CHARACTERISTICS AND SEASONAL EVOLUTION OF FIRNS AND SNOW CORNICES IN THE HIGH VOSGES MOUNTAINS (EASTERN FRANCE)

LAURENT WAHL, OLIVIER PLANCHON and PIERRE-MARIE DAVID

With 10 figures and 5 tables
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In homage to Dr. LAURENT WAHL who died on December 18, 2008

Summary: Despite their relatively low elevation (about 1300–1400 m) and because of their cold and humid climate, the High Vosges Mountains in eastern France (at about 48°N 7°E) usually experience a long-lasting snow cover and the persistence of residual snow patches into late spring and summer, sometimes until mid-September. Snow accumulation in winter results in the formation of firns and snow cornices. Climate, topography and land cover of the High Vosges are favourable to snow accumulation on the upper leeward edges of fossil glacial cirques. Firns and snow cornices re-form at the same locations. Therefore, 40 sites (including 23 "firn sites" and 17 "cornices sites") were identified in glacial cirques, most of them facing E to NE and above 1150 m. The variability and succession of weather observed in winter and spring affect on the snow depth and the formation and duration of firns and snow cornices. While snowy winters are followed by a late melting of snow patches (high frequency of NW and N circulation types), mild and winters with little snow cover are followed by an early melting of small firns and snow cornices (high frequency of alternating south-westerly and westerly circulation types). A high frequency of cyclonic/anticyclonic northerly circulation types in spring reduces the snowmelt and sometimes causes new snowfalls. However, heavy rainfall in spring and high temperature in summer cause a rapid snowmelt and disappearance of firns and snow cornices. Slides of firns and cornice collapses increase slope erosion and a serious risk of avalanches occurs during and after snowy winters. Avalanches occur in glacial cirques because of their steep slopes and the Hohneck Massif is particularly subject. A map of the risk of avalanches in the Hohneck Massif in association with the location of the main firns and snow cornices is provided.

Zusammenfassung: Aufgrund des kalten und feuchten Klimas weisen die Hochvogesen in Ostfrankreich (um 48°N / 7°E) trotz ihrer relativen geringen Höhe (um 1300–1400 m), in der Regel eine lang anhaltende Schneebedeckung auf. Klima, Topographie und Landbedeckung begünstigen dabei in den Hochvogesen die jährlich wiederkehrende Schneeakkumulation vorzugsweise an den oberen leewärtigen Rändern fossiler Kar-Gletscher. Die winterliche Schneeakkumulation führt hier zur Ausbildung von Firnfeldern und Schneewechten, welche bis in den Frühsommer, stellenweise gar bis in den September überdauern. Im Rahmen der vorliegenden Studie wurden in entsprechenden Lagen 40 Standorte ausgewählt (23 „Firnstandorte" und 17 „Schneewechtenstandorte"; die meisten davon ost- bis nordostexponiert und in einer Höhenlage um 1150 m). Die Schneedeckenmächtigkeit sowie die Ausbildung und das Überdauern von Firnfeldern und Schneewechten wurde maßgeblich durch die Variabilität des Wettergeschehens bzw. vorherrschende Großwetterlagen gesteuert. So folgte auf schneereiche Winter eine späte Schneeschmelze im Frühjahr (bei vorzugsweise N – NW Großwetterlage), während milde Winter (vorzugsweise wechselnde SW- und W-Großwetterlagen) durch geringe Schneedeckenmächtigkeit und früh einsetzende Schneeschmelze gekennzeichnet waren. Im Frühjahr auftretende zyklonale und antizyklonale Großwetterlagen mit nördlicher Strömung führten zu einem verzögerten Einsetzen der Schneeschmelze und gingen teilweise mit neuen Schneefällen einher. Starkregenfälle und hohe Temperaturen führten hingegen zu einer Beschleunigung der Schneeschmelze, so dass besonders nach schneereichen Wintern verstärkte Hangerosion durch Rutschungen des Firns sowie ein erhöhtes Lawinenrisiko durch kollabierende Schneewechten in den Steillagen der fossilen Kar-Gletscher zu verzeichnen war. Exemplarisch werden die Zusammenhänge am Beispiel des Hohneck-Massivs dokumentiert.

Keywords: Vosges, firn, cornices, snow cover variability, avalanches

1 Introduction

Seasonal extent and persistence of snow cover, with analysis of its interannual variability and relationships with the atmospheric circulation, is a much studied subject, especially in the context of climate change. Many papers deal with this at very large scales (Northern Hemisphere: e.g. Brown 2000; Cohen and Entekhabi 2001; Kumar and Yang 2003; Garcia-Herrera and Barriopedro 2006; Vicente-Serrano et al. 2007). At a regional scale in Europe, monitoring of snow in the Alps attracts a great attention, because of glacier retreat (e.g. Vincent 2002; Zemp 2006), the high avalanche risks (e.g. Lehning et al. 2002; Corripio et al. 2004; Jomelli et al. 2007), the influence of snow on hydrology (e.g. Baumgartner and Weingartner 1995; Seidel and Martinec 2004; Martin and Etchevers 2005) and ecology (e.g. Ellenberg 1988; Pomeroy et al. 2001; Holtmeier 2005), and the possible effect of climate change on winter sports (e.g. Bürki et al. 2003). Some regional studies including snow study were carried out in the Hercynian Mountains, e.g. Staron (1993) in the French Central Massif and Schönbein and Schneider (2005) in the German Hercynian Massifs, but not specifically in the Vosges Mountains except for the study of Juillard (1954). The Hercynian Massifs of Western and Central Europe are both too low in latitude (between 44 and 52°N) and in altitude (below 2000 m) to sustain permanent snow and glaciers under current climatic conditions, but some massifs experience a deep and long-lasting snow cover and are locally subjected to avalanches. The persistence of snow cover in the early warm season and the summer residual snow patches have an influence on soils, plants, animals, water supply and scenery (Harshberger 1929; Vincent and Lee 1982; Ellenberg 1988; Watson et al. 1994; Brouillet et al., 1998, Rango et al., 2007), but detailed studies of snow patches in relation to climate, including extensive space-time measurements, are rare. The thorough monitoring of snow patches in Scotland for more than three decades (Watson et al. 2002) is without equal in the Hercynian Mountains of Western and Central Europe. Studies of long-lasting and late residual snow cover and their impacts were carried out in the Giant Mountains (Czech Republic: Hejcman et al., 2006) and in the French Central Massif (Forez Mountains: Etlicher et al. 1993), but none in the Vosges Mountains (northeastern France).

Despite their relatively low elevation (Grand Ballon: 1424 m; Hohneck: 1362 m) and because of their cool and wet climate, the Vosges Mountains usually experience a long-lasting snow cover and the persistence of snow patches into late spring and summer on their east-facing high slopes (at about 1200–1300 m). A snow patch is an isolated area of snow which may last throughout the summer and initiate processes associated with nivation (Goudie 1994). Collomb (1847, 1848) and Grad (1871) reported the existence of small «glaciers» in the process of formation in the Vosges Mountains: the snow transforms into a firn with large grain size, then into low density ice and last into compact ice near the soil. The topography and the land cover of the High Vosges Mountains are favourable to the development of extensive snow patches: the wind sweeps

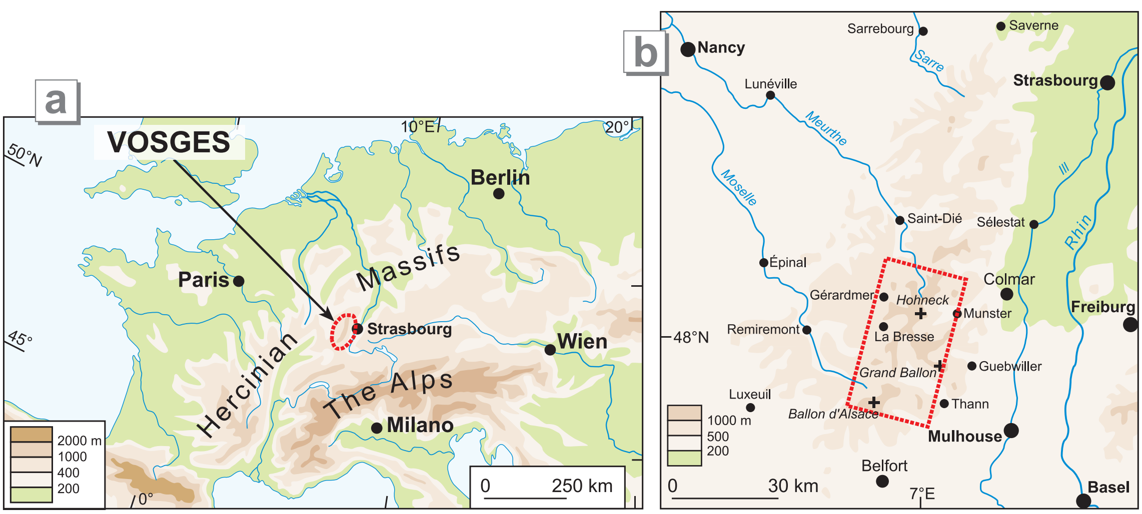

Fig. 1: Location of the Vosges Massif in Western and Central Europe (a) and location of the studied area (High Vosges: dotted line box) in the Vosges Massif (b)

the snow from the high and relatively flat tree-less surfaces (hautes-chaumes) and accumulates it on the upper leeward edges of fossil glacial cirques. The snow accumulation is observed in cornices or firns. Some snow cornices do cause avalanches and slope erosion. All snow patches disappear each year during the summer, but one is reported to have persisted until the next winter in 1860 at the site of Kastelberg (Grad 1871). In Canada, Lauriol et al. (1986) observed and reported that residual snow patches allow one to estimate the maximum snow depth of the previous winter. In this study, a detailed inventory of the favourable areas for the formation and long duration of snow patches is presented, and the topographical and climatic features of the firns and snow cornices development are analysed. Depending on the characteristics of snow cover and meteorological features, we have described and mapped the risk of avalanches in the High Vosges Mountains. This study is carried out in the framework of the GDR RICLIM 2663-CNRS multidisciplinary Research Group (RICLIM is the French acronym of "RIsques liés au CLIMat"/Climate Risks).

2 Data and methods

The High Vosges Mountains are located in the southern half of the Vosges Massif (Fig. 1) at about 48°N and 7°E and are characterized by a north-south 40 km long main ridge, including some of the highest Vosges peaks.

The climate data used for this study (temperature, precipitation, snow depth: Tab. 1), were mainly recorded at the weather station of the Schlucht University Chalet (elevation: 1220 m) for the period 1976–1997. The Schlucht University Chalet was managed jointly by both universities of Strasbourg and Nancy. Since the closing down of the Schlucht University Chalet in 1997, there have been no more snow depth measurements on the ridges of the High Vosges Mountains. Therefore, the snow-depth data of the Feldberg weather station (Germany) were used as reference data too (data source: DWD (Deutscher Wetterdienst)). The Feldberg is the highest summit of the Black Forest Massif (1493 m), and is located 75 km ESE of the Hohneck Massif. In order to give accuracies about climatic features of the High Vosges Mountains, monthly precipitation data recorded at the weather stations of Altenberg (Météo-France), Lac de la Lauch/Lauch Lake (Météo-France) and Schiessrothried (DIREN (Direction Régionale de l'Environnement)) were used. Daily temperature and precipitation data recorded since 1994 at the automatic Météo-France weather station of the Markstein (on the High-Vosges main ridge; elevation: 1184 m) were used for analysing variation of snow depth in relation to meteorological features.

The main sites of snow accumulation were identified during field work between the Lac Blanc (in the north) and the Ballon de Servance (in the south). Complementary detailed informations related to the locations was extracted from remote sensing data (National Geographic, 2008; Google Earth (http://earth.google.fr/). The dates of disappearance of firns and snow cornices recorded during 30 years of discontinuous observations between 1934 and 2008 were completed by the observations of the manager of the Hohneck Summit Hotel at the Schwalbennest Firn site (the most long-lasting firn in the High Vosges Mountains). These observations allowed us to build a database of the main sites of formation of firns or snow cornices in the High Vosges Mountains, including a detailed description of each site (cirque and site name, latitude, longitude and altitude, slope aspect, type of snow accumulation and average period of disappearance. The period of disappearance was based on a median date calculated for the 1934–2008 period.

The dates of disappearance of the Schwalbennest Firn were compared with the available data of maximum snow depth at the Feldberg weather station in 1934–2008 and for some characteristic cold seasons. In order to explain the variability of snow depth and snow-patch duration, the frequency of circulation patterns was calculated for the selected cold seasons

Table 1: Reference weather stations: geographical coordinates, measured climate elements (T: temperature, P: precipitation, S: snow depth), time period of available data and data sources. The location of the Vosges stations is specified on Fig. 3

Weather station	Lat. (N)	Lon. (E)	Alt. (m)	Element	Period	Data source
Altenberg	48°04'	7°03'	1084	P, S	1966-1985	Météo-France
Schlucht Chalet	48°03'	7°01'	1220	T, P, S	1976-1997	U. Strasbg-Nancy
Lauch Lake	47°56'	7°03'	925	P	1941-2008	Météo-France
Markstein	47°55'	7°02'	1184	T, P	1994-2008	Météo-France
Schiessrothried	48°02'	7°02'	930	P	1965-2000	DIREN
Feldberg (Germ.)	47°53'	8°00'	1493	S	1925-2008	DWD

(including a winter and spring differentiation), using the objective version of the Hess and Brezowsky Grosswetterlagen system of classifying European synoptic regimes. The Hess-Brezowsky classification is based on the mean air pressure distribution (sea level and 500 hPa level) over the North Atlantic Ocean and Europe and initially identifies 29 atmospheric circulation patterns (Grosswetterlagen, GWL: Gerstengarbe and Werner 2005). The Objective-GWL system is a computational version of the 29-type Hess and Brezowsky Grosswetterlagen system of classifying European synoptic regimes (James 2007; detailed information and daily catalogue available at http://www.cost733.org/GWL/ObjGWL.html). The Objective-GWL types have the same meaning and nomenclature as the original types (Tab. 2) and are also filtered so that the minimum allowed event duration is 3 days (as with Hess and Brezowsky). The main differences from the original series are that the Objective-GWLs have a greater spatial coherence outside Central Europe and that the classification is homogeneous and consistent throughout the years. A map of the risk of avalanche in the Hohneck Massif in association with the location of the main firns and snow cornices was drawn, using testimonies of the High-Vosges inhabitants, old newspaper articles and personal observations. The risk of avalanche was estimated by taking the avalanche frequency and secondarily the destructive force of avalanches into account.

3 Formation process, development and location of firns and snow cornices

A firn is a partially compacted granular snow that is the intermediate stage between snow and glacial ice. It is formed under the pressure of the overlying snow by the processes of compaction, recrystallization and melting. These processes take about one year. The snow is blown and accumulates on leeward slopes where it packs down

Table 2: List of Hess-Brezowsky Grosswetterlagen (GWL), according to James (2007)

	Grosswetterlagen / translated definition (English)	**GWL**
01	Anticyclonic Westerly	WA
02	Cyclonic Westerly	WZ
03	South-Shifted Westerly	WS
04	Maritime Westerly (Block E. Europe)	WW
05	Anticyclonic South-Westerly	SWA
06	Cyclonic South-Westerly	SWZ
07	Anticyclonic North-Westerly	NWA
08	Cyclonic North-Westerly	NWZ
09	High over Central Europe	HM
10	Zonal Ridge across Central Europe	BM
11	Low (Cut-Off) over Central Europe	TM
12	Anticyclonic Northerly	NA
13	Cyclonic Northerly	NZ
14	Icelandic high, Ridge over Central Europe	HNA
15	Icelandic high, Trough over Central Europe	HNZ
16	High over the British Isles	HB
17	Trough over Central Europe	TRM
18	Anticyclonic North-Easterly	NEA
19	Cyclonic North-Easterly	NEZ
20	Scandinavian High, Ridge over Central Europe	HFA
21	Scandinavian High, Trough over Central Europe	HFZ
22	High over Scandinavia-Iceland, Ridge over Central Europe	HNFA
23	High over Scandinavia-Iceland, Trough over Central Europe	HNFZ
24	Anticyclonic South-Easterly	SEA
25	Cyclonic South-Easterly	SEZ
26	Anticyclonic Southerly	SA
27	Cyclonic Southerly	SZ
28	Low over the British Isles	TB
29	Trough over Western Europe	TRW

and refreezes after some initial melting. The stratification of firns shows an alternation of snow layers with large grain size and small layers of compact ice (Rothe 1963). The formation of a firn depends on topographical distinctive features:

(i) A convex-concave slope or a slope with a large curvature radius (e.g. Schwalbennest Cirque on the NE slope of the Kastelberg: Fig. 2a).

(ii) A difference in altitude between 100 and 200 m. A too steeply sloping cirque allows the formation of a snow cornice only.

A cornice is a leeward growing mass of snow overhanging from a ridge or sharp break in slope (perpendicular to the ridgeline) due to windblown snow. The threshold for snow redistribution by wind is about 5–10 m/s (Seligman 1962; Kobayashi et al. 1988). The formation of snow cornices depends on the topography. The cornices disappear before the firns, by melting and falling. Firns sliding on the slopes allow the formation of crevasses, like those on glaciers (Fig. 2b) and trigger slope erosion by uprooting the alpine grassland. Bedrock is laid bare and is subjected to the freeze-thaw alternations, which increase the erosion. Rothe (1935) reported that the most persistent part of a firn is located between 30 and 40 m under the upper edge of the cirque and is laid on slopes of 40° inclination, where snow is deepest and best protected from direct sunshine. Firns and snow cornices re-form at the same sites (glacial cirques), which allows one to locate them precisely: 40 sites of formation of firns (23 sites) or snow cornices (17 sites) were identified between the *Lac Blanc* in the north and the *Ballon de Servance* in the south (Tab. 3 and Fig. 3). The description of each site (cirque and site name, geographic coordinates, aspect of slope, type of snow accumulation, average time period of disappearance) is shown in Tab. 3.

Except for the site of Felzach [36], all of the identified sites are located in glacial cirques above 1150 m and most of them (77.5%) are located on slopes facing E, ENE, NE or NNE (i.e. sheltered from the prevailing W or SW winds). The period of disappearance is based on a median date calculated for the 1934–2008 period. The snow cornices disappear between late April (Wormspel Cirque: Hohneck south-facing slope [17]) and early June (Leibelthal Cirque: Rotenbach North [26]) and the firns disappear between early May (Leibelthal Cirque: Rainkopf south-facing slope [26]; Grande Fecht Cirque: Lauchenkopf [30]; Ventron Cirque: Winterung [35]) and late July (Ammeltal Cirque: Schwalbennest [23]). The snow depth of firns and snow cornices depends on wind speed and wind direction during snowfalls, according to the investigations of Jeník (1959 and 1997) and Hejcman et al. (2006) in the Giant Mountains (Czech Republic), and studies in the Alps (Gauer 1998; Corripio et al. 2004; Guyomarc'h et al. 2006). The high, wide, relatively flat, tree-less and windswept areas of the Hautes-Chaumes (e.g. Kastelberg) allow large snow accumulations on their upper leeward edges (Fig. 2 and 4).

The Schwalbennest firn (NE slope of the Kastelberg) occasionally reaches 15 m depth (personal in situ estimation) and because of its extent and depth, this firn is the last one to disappear (latest date: September 15th, 1970 and 1978). The extreme dates of disappearance of the Schwalbennest firn recorded during the 1934-2008 period are June 3rd, 2007 and September 15th, 1970. The firn reached a maximum depth of 10-15 m in 2006, but it completely disappeared during the last decade in the hot month of July. The other snow patches usually disappear between early June and early July (firns of the Wormspel Cirque: Fig. 3). Fig. 4 shows a small discontinuous snow strip above the firns of the Wormspel Cirque due to snowfall of May 31st and June 1st, 2006.

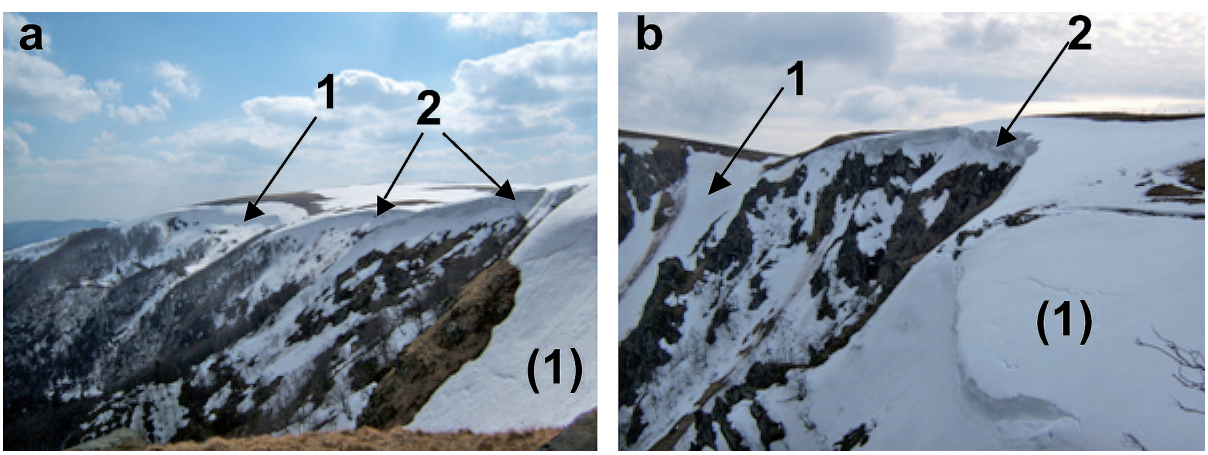

Fig. 2: Morphology of firns (1) and snow cornices (2) on the Hohneck Massif (April 20th, 2006). a) on the upper east-facing slope of the High Vosges main ridge (Kastelberg area) b) on the upper slope of the Frankental Cirque

Table 3: Description of the identified sites of formation of firns and snow cornices in the High Vosges Mountains (cirque and site name, latitude, longitude and altitude, slope aspect, type of snow accumulation and average time period of disappearance), according to field observations and records between 1934 and 2008. The site location is specified on the map below (Fig. 3) using the same identification numbers.

	Cirque name	Site name	Latitude	Longitude	Altitude (m)	Slope	Type	Disappear.
1	Lac Blanc	Crête lac Blanc	48°07'30	7°05'07	1230-1270	E	cornice	early May
2	Forlet	Reif	48°06'13	7°04'06	1280	ENE	cornice	late May
3	Forlet	Altenwasen	48°05'51	7°03'59	1240-1260	ENE	firn	early June
4	Tanet	Seestaettle	48°05'04	7°03'08	1230-1250	E	firn	mid May
5	Missheimle	Missheimle	48°04'42	7°02'20	1250	ESE	cornice	early May
6	Frankental	Rochers Verts	48°02'47	7°00'50	1260	NE	cornice	early May
7	Frankental	Martinswand	48°02'47	7°00'52	1275	E	firn	late May
8	Frankental	Haut de Falimont	48°02'40	7°00'45	1290	E	cornice	mid May
9	Frankental	Couloir de Falimont	48°02'31	7°00'42	1260	NE	firn	early June
10	Frankental	Couloir du Y	48°02'24	7°00'59	1310	N	firn	early June
11	Frankental	Gd. couloir Dagobert	48°02'21	7°01'05	1300	N	firn	mid June
12	Frankental	Petit couloir Dagobert	48°02'20	7°01'11	1300	N	firn	mid June
13	Frankental	Combe Dagobert	48°02'17	7°01'43	1300	N	firn	early June
14	Rothried	Schaeffertal	48°02'12	7°02'23	1200	N	firn	late May
15	Rothried	Couloir de la Bloy	48°02'11	7°01'04	1230-1250	N	firn	late May
16	Petit Hohneck	Combe de Schallern	48°02'12	7°00'48	1170	NE	firn	early May
17	Wormspel	Hohneck (S. Slope)	48°02'01	7°00'39	1320-1340	S	cornice	late April
18	Wormspel	Col du Wormspel	48°01'55	7°00'49	1280	E	cornice	early May
19	Wormspel	Cirque Wormspel	48°01'50	7°00'43	1250	NE	firn	late June
20	Wormspel	Rhodiola/Spitzkoepfe	48°01'43	7°00'34	1280	NNE	firn	late June
21	Ammeltal	Kaltenbrunnenrunz	48°01'35	7°00'32	1275	E	firn	early July
22	Ammeltal	Ammeltal	48°01'24	7°00'21	1300	ENE	firn	mid May
23	Ammeltal	Schwalbennest	48°01'20	7°00'26	1260-1280	NE	firn	late July
24	Altenweiher	Pferrey - Rainkopf	48°00'37	6°58'59	1260-1280	NE	cornice	early May
25	Leibelthal	Rainkopf (S. Slope)	48°00'31	6°58'58	1240	SE	firn	early May
26	Leibelthal	Rotenbach Nord	48°00'10	6°58'51	1220-1260	E	cornice	early June
27	Leibelthal	Rotenbach Sud	47°59'58	6°58'55	1230-1270	NE	firn	mid June
28	Steinwasen	Batteriekopf	47°59'30	6°58'54	1240-1270	E	cornice	early May
29	Schweisel	Schweisel	47°58'18	6°59'42	1250	NE	firn	mid May
30	Grande Fecht	Lauchenkopf	47°58'49	7°02'34	1240	ENE	firn	early May
31	Lechterwann	Hilsenfirst	47°58'40	7°05'25	1230	NE	cornice	early May
32	Petit Ballon	Strohberg	47°58'50	7°07'46	1240	ENE	cornice	early May
33	Markstein	Trehkopf	47°56'20	7°01'35	1190	E	firn	mid May
34	Grand Ballon	Hôtel Club Vosgien	47°54'50	7°06'40	1370	NE	firn	late May
35	Ventron	Winterung	47°57'32	6°55'38	1170	E	firn	early May
36	Felzach	Haut de Felzach	47°56'20	6°56'05	1140	ENE	cornice	early May
37	Drumont	Lochberg	47°54'08	6°55'06	1180	E	cornice	mid May
38	Ballon d'Alsace	Boedelen	47°49'19	6°50'44	1220	E	cornice	early May
39	Ballon d'Alsace	Morteville	47°49'26	6°50'46	1220	NNE	cornice	late May
40	Ballon Servance	Goutte du Ballon	47°49'49	6°47'43	1200	NNE	cornice	mid May

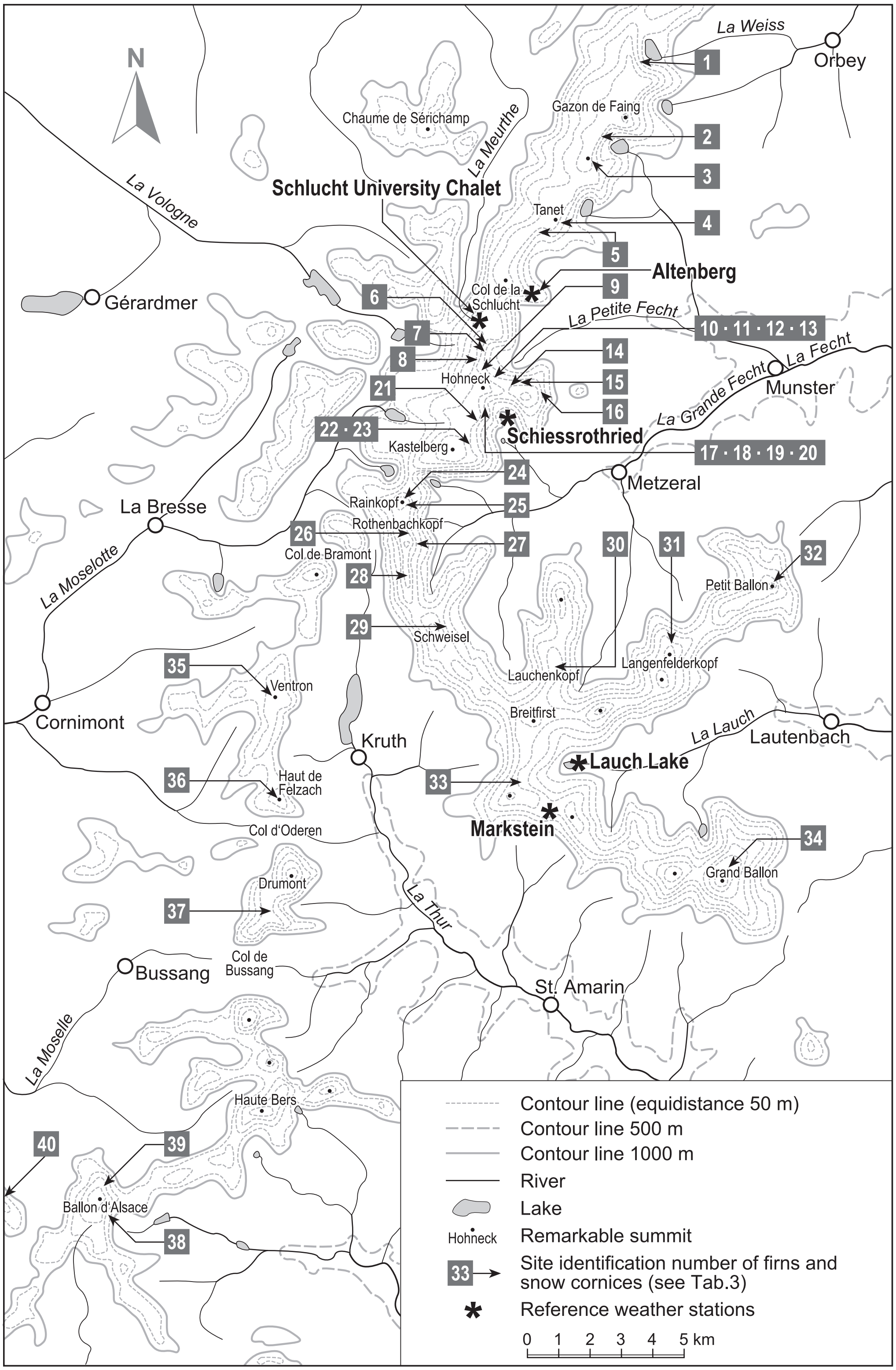

Fig. 3: Location of the main sites of formation of firns or snow cornices in the High Vosges Mountains (identification numbers: see Tab. 3). Reference weather stations (detailed information: see Tab. 1): A: Altenberg, C: Schlucht University Chalet, L: Lauch Lake, M: Markstein, S: Schiessrothried

Fig. 4: Firns on the upper slopes of the Wormspel (foreground) and Kastelberg (middle ground) cirques (June 4th, 2006)

4 Climate of the High Vosges and causes of snow cover variability

The Vosges Mountains belong to the cool temperate climate area of northwestern and Central Europe (the *Cfb* type of climate, according to Köppen's classification), but receive a colder and wetter climate than surrounding lowlands. The western and southwestern slopes are exposed to the Atlantic disturbed weather systems and locally receive an average annual precipitation of more than 2000 mm, e.g. on the Hohneck (2094 mm at the weather station of Schiessrothried, 1765 mm at the weather station of the Schlucht University Chalet (elevation: 1220 m) and 1724 mm at the weather station of Altenberg). Therefore, the High Vosges Mountains have an oceanic precipitation, with large amounts in late autumn and winter, with frequent snowfall (Tab. 4 and Fig. 5).

The weather stations located in the bottom of the valleys are subjected to the same precipitation regime (Shamsi 1968; Humbert et al. 1984). The proportion of snow increases with altitude. The snow proportion is about 4% of the total precipitation in the Alsace Plain (upper Rhine Plain), 20% at 700 m, 30% at 1000 m and 60% at 1350 m (Juillard 1954). According to observations by Juillard (1954) at the Hohneck summit, more than 50% of the total precipitation is solid (snow or fine hail) and snow can occur in most months year (on June 1st, 2006, between 10 and 15 cm of snow covered the highest ridges). Only in July and August is fresh snow cover not observed. Between 70 and 90 days with snowfall are estimated between 1200 and 1400 m, with more than 160 days of snow cover at about 1200 m (163 days at the Schlucht University Chalet). The occurrence of snow depends on the temperature decrease with increasing altitude (about -0.65°C in 100 m). This temperature gradient shows seasonal variations: between -0.2°C in December (due to the frequent occurrence of thermal inversions) and -0.8°C in April-May (upper level cold air advection due to northerly air flow). The average annual temperature is +9°C at about 400 m and +3°C at about 1400 m (+5.1°C at the Schlucht University chalet, Fig. 5; +3.4°C at the Hohneck summit). The coldest month is January (-2.1°C at the Schlucht University chalet; -3.2°C at the Hohneck) and the warmest July (+13.6°C at the Schlucht University chalet; +11.0°C at the Hohneck).

The first snowfalls occur about mid-October, but the snow depth is significant from the second decade of November and reaches an average and median height of 100 cm in late February or mid-March (Fig. 6).

The value of the inferior quartile is frequently less than a snow depth of 50 cm. The snow cover quickly disappears during the first two weeks of May, partly because frost seldom occurs (4 or 5 days with a daily minimum temperature below 0°C on average). On the main tree-less and windswept high ridge (Gazon du Faing, Haut de Falimont, Hohneck, Kastelberg, Rotenbachkopf), the snow depth does not exceed more than 30 cm, because snow is redistributed by wind and therefore, the snow accumulates in cornices.

The climatic features of the High Vosges Mountains are similar to the French Central Alps at 45° North Latitude and about an elevation of 1800 or 2000 m. The High Vosges are subjected to a wet and windy mountain climate with a high variability of the observed weather types, which causes large and abrupt temperature variations and has an effect on the snow cover. The relation between the interannual variability of snow depth, the dates of disappearance of the Schwalbennest firn and the atmospheric circulation patterns for the 1934–2008 was analysed using the snow depth data series of the Feldberg

Table 4: Average monthly precipitation (Pmm) and number of days with precipitation (N day) recorded at the weather station of the Schlucht University Chalet, elevation: 1220 m (period of 1976–1997)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YR
Pmm	144.2	146.9	147.8	95.2	141.6	146.2	133.6	106.5	163.6	167.1	168.3	204.3	1765
N day	15.2	17.9	17.8	16.8	18.3	19.0	15.6	14.5	16.6	17.5	17.3	18.2	204.7

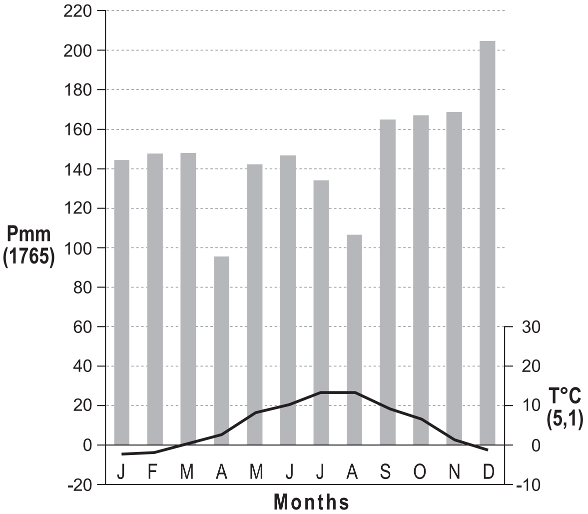

Fig. 5: Annual precipitation regime and temperature oscillation at the Schlucht University Chalet (period of 1976–1997)

weather station in the Black Forest (Germany), because of the lack of long runs of data in the Vosges Mountains (Tab. 1). The results of the statistical correlation between the date of disappearance of the last snow patch (the Schwalbennest Firn) and the amount of snow deposited during the previous winter at the Feldberg weather station are given in the legend of figure 7.

The extreme cold seasons characterized by the highest or lowest maximum snow depth recorded at the Feldberg weather station were associated with the latest (earliest) dates of disappearance of the Schwalbennest Firn. Large snow depths and late snow patches were observed in some years e.g. in 1951, 1970, 1978 (as shown in the Forez Mountains too by Suchel 1992), in contrast to small snow depths and early disappearance of snow patches in other years e.g. in 1964, 2003, 2005, 2007. As a result, the linear correlation between the maximum snow depth at the Feldberg weather station and the date of disappearance of the Schwalbennest Firn was statistically significant at a 98% confidence level ($\alpha = 0.02$) with a Bravais-Pearson's correlation coefficient $r = 0.66$ and a coefficient of determination $R^2 = 0.44$. However, many recorded cold seasons seem to show a complex relation, which must be studied in association with the frequency of atmospheric circulation patterns. The frequency of atmospheric circulation types identified by Hess and Brezowsky (objective method) was calculated for the cold seasons (October–April period) with low and high maximum snow depth recorded on the Feldberg Mountain (reference period of 1934–2008). Figure 8 points out the most frequent circulation types, which allow one to explain these extreme and contrasting cold seasons.

With reference to the Hess-Brezowsky classification of circulation patterns (see Tab. 2), a high frequency of long-lasting periods of Cyclonic Westerly/South-Westerly (SWZ) or Anticyclonic Westerly/South-Westerly (SWA) circulation types, bringing a relatively warm air, hampers the development of a deep, stable and long-lasting snow cover (e.g. winter 1989–1990 or 2006–2007). Such weather conditions can cause complete disappearance of snow even in the middle of winter. This reduces the formation of firns and snow cornices. A high frequency of Cyclonic North-Westerly (NWZ) circulations type (or possibly with periods of snow-producing Cyclonic Easterly circulations types – HFZ or HNFZ), in alternation

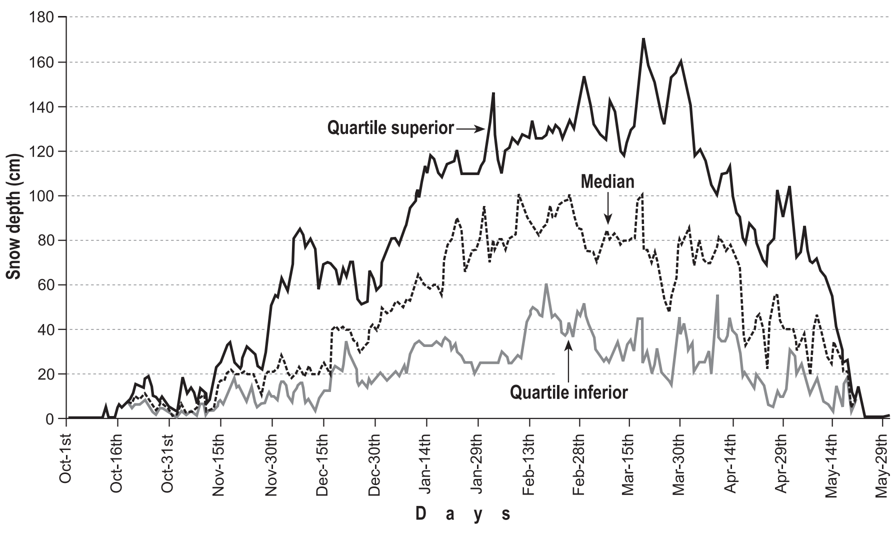

Fig. 6: Variability of snow depth at the Schlucht University Chalet (period of 1976–1997)

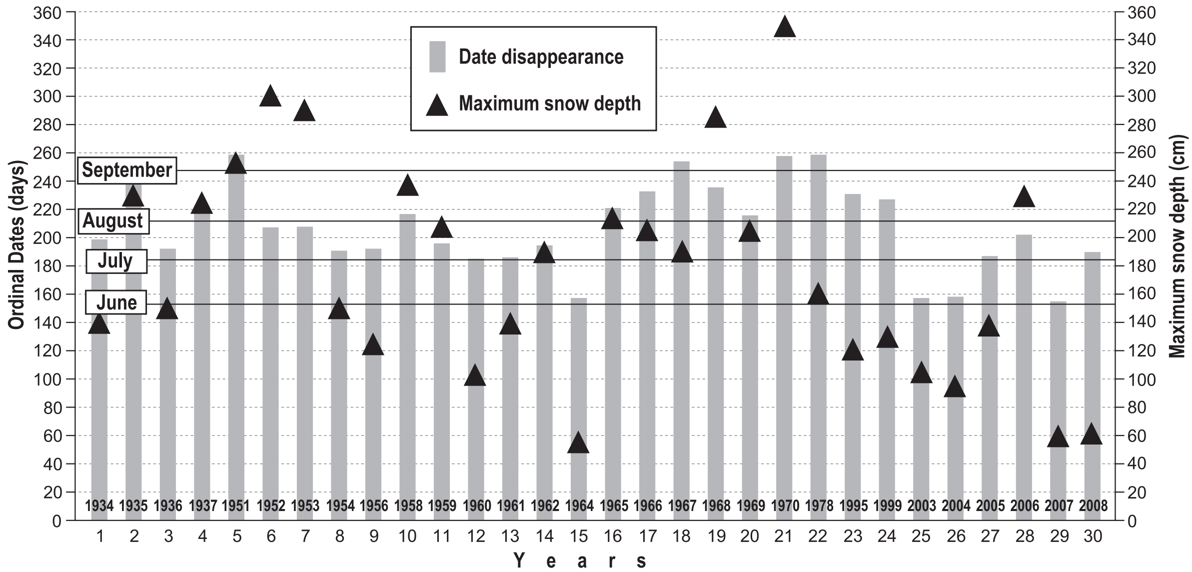

Fig. 7: Available dates of disappearance of the Schwalbennest Firn (1934-2008 period; ordinal date calender) compared to the maximum snow depth recorded at the Feldberg weather station (Black Forest, Germany, 1493 m). Data and results of the linear correlation: - Value number (*n*) from a variable: *n* = 30; - Explicative variable (*p*): maximum snow depth; - Coefficient of determination R^2 = 0.44; - Correlation coefficient *r* = 0.66

with cold anticyclonic weather patterns, leads to a deep, stable and long-lasting snow cover (e.g. winter 2005–2006). The occurrence of anticyclonic weather in winter (e.g. BM) induces long-lasting snow cover, if a first layer of snow occurs in early winter before the anticyclonic weather comes. These above-mentioned weather patterns appear to be necessary to maintain a snow cover that has been produced by a Cyclonic Westerly circulation event.

Hence the variability and succession of weather patterns in winter and spring seems likely to affect snow depth and the formation and duration of firns and snow cornices. However, the occurrence of successive circulation patterns sometimes involves contradictory effects (Tab. 5).

During the 1969–1970 cold season, the Feldberg weather station recorded 204 days of snow cover and an exceptional maximum snow depth of 350 cm, due to the frequent occurrence of cold cyclonic circulation patterns (NWZ, TRM, TM). This exceptional snow depth associated with the recurrence of snow-producing northerly or north-westerly flows was followed by the persistence of the Schwalbennest Firn until mid-September.

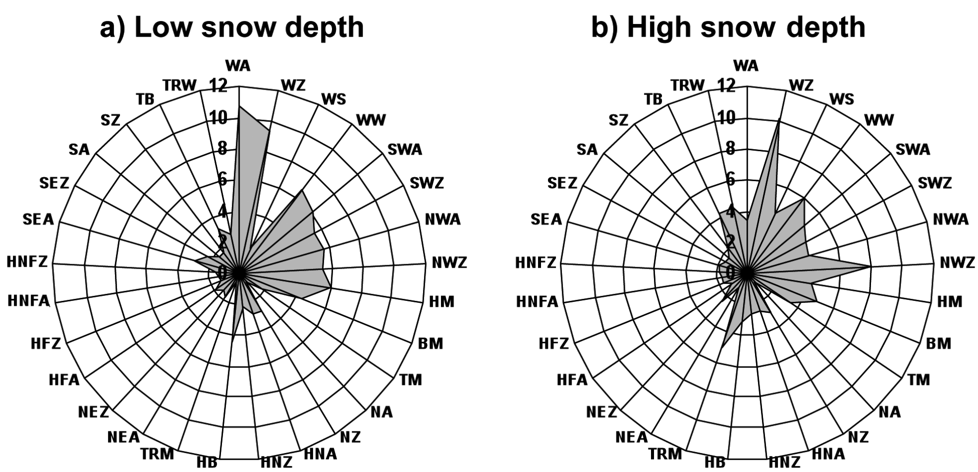

Fig. 8: Frequency (%) of atmospheric circulation types associated with cold seasons (October-April period) with low and high maximum snow depth recorded on the Feldberg Mountain (reference period of 1934–2008) a) "Low snow depth": cold seasons with a maximum snow depth < 1 m (14 cold seasons); b) "High snow depth": cold seasons with a maximum snow depth ≥ 2 m during at least a week (14 cold seasons)

Table 5 : Climatic features for some characteristic years during 1934-2008 (data sources: see section 2)

	1969-1970	1994-1995	2005-2006	2006-2007	2007-2008
1	September 14th	August 18th	July 20th	June 3rd	July 8th
2	350	121	230	60	62
3	204	151	182	131	176
4	ND	- 0.7°C	- 3.3°C	+ 1.4°C	+ 0.5°C
5	ND	+ 3.9°C	+ 3.8°C	+ 7.4°C	+ 4.5°C
6	59	68	52	53	43
7	64	52	66	44	62
8	WW (15.6%) TRM (13.3%) WZ (12.2%)	WZ (28.9%) BM (17.8%) WA (12.2%)	WW (17.8%) NWA (13.3%) HB (13.3%)	WZ (21.1%) WA (16.7%) WS (12.2%)	WZ (21.1%) WA (18.9%) SWZ (14.4%)
9	NWZ (18.5%) TM (13.0%) WZ (13.0%)	NWA (14.1%) HNZ (12.0%) WW (10.9%)	WZ (16.3%) SWZ (15.7%) TRM (9.8%)	WZ (18.5%) BM (17.4%) HM (12.0%)	NZ (16.3%) HNFZ (16.3%) TB (10.0%)

ND : No Data available.

1. Date of disappearance of the Schwalbennest Firn
2. Maximum snow depth (cm) recorded at the Feldberg weather station (Black Forest)
3. Snow cover duration (days) at the Feldberg weather station (Black Forest)
4. Average temperature at the Markstein weather station in winter (December, January and February)
5. Average temperature at the Markstein weather station in spring (March, April and May)
6. Number of days with precipitation (≥ 0.1 mm) at the Markstein weather station in winter (in italic : Lauch Lake weather station); December, January and February
7. Number of days with precipitation (≥ 0.1 mm) at the Markstein weather station in spring (in italic : Lauch Lake weather station); March, April and May
8. Frequency of the most frequent atmospheric circulation patterns (according to the objective version of the Hess-Brezowsky classification), in winter (December, January and February)
9. Frequency of the most frequent atmospheric circulation patterns (according to the objective version of the Hess-Brezowsky classification), in spring (March, April and May)

The wet winter of 1994–1995 had a remarkably high frequency of the cyclonic westerly circulation type (WZ: 28.9%), which caused severe floods in western Europe (Berlamont 1995; Dupont et al. 2008) and probably a high variability of the snow cover and depth, including its partial melting several times. The Feldberg weather station recorded 151 days with snow cover, with a maximum snow depth of 121 cm only. However, during the relatively cold spring, cyclonic northerly circulation periods (HNZ) caused late snowfall, and the frequent occurrence of north-westerly and northerly circulation types reduced the snowmelt. Therefore, the Schwalbennest Firn was observed until mid-August.

Because of the cold periods observed during winter and spring in 2005–2006, the Feldberg weather station recorded 182 days with snow cover and a maximum snow depth of 230 cm. In winter, the most frequent circulation types tended to maintain the snow cover, because of the occurrence of cold weather with a blocking anticyclone over eastern Europe (WW) or with prevailing north-westerly/northerly flows (NWA/HB). The prevailing cyclonic circulation types caused a wet spring including high snow-producing weather (TRM). In March, snow accumulations of almost 3 m were observed on the site of the Schlucht University Chalet (personal observations), following the March 2nd–4th snowfall event (HNZ). The latest snowfall event occurred on May 31st, 2006 (NZ). However, despite their large depth until early June, the High Vosges firns quickly melted and disappeared because of heavy rainfall in late spring followed by a remarkably hot period in July (+5.5 K above the mean average for 1961–1990).

Following the warm and relatively snowless winter-spring of 2006–2007, the High Vosges firns disappeared as early as late May/early June. The winter had prevailing westerly circulations, cyclonic and anticyclonic alternately. Spring was warm, with a high frequency of anticyclonic weather (BM and HM). Therefore, the relatively snowless winter weather was followed by spring weather that induced much snow-melting. The winter and spring of 1989–1990 had similar weather (W and SW circulations types: 51.7%) and similar snow cover (maximum snow depth at the Schlucht University Chalet: 45 cm; at the Feldberg weather station: 33 cm).

A relatively snow-free winter can be followed by a cold snowy spring. Because of this, and because of the highest frequency of snow-producing cyclonic northerly (NZ) or north-easterly/easterly circulation types (HNFZ) in spring (maximum snow depth in March), the cold season 2007–2008 induced firns and snow cornices. The cornice of the Strohberg Cirque [32] disappeared in February and re-formed in March and April. Therefore, the date of disappearance of the Schwalbennest Firn was observed one month later than in 2007 (July 8th).

5 Risk of avalanches in the High Vosges Mountains

Compared with the European Alps and some particular areas e.g. in the mountains of north-eastern North America (Boucher et al. 2003), avalanches have been little studied in low mountains. In the Hercynian Massifs of Western and Central Europe, the risk of avalanche has been studied in the Forez Mountains (French Central Massif; max. elev. 1634 m: Etlicher et al. 1993) and in the Giant Mountains (Bohemian Massif; max. elev. 1602 m: Jeník and Kociánová 2000; Spusta et al. 2006), but not in the Vosges Mountains. There is a risk of avalanches in the High Vosges Mountains too, during and after snowy winters (e.g. 1910, 1952, 1970, 1988 and 2006). The risk is serious in the High Vosges, and human and material damage has been reported since the 18th century (Martin and Giacona 2009). Due to their steep slopes, the cirques of the Hohneck Massif are particularly subject to avalanches (Fig. 9).

Years with deep snow induce a high occurrence of avalanches of powder snow, slab or loose snow. The collapse of snow cornices sometimes causes avalanches too, as shown in the Forez Mountains by Suchel (1992). Three types of cornice failure

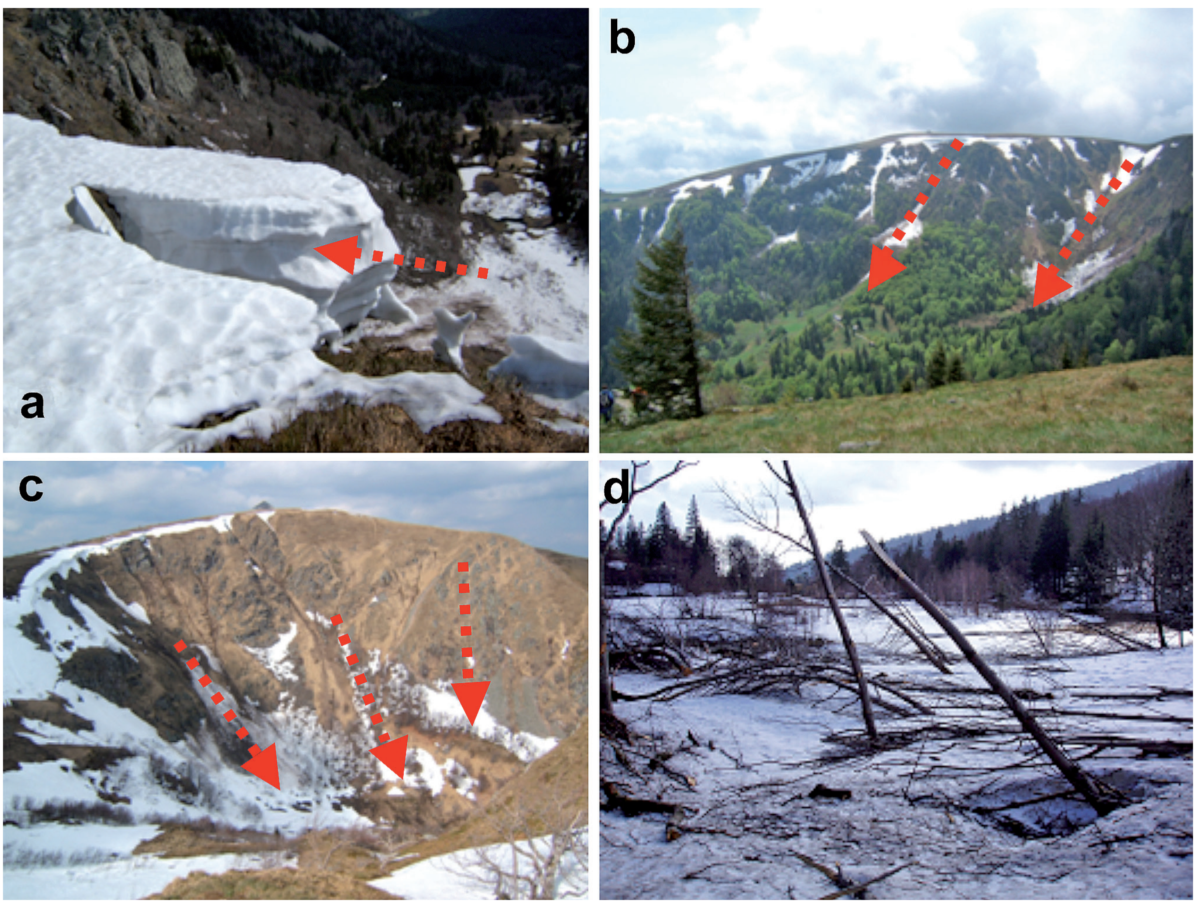

Fig. 9: Snow cornices and traces of avalanches in the Hohneck Massif (red arrows show the different facts): a) Collapse of a snow cornice above the Frankental Cirque (April 20th, 2006); b) Northern slope of the Hohneck with the avalanche paths (May 13th, 2006); c) Traces of avalanches on the southern slope of the Hohneck (April 20th, 2006); d) Trees felled by an avalanche in the Frankental Cirque (March 2006)

triggered by meteorological conditions have been identified by Conway (1998): i) snow loading of the cornice overhang during storms and winds; ii) abrupt temperature changes at the surface of the cornice due to abrupt warming or cooling through rain-on-snow or heating by sunshine; iii) seasonal warming/in prolonged midwinter warm periods. Cornice avalanches destroy vegetation further down. The distribution of the vegetation type allows one to locate the most frequent avalanche paths (Fig. 10).

The results of observations reported on figure 10 show that avalanches occur in the glacial cirques, because of their steep slopes without trees, in accordance with observations in similar massifs (elevation and topography) of Forez (Suchel 1992) and Giant Mountains (Jeník and Kociánová 2000). The risk of destructive avalanches is particularly high in the cirques of Frankental (Fig. 9a, 9d), Wormspel and Leibelthal, which are subjected to the formation of snow cornices (steep slopes). Because the slopes are less steep at locations with only firn, the avalanche risk is lower at these sites. The Schwalbennest Cirque has a relatively low risk of avalanches, because of its large curvature radius. The areas most subjected to avalanches (in red on Fig. 10) in the Hohneck Massif were identified as follows:

(i) The slopes of the Frankental Cirque, including the avalanche path of Falimont, the great and little avalanche paths of the "Y" on the north slope of the Hohneck (Fig. 5b), have a very high avalanche risk. Avalanches of powder snow or loose snow occur almost each year in the «Great Y» path, which is one of the most active and dangerous avalanche paths in the Vosges Mountains. In March 2006, a powder-snow avalanche followed by a cornice-fall avalanche from the Martinswand felled between 1 and 2 hectares of forest (Fig. 9d).

(ii) Loose snow and cornice fall avalanches frequently occur in the Wormspel Cirque, between the south slope of Hohneck and the north slope of Spitzkoepfe. The former Wormspel Farm was destroyed several times and was never reconstructed after the First World War.

(iii)The Leibelthal Cirque, between the SE slope of Rainkopf and the east slope of Rotenbachkopf are subject to dangerous avalanches too. Several powder-snow avalanches occurred in 1952. On February 11th, 1952, an avalanche from the SE slope of Rainkopf felled 10 hectares of the forest of the Leibelthal Valley and stopped near the Kolbenwasen Farm at 734 m. Collomb (1847) reported that an avalanche in March 1845 from the Rotenbach Pass slid for about 1000 or 1200 m and accumulated a mass of trees, rocks, mud, sand and snow.

Other areas with avalanches risks were identified in the cirques of Lac Blanc, Lac du Forlet, Tanet, Drumont and on the east slope of Ballon d'Alsace. The other areas of the Vosges Mountains are less risky, because of slopes being less steep and a dense forest cover. Historical sources reported by Martin and Giacona (2009) attest that avalanches sometimes cause human victims and material damage. In the Hohneck massif, the Frankental Farm was destroyed in 1884 and in 1910 by an avalanche from one of the north avalanche paths of the Hohneck. The farm was reconstructed 250 metres farther down at a more sheltered site. In 1982, a skier died in a slab avalanche in the area of the Schallern Valley. The powder-snow avalanche of March 2006 stopped near the Frankental Farm.

6 Conclusion

Because of their cold and wet climate, the High Vosges Mountains carry residual snow patches into late spring and summer. Firns and snow cornices re-form at the same locations, depending on topography. A total of 40 sites (23 "firn" sites and 17 "snow cornices" sites) was identified in glacial cirques essentially facing E to NE and at elevations of about 1200–1300 m. The variability of weather patterns observed in winter and spring explains large differences between snowy winters followed by late melting (lasting until late summer, e.g. 1969–1970) and mild winters with little snow followed by early melting of small firns and snow cornices (e.g. 2006–2007). The snow-producing Cyclonic North-Westerly and Northerly circulation types, which induce deep and long-lasting snow cover, have the opposite effects from Cyclonic or Anticyclonic South-Westerly circulations types that reduce the development of deep, stable, long-lasting snow cover. The large variability of weather patterns between years involves a great variety of snow-cover conditions (Wahl and David 2004), which explains a significant linear correlation ($r = 0.66$) between the maximum snow depth at the Feldberg weather station and the date of disappearance of the Schwalbennest Firn. However, the variance accounted by this correlation is small (44%). Therefore, the effect of the occurrence of weather patterns and the

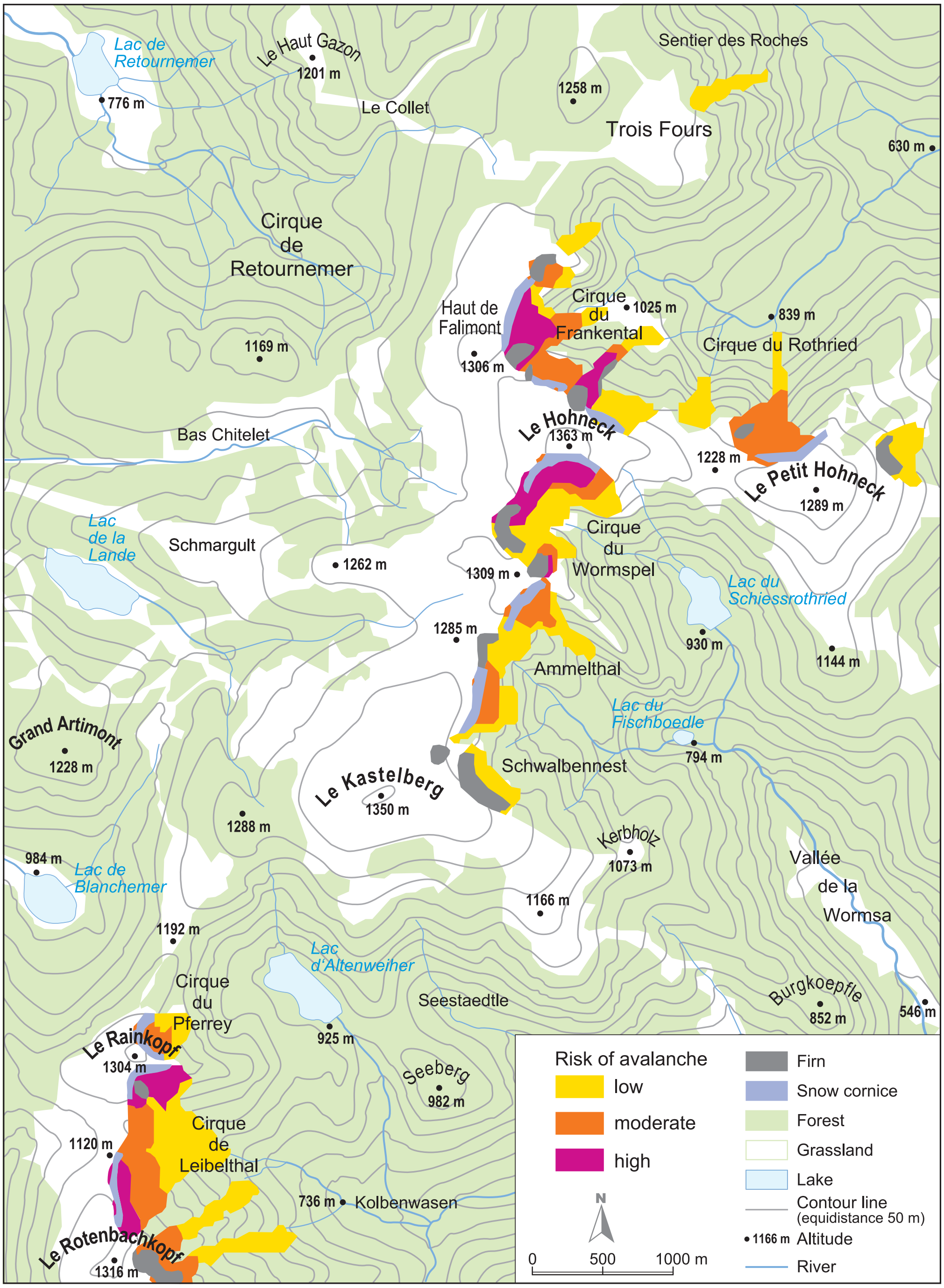

Fig. 10: Map of the avalanche risk in the Hohneck massif.
- Low (yellow): weak avalanches occurring once every five years;
- Moderate (orange): weak or moderate avalanches occurring once every two years;
- High (red): moderate or strong avalanches occurring every year.

succession on snow cover variability needs to be clarified in the Vosges Mountains, in accordance with previous and similar studies about the neighbouring German Hercynian Massifs (Schönbein and Schneider 2005). Firn slides and cornice collapses increase slope erosion, and a serious risk of avalanches was observed and reported during and after snowy winters in the cirques of the High Vosges. Such studies should be carried on and developed in the context of climatic change.

7 Further study

The study of variability in snow depth and duration will be developed using long-time data series and further field observations and measurements. The monitoring of snow cover by teledetection at a high resolution is in preparation. Snow data are scattered and discontinuous in the Vosges Mountains, but they exist since the late nineteenth century, and should be explored in comparison with the long term data series recorded in the neighbouring Black Forest Massif in Germany should. A decrease of snowfall occurrence associated with a temperature increase of 2 or 3 K could reduce the extent and duration of snow cover during the 21st century. The impact of climate change on snow in low mountains of temperate areas must be taken into account, because of its environmental and economic consequences (Hennessy et al. 2003; Schneider and Schönbein 2006; Schneider et al. 2006; Hamilton et al. 2007). After snowy winters in the 1980s with a positive snow-depth anomaly of 20 cm (period 1976–1997), a negative snow-depth trend was recorded since the late 1980s in the Hohneck Massif (Wahl and David 2004), in accordance with similar observations in the Black Forest Massif (Schönbein and Schneider 2003) and in the northern French Prealps (Martin and Etchevers 2005). Several events of complete (or almost complete) disappearance of the snow cover in the High Vosges occurred in several winters since the 1990s (Wahl and David 2004), that reduced the formation of firns and snow cornices, as shown in Scotland by Watson et al. (2006). During the very mild winter 2006–2007, lack of snow reduced the formation of firns and cornices, which disappeared about late May or early June. The connection between weather conditions, snow melting and the risk of avalanches will be analysed in a more detailed way by further studies in the framework of the GDR RICLIM 2663-CNRS multidisciplinary Research Group. The role of the atmospheric circulation patterns and their variability, frequency and succession in winter and spring must be investigated in more detail in order to better understand the space-time variability of snow conditions and changes in a comparative study of the Western and Central European low mountains.

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Authors

Dr. Laurent Wahl †
CERPA – EA 1135
Nancy-2 University
Department of Geography
23 boulevard Albert 1er
54015 NANCY (France)

Dr. Olivier Planchon
COSTEL – LETG UMR 6554 CNRS
FR CAREN
Rennes-2 University
Place Recteur H. Le Moal
35043 RENNES Cedex (France)
olivier.planchon@uhb.fr

Pierre-Marie David
Nivologist and voluntary meteorological observer
75 rue Paul Martin
88 400 Xonrupt-Longemer (France)