EFFECTS OF SAHARAN DUST OUTBREAKS ON THE SNOW STABILITY IN THE PYRENEES

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ABSTRACT: Saharan dust outbreaks occur nearly every winter in the Pyrenees. It is well established that dust layers on the top of the snowpack reduce the snow albedo and hence potentially accelerate snow melt. In addition, such dust layers once buried in the snowpack may behave as critical layers and are often reported as associated to avalanche activity. However, studies addressing in detail why buried dust layers might form potentially dangerous layers causing significant avalanche release are scarce. A study involving both monitoring of natural deposited dust layers and a field experiment in the Pyrenees have been conducted to test and support previous observations that faceting and crust formation within the dust layer are key processes for avalanche release. The field experiment consisted in reproducing a pair of dust deposition events artificially on North and South aspects slopes at tree-line elevation, and monitoring the metamorphism and stability of these artificial dust layers with subsequence snowfalls in the snowpack. Both natural and artificial dust layers were investigated first in dry cold and then wet, isothermal snowpack.

KEYWORDS: Snowpack structure, variability and metamorphism; Avalanche formation, release and dynamics.

1. INTRODUCTION

In the Pyrenees mountains range, mineral dust deposition events are frequent. In Eastern Pyrenees, between 1983 and 1994, the average number of weeks per year with observed African dust in rainfall was 3.3. The average annual dust deposition was 5.3 g m-² [Avila et al. (1997)]. Mineral dust cloud comes from Saharan desert and cross Europe up to Norway. Dusty layers are clearly visible on the snowpack due to their reddish color. Such dust layers once buried in the snowpack may behave as critical layers and are often reported as associated to avalanche activity. On April 2016, a French skier disappeared with an avalanche showing a shear failure just above the dust layer.

Only a few studies can be found in the literature to describe how dust can affect the mechanical stability of the snowpack [Landry (2014), Hardy et al (2001)]. Dust on snow directly affects the snowpack energy balance by reducing snow albedo and thus enhancing the amount of solar energy absorbed by the snowpack. A few studies have reported the dust impact on snowpack structure. The Center for Snow and Avalanches Studies, in Silverton, Colorado, has documented and monitored 91 dust events. In dry and cold conditions, dust can enhance gradient metamorphism at or near snowpack surface, creating persistent weak layer by the growth of near-surface faceted crystals in the still-cold snowcover [Landry, 2014]. At the end of the winter, dust radiative forcing accelerates snowpack melt [Painter et al., 2012].

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Recent development in detailed snow model such as the multi layer model SURFEX/ISBA-Crocus [Brun et al., 1989 ; Vionnet et al., 2012] allow to represent the effect of light absorbing impurities such as mineral dust on snowpack metamorphism and melt [Dumont et al., 2015].

In Pyrenees mountains range, the Sahara dust deposition occurs two or three times each winter. According to LIDAR observations, the source-region of the dust transport across Mediterranean and into Europe comes from North Africa : Tunisia, Algeria, Libya [Knippertz et al, 2012]. The convection force, formed by the strong heating of the Sahara and the Sahel regions, allows uplifting of huge quantities of dust. This one is transported westward into the Atlantic Ocean and southward with the strong northerlies, especially in the summer months. However, a significant part, estimated as 80–120 Tg per year, transported northward across the Mediterranean into southern Europe, some time as far north into Scandinavia [Barkan et al., 2004a, 2005]

To our knowledge, no studies have reported the dust effect on the snowpack stability in the Pyrenees mountains range. Our study has built upon considerable work investigating buried dust layers in response to avalanche release resulting in dangerous Sahara dust layers. This study describes snowpack observations during winter 2013-2014 and 2015-2016 under natural dust deposition conditions in the Eastern Pyrenees. We also conducted an experiment consisting in reproducing a pair of dust deposition events artificially on North and South aspects slopes. Examples of dust effect on snow stability are presented and associated with “clean” snowpack structure.

In addition, in order to better understand the impact of dust on snow metamorphism, snowpack simulations using the multilayer snow model SURFEX/ISBA-Crocus were performed for winter 2015-2016 in Aran Valley (Spain) simulating a dust deposition event in February 2016.

2. STUDY SITE.

Datas were collected in the Eastern Pyrenees, in the Aran Valley, Catalonia, Spain (Fig. 1). This valley is subject to Atlantic climat. The precipitation is around 150cm.yr^{-1}. Snow height ranges from 1 to 3 m at Bonaigua site (2263 m).

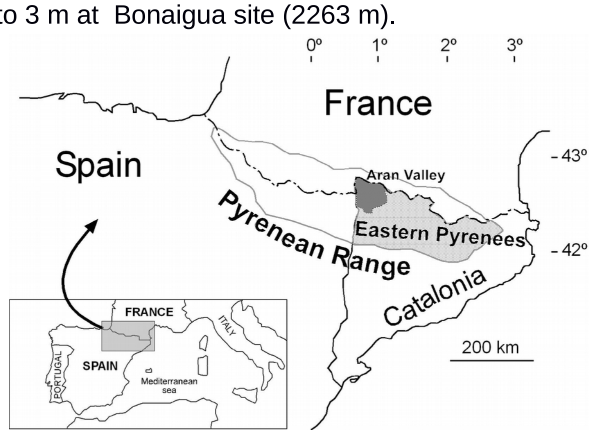

Figure 1: Study site location

3. DUST DEPOSITION ON THE SNOWPACK

3.1. *Weather and deposition*

During winter 2013-2014 and 2015-2016, the south storm brought a huge dust quantity from the Sahara desert. In the atmosphere, the dust load for each event was between 0.5-2.5 g/m² and the dust cloud cover stayed 36 to 48h in the atmosphere above the Eastern Pyrenees (data from the NMMB/BSC-Dust model, operated by the Barcelona Supercomputing Center*)* . The figure 2 presents the dust load in the atmosphere on February 2014 over Europe. The dust cloud crossed Europe up to Norway, with strong northward wind.

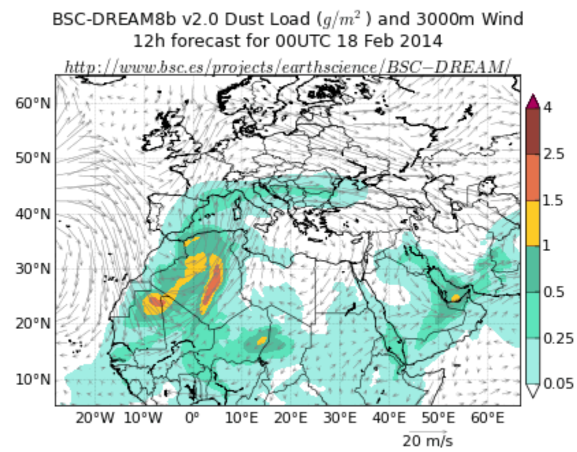

Figure 2: Dust load distribution from the BSC-DREAM8b model, operated by the Barcelona Supercomputing Center. (http://www.bsc.es/projects/earthscience/BSC-DREAM/)

3.2. *Impact on the snowpack*

On February 18th 2014, dry deposition occurred at the top of the snowpack. During the following week, the temperatures kept high (-5°C to 0°C at 2263m during the day), with mostly clear skies. Close to the surface, dust layer enhances the solar energy absorption by reducing the snow albedo, increasing the snow surface temperature. Then, the Saharan dust layer was buried by one meter of snow accumulated over 3 days. The snowfall was accompanied with a decrease in temperature (-4°C over 24h, data from Bonaigua station). A temperature gradient (moderate to strong : 5 to 20°C/m) appeared between the warm dust layer and the cold snow (data from snow profiles). According to Jameison (2006), these conditions enable the faceted snow crystal growth above the Sahara dust crust. The faceted snow layers behaved as weak layers for the observed avalanches activities. Ten snow profiles were recorded (in all aspects, 2000-2800m) after the dust deposition and almost all of them have the same snowpack structure (Fig. 3). The Saharan dust formed an hard melt freeze crust. Above this one, facets behave like a weak layer with low hardness (“fist"). Figure 3 shows a snow profile recorded close to a long avalanche crown on the Saharan crust, on March 3th 2014. The avalanche crown was on the weak layer, in red on the figure 3.

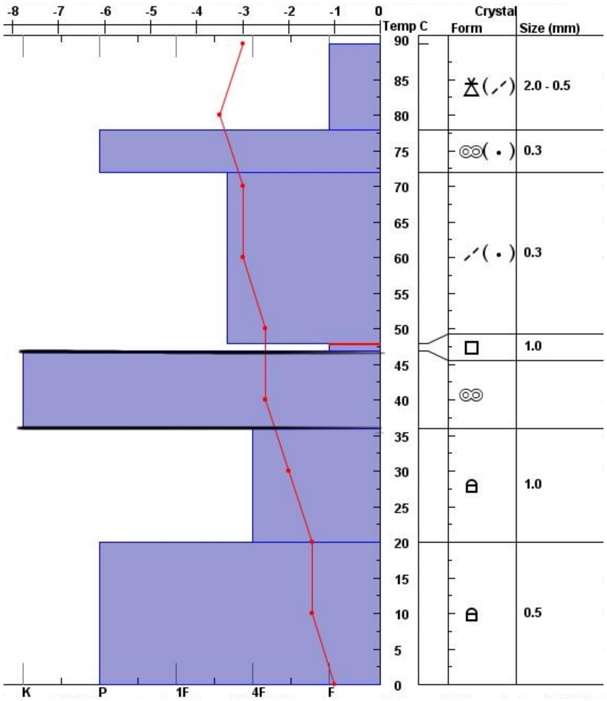

Figure 3: Snow stratigraphic profile observed closeto the avalanche crown, Llança, 2550 m,SW, slope 42°, air temperature :-8.1°C,covered sky 8/8, 03/03/2014. Black: dustlayer, Red: avalanche starting zone.

On February 21th 2016, the Saharan dust deposition was important and wet. On february 22th-23rd 2016, we collected three snow samples on different sites (Bonaigua site 2263m, Sasséuva site 2126 m , Comalada site 2153m). We filtered them with 'Glassmicrofibre filters GF/F 47 mm' and dried them into an oven (12h at 50°C). The median quantity of dust on the snowpack surface measured from the samples is 1.8 g/m². This year, the winter was warmer than 2014. Snow depth was smaller than in 2014 and we did not observe a new weak layer formation above Saharan dust layer. The dust layer stayed a long time within the first 30 cm of the snowpack. The temperature gradient at the top of the snowpack was weak, resulting to the formation of rounded grain near the dust layer.

4. DUST DEPOSITION EXPERIMENT

To understand dust layer impact on the snowpack, we set up an experiment that compares a snowpack with a dust layer and a clean one.

The experiment was realized close to the Baqueira ski station at 2150m, near a mountain pass, in North and South aspects. The wind effect on the experimental parcels is negligible. Red clay was spread on the snowpack, the color is visually similar to Saharan dust (Fig. 5). Red clay distribution size is around 10 micrometers. According to McTainsh et al (1997), long-distance dust deposition from West Africa produces fine deposits (mainly < 5 µm).

The experimental protocol for dust deposition is as follows :

- Four fields 10*10 m² are used, two in North aspect, and two in South.
- One field at each aspect is kept without dust, those fields are the references.
- The other fields (one at each aspect) are divided in two, one part is for wet deposition on the 19-02-2016, the other part is for the wet deposition on the 15-03-2016 (Fig. 4).
- Wet dust deposition simulates 0.2 mm precipitation containing 2g/m² of dust. To keep the deposition easier, we worked on plots of 25m². We used a 5 liters air spray of water with 50g of dust for each wet plot.

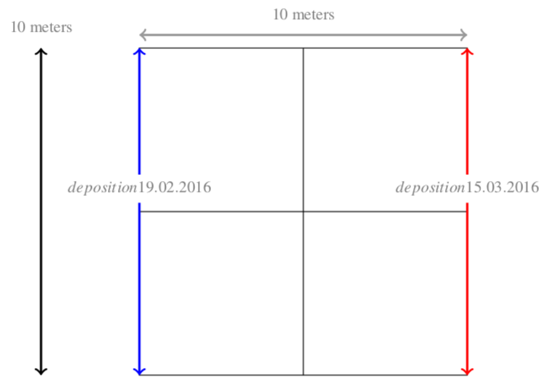

Figure 4: Ground scheme, red clay deposition

In order to follow the snowpack evolution, we recorded complete snow profiles (temperature, grain shape, grain size, humidity, snow depth, hardness) and performed a stability test: Compression test according to Jameison et al. 1997, Extended column test according to Simenhois et al. 2006. Profiles were recorded 2 or 3 times a week. The first red clay deposition was directly buried by the Saharan dust deposition and mixed with it. Unfortunately, we could not compare the dust snowpack with the clean one in dry and cold conditions.

Figure 5: North experimental plot, 2150m, slope 23°, 15/3/2016.

After the second red clay deposition, a melt freeze crust appears on all plot except in North 'clean' plot. On North aspect, facets are formed on the dust melt-freeze layer, over the “dirty” plot. Just enough solar radiation is absorbed by the red clay dust to establish (once buried) a temperature and vapor gradient. Snow profiles show temperature gradient from 5 to 20°C/m close to the dust melt freeze layer. Then, increasing temperature promotes a quick transformation of facets to rounded grains.

In South aspect, the dust layer stays close to the surface. The spring conditions rapidly cause snowpack melt, particularly important on the dust field. The humidity is stronger on dust field than on 'clean' one. On march 21^{st}-23^{rd} 2016, on the dust field, wetness index is 3, according to Fierz et al, liquid water content (LWCm) in terms of volume fraction is 3-6%. While on the 'clean' one, the LWCm in terms of volume fraction is 3%.The Saharan layer close to the surface decrease the snow albedo.

5. DUST DEPOSITION SIMULATION ON SNOWPACK WITH CROCUS MODEL

The detailed snowpack model SURFEX/ISBA-Crocus has been developed by Meteo France for the avalanche forecasting over French mountains for 20yr [Brun et al., 1992 ; Vionnet et al., 2012]. Crocus is also used for a wide range of applications including hydrological and climatic studies. This model allows to represent the effect of light absorbing impurities such as mineral dust on snowpack metamorphism and melt [Dumont et al., 2015]. We present here the time evolution of the internal physical properties of the snow carried out by the snowpack scheme SURFEX/ISBA-Crocus.

The meteorological station at Sasséuva (2.226m altitude, 42°770' N, 0°732' E) in Aran Valley, Spain, has been used to collect meteorological data. The snowpack simulation has been realized from September 1^{st} 2016 to April 30th 2016 using meteorological parameter from the meteorological station and SAFRAN analysis for long and shortwave radiation (Durand et al., 1999). The wet mineral dust deposition, on the model, is from February 21^{st} 2016 at 18 UTC until February 22^{th} at 15 UTC (corresponding to the wet Sahara dust deposition over Eastern Pyrenees). Wet deposition fluxes are set so that the snowpack impurity content after the event is similar to the measured one.

Figure 6 shows that the direct dust effect on the snow is the increase of the solar radiation absorption, decreasing the snow broadband albedo (-0,2). By accelerating grain growth, the dust layer further reduce the albedo. This phenomenon induces a rapid snow metamorphism decreasing by 5 $m^2.kg^{-1}$ the specific snow surface (Fig. 7). Figure 8 shows that the dust layer increase near surface snowpack temperature by +1°C .

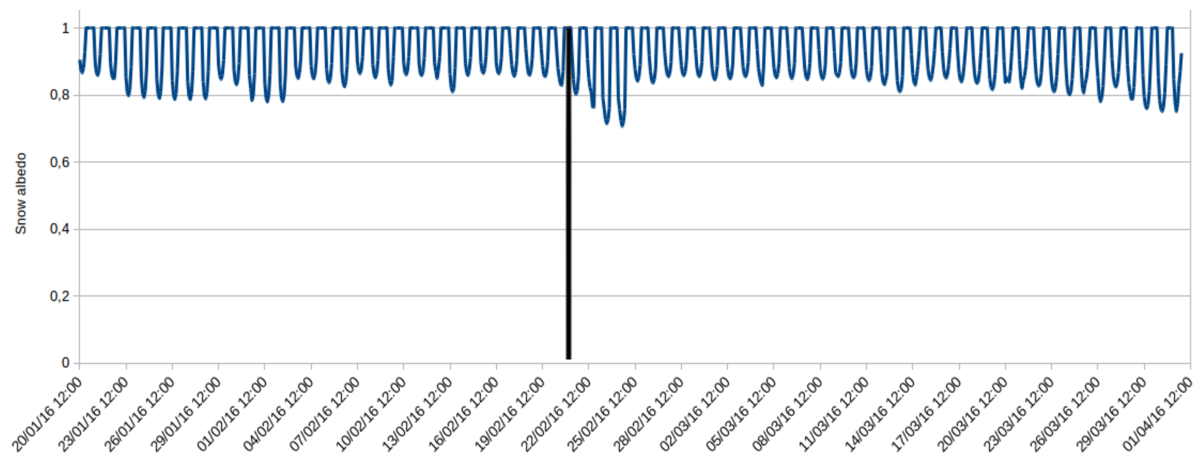

Figure 6: Snow albedo simulated by SURFEX/ISBA-Crocus snowpack scheme, dust deposition from February 21st 2016 18 UTC to 22nd at 15 UTC. Black line: impurities deposition on the model.

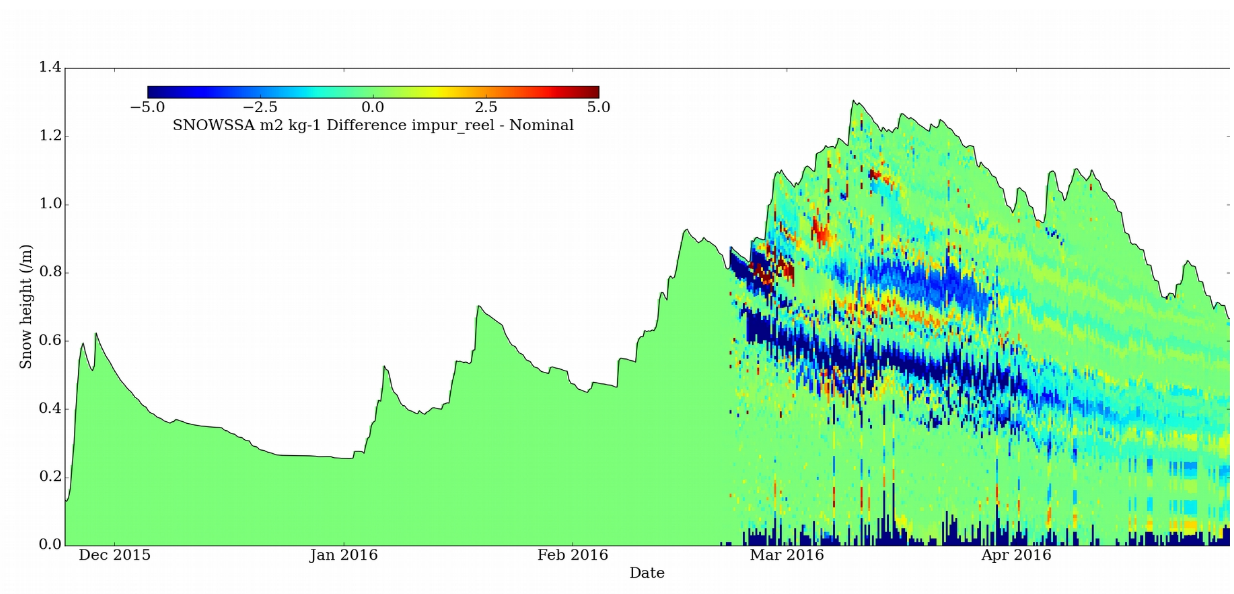

Figure 7: Time series of difference in snow SSA (m^2/kg) snowpack between the clean and the dusty snowpack simulated by SURFEX/ISBA-Crocus snowpack scheme, dust deposition from February 21st 2016 18 UTC to 22nd at 15 UTC. The difference was computed using the algorithm developed in Pilloix and Hagenmuller, 2016

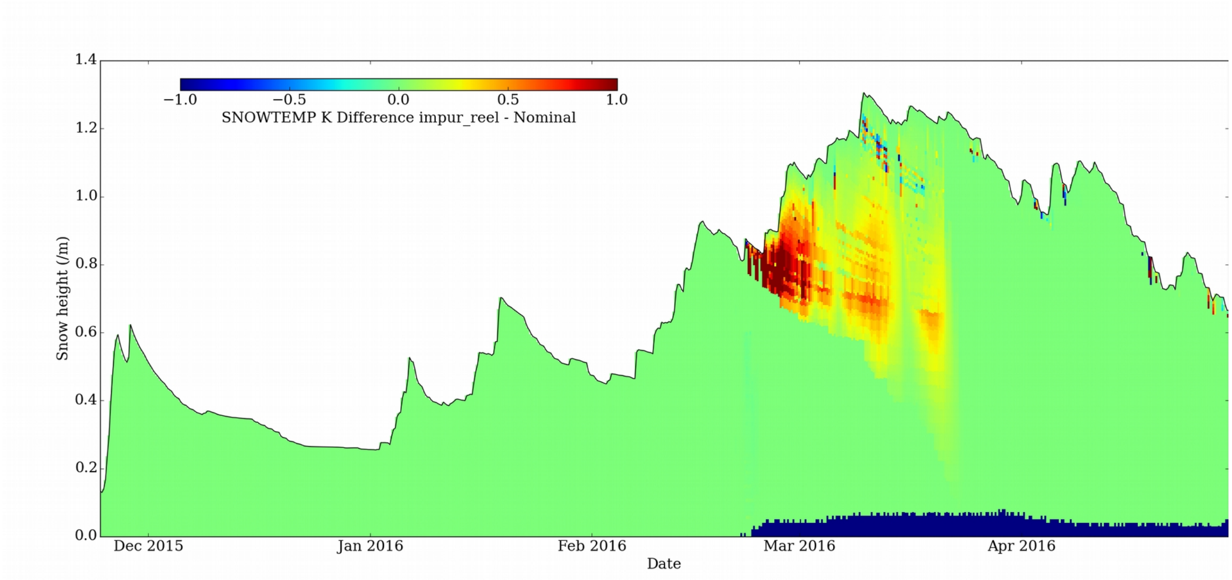

Figure 8: Times series of difference in surface snow temperature (K) between the clean and the dusty layers simulated by SURFEX/ISBA-Crocus snowpack scheme Crocus. Dust deposition from February 21st 2016 18 UTC to 22nd at 15 UTC. The difference was computed using the algorithm developed in Pilloix and Hagenmuller, 2016

6. DISCUSSION AND CONCLUSION

In the Pyrenees mountains range, dust deposition effect depends on the weather conditions. In fact, in 2014, the dust layer stayed one week on the surface, allowing a strong increase in absorbed solar radiation. The following cold snowstorm enhanced gradient metamorphism at the interface between the dust layer and the cold snow layer. A persistence weak layer formed above dust layer was the cause of many avalanches. In 2016, the winter was warm with less precipitations. The dust deposition stayed a long time on the first 30 cm of the snowpack. No weak layer was formed on the dust layer. The avalanches activities were weak in winter 2016.

For the first time in Pyrenees mountains range, an experiment on the dust effect on snow stability was performed. The weather conditions in winter 2016 were not favorable for the experiment (warm, small amount of precipitation). The experiment is then prepared for the next winter. To expand the data range, it will be interesting to do the first experiment at the beginning of the winter, repeat the experiment along the winter and change the dust deposition conditions. Furthermore, objective mechanical measurements should be done in the next experiment, using devices such as SnowMicroPen to quickly measure the snow penetration resistance.

The Crocus simulation with impurities allows to identify and quantify the positive feedbacks loops triggered by the presence of dust.

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