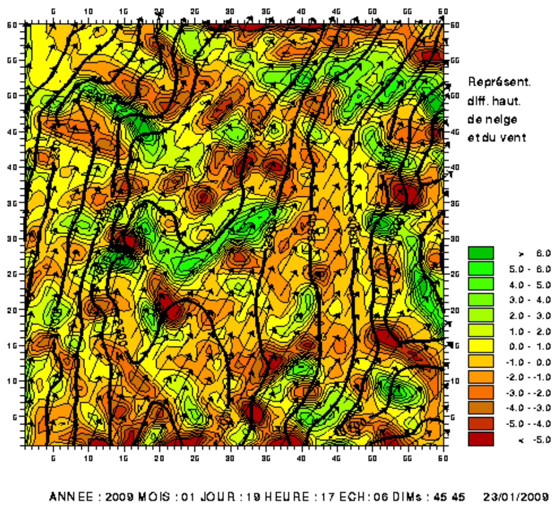

Figure 12. Effects of wind-induced snow transport simulated at Col du Lac Blanc. This map shows the difference of snow depth in meters between 6 pm and 0 am on January 19 2009 and the wind field at the end of the event. The unit for the domain is the mesh (it must be multiplied by 50 to obtain the distance in meters)

Figure 12 shows the effects of wind on the total snow depth simulated by Sytron 3 over a domain centered at Col du Lac Blanc during a 18-

hour blowing snow event. It illustrates the complex interactions between the wind field, the topography and the snowpack. Arrows represent the wind field for a southern flow computed by a diagnostic 2D wind model at the same horizontal resolution (50 m). Green and blue colors depict areas of snow deposition generally located on leeward side while regions snow of erosion are shown in red. The maximum snow depth difference reaches 7 cm for wind speed ranging from 10 to 15 m s^{-1}.

The latest advances in term of distributed simulation of wind-induced snow transport concern the development of the fully coupled snowpack/atmosphere model Meso-NH/Crocus which has been evaluated at Col du Lac Blanc (Vionnet et al., 2011, Vionnet et al, 2013b). Such system allows the interactive simulation of 3D atmospheric flow in alpine terrain, snowfall and resulting wind-induced snow transport in saltation and turbulent suspension. The loss of snow mass due to the sublimation of suspended snow particles is also included. Figure 13 shows a map of difference of snow water equivalent (SWE) around Col du Lac Blanc simulated for a blowing snow event with concurrent snowfall. During this event, the wind blew continuously from the south. Large areas exposed to the wind show no accumulation of snowfall (see dashed region on Figure 13 for example). On the other hand, regions sheltered from the wind receive snow accumulation from snowfall and from snow eroded upwind. Meso-NH/Crocus appears as a promising numerical tool to better understand the different sources of spatial variability of the mountain snow cover (Vionnet et al., 2013b).

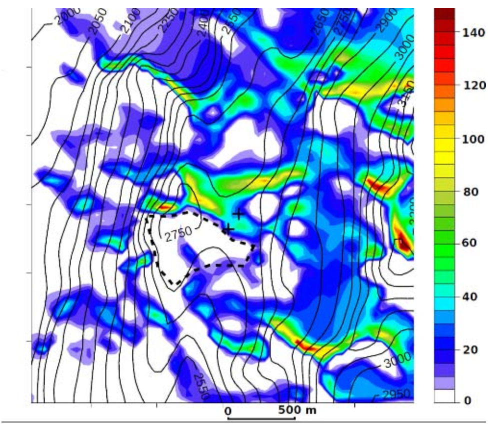

Figure 13. Maps of SWE difference (mm) between 12 am on February 15 2011 and 15 pm on February 14 2011 simulated by Meso-NH/Crocus at an horizontal resolution of 50 m.

4 CONCLUSIONS AND PERSPECTIVES

Drifting snow is a complex phenomenon at different spatial scales and is representative of the mutual interaction between atmosphere and snow cover. The detailed knowledge of involved physical processes is extremely difficult to acquire. Addressing this problem therefore requires a synergy of resources, teams, sites, specialties and expertise. It was done at Lac Blanc Pass, an experimental site which has allowed to observe, model, validate, and observe again in a different way to refine existing models. It leaded to a continuous improvement of our knowledge in drifting and blowing snow area. Lac Blanc Pass is also a climatological reference for 25 years at 2700 m. We look forward to continuing with partners toward that goal.

5 ACKNOWLEDGMENTS

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