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FACULTY OF MATHEMATICS, PHYSICS & INFORMATICS

THE DYNAMICS OF SNOW COVER IN MOUNTAINOUS REGIONS OF SLOVAKIA

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The dynamics of snow cover in mountainous regions of Slovakia

Dissertation by

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The LORD does whatever pleases him,
in the heavens and on the earth,
in the seas and all their depths.
He makes clouds rise from the ends of the earth;
he sends lightning with the rain
and brings out the wind from his storehouses.

(Psalm 135:6,7)

He giveth snow like wool,
He scattereth the hoarfrost like ashes.
He casteth forth His ice like morsels,
who can stand before His cold?
He sendeth out his word, and melteth them,
He causeth his wind to blow, and the waters flow.

(Psalm 147:16-18)

But ask now the beasts,
and they shall teach thee,
and the birds of the air,
and they shall tell thee.
Speak to the earth,
and it shall answer thee,
and the fishes of the sea shall tell.
Who is ignorant that the hand of the Lord hath made all these things?

(Job 12:7-9)

ABSTRACT

The dynamics of snow climate influence several human activities, such as tourism, agriculture, drinking water sources, traffic, architecture, etc. This thesis concerns with two main objectives: 1. to broaden our horizons in climate change, focusing on the climate trends in mountainous regions with emphasis on snow characteristics, and 2. to develop a numerical model for avalanche forecasting in the High Tatra Mountains. Remarkable part and a lot of effort was dedicated to the quality control of precipitation and avalanche data. The SLPDB database created by the author was improved and filled with historical avalanche records from the paper archives. Nowadays it is used in the Avalanche Prevention Centre in Jasná. Air temperature, precipitation totals, snow depth and new snow height daily time series from 21 mountainous stations were tested for homogeneity using AnClim [99], and adjusted if necessary by q-q method in ProClim [101].

Authors of snow climate studies have dedicated marginal attention to the precipitation types and their changes. Therefore, the trends of solid, liquid and mixed forms were investigated and an interesting relationship with altitude was found. Other snow characteristics prove the general decrease of snow. Delayed beginning, delayed annual maximum, earlier and more intensive melting at the end of winter characterises the new snow regime at majority of stations below some 2000 m. Similarly as in the Alps, also in the Western Carpathians exists a "crossover level", where negative snow trends turn to slightly positive. Increasing trends of both precipitation amounts and temperature are the key factors that drive snow trends. Increase in mixed forms of precipitation along with snow water equivalent plays in favour of denser snowpack, which has an impact on avalanche formation, and leads into conclusion that in future the wet avalanches will probably occur more frequently and earlier.

Various methods of avalanche forecasting based on daily data are studied in this work and the most suitable methods for the conditions in Slovakia are selected. The High Tatra Mountains region was selected as an area of interest, due to relatively numerous avalanche records as well as long and reliable meteorological data. A variety of regression models used for the forecasting of avalanche danger levels were developed, and the best one achieved overall accuracy of 74% on testing dataset (2003-2008). This relatively successful performance was achieved, inter alia, by introduction of some original elaborate variables that represent non-linear effects. The overall accuracy ranges between 66% in May to 93 % in November, if the best model is selected for each month. On the down side, all models have problem with underforecasting of the avalanche danger level 3. An alternative is the method of nearest neighbours, which is designed to predict avalanche and non-avalanche days. This method needs further improvements, because the unweighted average accuracy is about 63% for the best NNB model using 26 neighbours. Anyway, computer-assisted models help the avalanche forecaster to gain confidence and reduce the risk of failure caused by the human factor. The same methods with slight variations could be applied to other avalanche regions in Slovakia.

Keywords: homogenization, snow climatology, avalanche forecasting

ABSTRAKT

Dynamika snehovej pokrývky vplýva na mnoho ľudských aktivít, ako napríklad turizmus, poľnohospodárstvo, hydrológia, doprava, architektúra, a i. Predkladaná dizertačná práca sleduje dva hlavné ciele: 1. klimatickú zmenu v horských oblastiach, s dôrazom na trendy charakteristík snehovej pokrývky, 2. vývoj numerického modelu na predpovedanie lavín vo Vysokých Tatrách. Značné úsilie autor venoval kontrole kvality zrážkomerných a lavínových údajov. Databáza SLPDB, vytvorená autorom a v súčasnosti používaná v Stredisku lavínovej prevencie v Jasnej, bola vylepšená a rozšírená o historické lavínové záznamy zdigitalizované z papierových záznamov. Denné časové rady teploty vzduchu, úhrnov zrážok, výšky snehovej pokrývky a výšky nového snehu z 21 horských staníc boli testované programom AnClim [99] a v prípade nájdených nehomogenít boli tieto „odstránené“ metódou percentilov (q-q) v programe ProClim [101].
Doposiaľ venovali autori klimatických štúdií len okrajovú pozornosť zmenám druhu padajúcich zrážok. Preto sme sa zamerali na trendové analýzy tuhých, zmiešaných a kvapalných zrážok a výsledkom bolo objavenie zaujímavej závislosti od nadmorskej výšky. Ďalšie klimatologické charakteristiky snehu naznačujú všeobecný pokles. Nový režim snehovej pokrývky na staniciach pod 2000 m charakterizujú oneskorené začiatky zimy a výskyty ročného maxima, a naopak skoršie a intenzívnejšie topenie snehu na konci sezóny. V Západných Karpatoch existuje podobne ako v Alpách istá kritická nadmorská výška, v ktorej sa negatívne trendy menia na mierne pozitívne. Nárast zrážkových úhrnov a teploty sú rozhodujúce faktory vplývajúce na trendy snehovej pokrývky. Nárast zmiešaných foriem zrážok spolu s nárastom vodnej hodnoty vedie k vyššej hustote snehovej pokrývky, čo má vplyv na vznik lavín. V budúcnosti teda môžeme očakávať častejší a skorší výskyt lavín z vlhkého snehu.
Po preštudovaní rôznych metód predpovedania lavín z denných údajov boli vybrané vzhľadom na miestne pomery 2 najvhodnejšie metódy. Oblasť Vysokých Tatier sme zvolili vzhľadom na pomerne početné a spoľahlivé lavínové a meteorologické údaje. Vzniklo množstvo regresných modelov na predpovedanie stupňa lavínového nebezpečenstva, pričom najlepší dosahuje na testovacej vzorke (2003-2008) celkovú úspešnosť 74%. K vylepšeniu prispelo okrem iného aj zavedenie odvodených premenných, ktoré vyjadrujú nelineárne efekty. Ak vyberieme pre každý mesiac najúspešnejší model, tak celková presnosť kolíše medzi 66% v máji a 93 % v novembri. Slabou stránkou regresných modelov je podhodnocovanie predpovedí stupňa 3. Druhá metóda predpovedá lavínové a nelavínové dni. Optimálny model používa 26 najbližších susedov, avšak presnosť dosahuje v priemere 63%, takže sú potrebné ďalšie vylepšenia. Numerické metódy s využitím počítača každopádne pomáhajú prognostikovi uistiť sa v predpovedi a znižujú riziko zlyhania v dôsledku ľudského faktora. Podobná metodika s miernymi obmenami sa môže použiť aj v ďalších lavínových oblastiach Slovenska.

Kľúčové slová: homogenizácia, klimatológia snehových pomerov, predpovedanie lavín

Foreword

Climate change is becoming a bigger concern not only for scientists. One of the tasks of this thesis is to explain how the climate changes in mountainous regions of Slovakia. Provided results may serve as a contribution to climate change discussions, either scientific or public. Snow has always been a fascinating phenomena for me since my childhood, and avalanches became the subject of my interest during my studies at the university, when a friend of mine suggested me an attractive topic for my diploma thesis. Even today I can recall my first visit to the APC in spring of the year 2000, when I was impressed by snow and avalanche research. Step by step, I fell in love with mountains. After finishing the diploma thesis, a lot of unanswered questions and stimulating ideas emerged. A need to improve the avalanche forecasting methods was challenging for me. Therefore, I did not hesitate to continue with snow and avalanche research as a PhD student. The submitted thesis is a result of 7-year effort, more or less intense and with some interruptions, and along with climate trends analysis it is a contribution to computer-aided avalanche forecasting in Slovakia.

Martin Vojtek
April 2010

List of Abbreviations

APC	Avalanche Prevention Centre, located in Jasná (1200 mASL), Slovakia (northern side of Chopok); founded in 1972. Its fundamental task is observation of snow conditions and evolution of avalanche processes, in order to determine avalanche prognosis and to design suitable defence structures and measures in avalanche-prone areas in Western Carpathians.
AINEVA	Italian Interregional Association Snow and Avalanches
AWS	Automatic weather station
BF	the Big (Veľká) Fatra Mountains
BSDx	The ***first date*** with snow cover of x cm and more
BT	the Belianske Tatra Mountains
CHMI	Czech Hydrometeorological Institute
DEM	Digital elevation model
DJF	Winter months: December, January, February
DSDx	The longest continuous ***duration*** of snow cover of x cm and more
E	Water vapour tension [hPa]
EAWS	European Avalanche Warning Services
ESDx	The ***last date*** with snow cover of x cm and more
GIS	Geographic Information System
GR	Global radiation
GS	Grain size
GT	Grain type (shape)
HT	the High (Vysoké) Tatra Mountains
IMGW	Instytut Meteorologii i Gospodarki Wodnej (Polish meteorological service)
K	Ram hardness
KMIS	Climatological and Meteorological Information System (database of SHMI)
LT	the Low (Nízke) Tatra Mountains
MRS	Mountain Rescue Service
MST	Mean solar time
N	Cloudiness
NNB	Nearest neighbour (method)
NNSx	The ***number of snowfall days*** of x cm and more
$\mathbf{NS_{-1}}$	New snow height [cm], measured at 07 MST (today)
NSDx	The ***number of days*** with snow cover of x cm and more
PD	Penetration depth (of ram penetrometer)
PI	Precipitation intensity [mm/h]
PT	Precipitation type (see Tab. 3)
$\mathbf{R_{-1}}$	Precipitation total [mm] for 24 hours, measured at 07 MST (today)
RH	Air relative humidity
SD	Total snow depth [cm], measured at 07 MST (today)
SD100D	Snow depth reached in the minimum during 100 days
$\mathbf{SD_x}$	Maximum snow depth in cm
$\overline{\mathbf{SD_x}}$	Average maximum snow depth in cm
SF	the Small (Malá) Fatra Mts.
SHMI	Slovak Hydrometeorological Institute
SI	Snowfall intensity [cm/h]

SLF	Swiss Federal Institute for Snow and Avalanche Research
SLPDB	Avalanche database developed for APC
SMA	Swiss meteorological agency (institute)
SS	Snow surface
SunD	Sunshine duration
SWE	Snow water equivalent [mm] , measured at 07 MST on Mondays
$\mathbf{T_7}$	Air temperature measured in screened box at 7:00 MST
TANAP	The (High) Tatra National Park
TP	Temperature profile
$\mathbf{W_d}$	Wind direction
$\mathbf{W_s}$	Wind speed
WG	Maximum wind gust speed
WT	the Western (Západné) Tatra Mountains
$\mathbf{Y_{+/-}}$	Avalanche danger tendency toward the next day
Ω	Avalanche danger level computed by model
ρ	Snow cover density
ΣSD	The sum of snow depths over specified period in cm

The winter season is defined here as a period from 1st July to 30th June of the next year. For example, the winter season of 1968/69 (1.7.1968-30.6.1969) may be abbreviated as ‘winter 1969’.
Subscript after the name of variable denotes values of the given variable shifted in time relative to the date of database record, e.g. snow depth measured on yesterday $\mathbf{SD_{-1}}$, or tomorrow $\mathbf{SD_{+1}}$.

Mean daily temperature is defined in this work as following:

$$T = \frac{T_7 + T_{14} + 2 \cdot T_{21}}{4}$$

Mean term temperature is defined in this work as following:

$$T_t = \frac{T_7 + T_{14} + 2 \cdot T_{21} + (T_7)_{+1}}{5}$$

‘Minmax’ temperature is defined in this work as following:

$$T_{nx} = \frac{T_n + T_x}{2}$$

References are listed in Bibliography and marked in text as numbers in [square brackets]

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Introduction

The snow slab started sliding slowly at first. After reaching the rocky edge of the first terrace, the slab began splitting, and, while rapidly accelerating, it broke on the second edge. At the bottom of the slope it ran on the frozen lake level, which collapsed soon after the avalanche stopped, and the deposit partly sank 1,5 m into water. The accompanying cloud rose up to 50 meters above the lake so that the sun was temporarily invisible due to falling of snow particles. After all, the sun appeared again.
(V. Suchý from Prague, an eyewitness of avalanche accident under the Mengusovské sedlo, 1985-02-10)

Roaring avalanche often freezes blood in veins and evokes a respect to the power of nature. Snow mass rolling down the slope is captivating, when observed from a safe place. On the other hand, it might be very devastating and dangerous. Survival chances of a victim buried completely in an avalanche rapidly decreases with time: after 15 minutes it is 93%, after 30 minutes only 26%, and after 45 minutes nearly none. [27] In the High Tatra Mountains, only about 10 % of all buried persons survived [108]. The most of accidents happen during avalanche danger degree 2 and 3 (see Appendix C), as the travel on steeper terrain is very limited when degrees 4 and 5 are issued.
This fascinating phenomena would not be possible without snow, which is just one of the form of water. And water is life! But will the snow be in our mountains forever? Will the “White Christmas” be something unusual for our grandchildren? What has really happened to the snow climate?

This thesis consists of two main topics: the first part deals with snow climatology and climate changes, preceded by quality checking of essential data. The aim of the second part is to develop an avalanche forecasting method suitable for operational use by Avalanche Prevention Centre, located in Jasná.

The first chapter offers a brief literature review, taking in hand snow and avalanche research in Slovakia and abroad. All the data sources necessary for this work are described in the second chapter. Methods in chapter 3 are divided into three topics: homogeneity testing, snow climatology characteristics and avalanche forecasting.
The core results of the work can be found in chapter 5, which also includes discussions. Principal results and achieved objectives, which are stated in chapter 4, are summarized in closing chapter 6.
Appendix contains supplementary information such as Glossary, station list and map, etc.

1. Literature review

Snow and avalanche research nowadays covers many scientific disciplines. Hence, this review focuses on snow climatology, as well as on avalanche forecasting techniques and methods suitable for operational use in Slovakia. The review is written rather chronologically, and distinguishes between national and foreign sources. The first objective of the thesis was to perform an overview of the current research. Some of the studies were partly implemented in Chapter 3.

1.1 Snow climatology

Domestic sources

The oldest snow observations in Western Carpathians are recorded mainly in diaries and chronicles made by some enthusiasts – mostly intellectuals, administrators or monks. These are usually descriptive and sporadic data. Žigmund Torda, governor of the Royal Court Chamber in Bratislava and Prešov, recorded short weather notes while travelling in the 16th century. Similar occasional observations were recorded in Bratislava (1512-1528) by Magister Christoforus Hüftenus. Juraj Dobronoki, the first Rector of the University of Trnava, wrote into his diary: *"3rd February 1637, strong wind, falling snow, windy and rainy…"*. A lot of snow has fallen in Kežmarok on 26th August 1716, according to Réthly's notes. Another records can be found in Jesuit chronicles in Levoča (1673 - 1679, 1686 - 1706) and in Košice (1677 - 1681), in diaries of Mauksch (1794), Ján Genersich from Kežmarok (1789 - 1800), Ján Adam Reimann from Prešov (1717 -1720), Jeszenák-Gombos from Bratislava (1770 - 1773). There are recorded usually somewhat extreme weather episodes, such as cold and snowy winters, floods, etc.

Widespread implementation of measuring instruments enables systematic weather observations in 18th century. Regular snow observations begin in 1851, when day with snowfall was marked and water equivalent of new snow in Bratislava and Banská Štiavnica. Measurement of new snow height (still without total snow depth) has been performed at weather stations since 1871 [34]. The number of stations was still on increase, however, the total snow depth was added into regular observations in 1921, after the foundation of met-service in Czechoslovakia.

The first influential monograph taking in hand snow records was published in 1964 by Konček and Briedoň [46], where 208 stations for the period 1921/22 - 1950/51, and two high-elevation stations for short period are processed. Common terms, characteristics and methods used in climatology were introduced here.

Various climate and phenology elements (including snow) were processed into tables, graphs and maps in 60's and 70's [89], [90], [91].

Tatra mountains climate is summarized in a study [17] headed by Prof. Konček. Changes in snow climate are outlined here by Ladislav Kňazovický – a founding father in avalanche research in Slovakia.

Snow conditions from 149 stations for the period 1920/21 - 1979/80 with some new statistical characteristics were brought out by Šamaj and Valovič [97].

Composite authors in [93] devote to variability of snow characteristics, time-series processing, winter patterns, and long-range changes and periodicity during the period 1920/21 - 1984/85.

Rapid progress in digitizing and wider availability of personal computers in 1990's makes data processing more effective. Further characteristics of snow cover for the normal period 1960/61-1989/90 can be found in diploma thesis:
Šándor [98] in 1995 elaborated snow conditions in Tatra mountains in the view of winter sports. Dušan Kočický [45] compares the latest snow characteristics with the normal period 1930/31-1959/60.
More extensive diploma thesis by Handžák [34] contains long-range characteristics for the Low Tatras. Similarly, Matejková [57] selected stations from north and north-west Slovakia, and Kostolány [47] chose low elevation stations from west Slovakia and upper Nitra region. Some long-range snow cover characteristics were processed in the form of maps by Vívoda [103].
Climate change scenarios outputs are for the first time published in the Final Report of the Slovak Republic's Country Study [52]. Assuming 10% precipitation increase in mountainous regions, the sum of daily snow cover heights for winter months (DJF) increases by 9%, and the number of days with snow cover by 1%. On the other hand, air temperature increase by 1°C induces decrease by 7% for the sum of daily snow cover heights, and by 2% for the number of days with snow cover.
Atmospheric precipitation, sums and maxima of snow cover depth, and numbers of days with snow cover in the Low Tatras (1921–1995) were examined by Faško, Handžák and Lapin [28]. Comparing the climatological normals 1930/31-1959/60 and 1960/61-1989/90, the sums increased, but the numbers of days with snow cover decreased at the most of stations. Due to weaker influence of Mediterranean cyclones in late 80's and early 90's, low precipitation totals caused deep depression in the sums, predominantly on southern slopes, which are in Slovakia usually more abundant in snow than the northern ones.
Faško and Šťastný [29] evaluated precipitation amounts measured by totalizers and gauges. Clear increase of annual totals in the northern part of Tatra mountains was confirmed during the second half of the 20th century.
Dissertation by Bochníček [11] investigates snow conditions in the High and in the Low Tatras in the view of winter sports suitability. Some problems with measurements of snow cover temperatures are analyzed here.

Foreign sources

Since the termination of the "Little Ice Age" in the mid-nineteenth century, the glaciers in Europe have lost 50% of their volume and 35% of their surface area. General loss of snow is observed during recent decades due to global warming. Mean air temperature rise by 1°C in alpine regions corresponds to snowline shift by 150 m to higher elevations [35].
Brown [14] explored snow cover variability and change for 1915-1997 utilizing meteorological stations lying in USA, Canada, the former Soviet Union and China. The reconstruction of snow cover data provided evidence of an increase in North America snow cover extent, with significant increases in winter (DJF) SWE, consistently with increasing winter snow depth over Russia. North American spring snow cover was characterized by rapid decreases during the 1980s and early 1990s with a significant long-term decrease in April SWE. Brown estimated Northern hemisphere snow cover extent loss of 3.1×10^6 km^2 per 100 yr associated with significant warming of 1.26°C over mid-latitudinal land areas. March was also observed to have experienced the largest warming during the November-April snow season with significant post-1950 warming trends averaging 4.1°C per 100 yr.
Laternser [53] processed Swiss snow and avalanche data, and published unique long-term trends (1931-1999) in his thesis. Increases were prevalent in snow characteristics until 1980s, followed by significant decreases till 1999. Besides, Laternser suggests station network optimization, based on frequency and spatial distribution of heavy snowfall events. Triangular

network with distances of 15 km should capture at least 80% of all spatially continuous snowfall areas, while 20-km spacing results in only 50 % capture probability. Laternser further used cluster analysis to suggest new snow-climatological regions.

Recent regional studies from the Swiss Alps leaded by Beniston [10] revealed moderate increase in snow characteristics above 1700-2000 mASL, since mild winters are accompanied with more abundant precipitation, falling as snow at higher altitudes. On the contrary, lower altitudes are exposed to more frequent liquid rainfalls. Similar trends are observed also in Slovakia [109].

Scherrer a Appenzeller [84] used new homogeneous Swiss Alpine new snow data set to explore the role of large scale flow patterns in explaining the observed snow variability. The third snow principal component (dependent on altitude) is significantly correlated with the North Atlantic Oscillation (NAO) index, and shows an increasing correlation in time (since the late 1950's).

Stancalie et al. [96] presented the influence of location, relief, land cover, air temperature, precipitation, wind speed and direction on snow depth, snow cover extent, snow density and water equivalent in Romanian mountainous basins.

Recent winters 2004/05, 2005/06 were relatively rich in snow, when also mass media reported more tragic events of collapsed roofs on public buildings due to heavy snowfalls in Central Europe. An estimation method of the SWE from other four meteorological elements (R, NS, SD, e) was developed in CHMI by Němec et al. [71]. This algorithm, slightly modified, was also used for completing of daily SWE values, because SWE is measured only once a week in Slovakia. Moreover, the method can be useful also for stations where SWE measurements are not available.

1.1.1 Homogenization of time series

Easterling and Peterson (and later Karl) deals with various homogeneity techniques and their comparison in [23] [24] [25]. There can be found methods for detecting and adjusting discontinuities in climatological time series – even if we have no metadata. The creation of the so-called reference series described in [75] is very important.

In a review of techniques [23], the best results were achieved by Alexandersson's test [1], Potter's test [78] and t-test [112]. Other techniques – such as Regression, Double-mass analysis, CUSUM, Craddock test, Two-Phase regression, and others were not so successful.

Easterling a Peterson method [24], a combination of regression analysis and non-parametric statistics, is more suitable than Alexandersson's test, when two discontinuities lies very close each other [36].

AnClim software [99], which has been developed by Štěpánek since 1995, allows performing various homogeneity tests, time-series analysis, and much more. This tool was used for homogenization.

1.2 Snow avalanches

Domestic sources

The greatest avalanche fatality in 1924 (18 inhabitants of Rybô settlement died) was the first impulse to introduce defence measures in Czechoslovakia by forest rangers. However, more complex research on snow and avalanches started after another fatality in 1956 with 16 victims. Some preliminary results were published by Vrba and Urbánek [110]. Their contribution helped to better understand the snow metamorphosis and avalanche formation processes.

Introducing the regular avalanche reporting service in 1960 by the TANAP research station and Hydrometeorological institute contributed to a great extent in avalanche prevention. [2]

Further avalanche research continued in 1960s, and after the foundation of APC (1972), when a plenty of science popularization handbooks were issued by several authors. On the other hand, the developing cooperation with countries beyond the Iron Curtain was frozen due to political reasons during the Husakism period (1969-1989).

However, systematic research in Jasná led by Ladislav Kňazovický included cold chamber laboratory for ice crystals microphotography. Several world authors dedicated to categorization of ice crystals at that time in parallel. The principal meteorological and topographical factors for avalanche formation are summarized in [44]. Rather practical book by Milan [66] analyses significant avalanche incidents in Slovakia, focuses on prevention and puts together some rescue instructions.

Avalanche path atlas put out in 1980 by Kňazovický [43] contains detailed topographic parameters of avalanche paths and terrain in Slovakia. The cadastre of avalanche terrains was extended over some new paths and parameters by Milan [67] (see section 2.1).

Dissertation by Holý [39] takes in hand the influence of meteorological and topographical conditions of avalanche formation on a model terrain of Chopok.

The influence of meteorological conditions on avalanche formation is analyzed in diploma thesis by Kuchtová [49] on some serious avalanche cases. As a free continuation, diploma thesis by Vojtek [104] discussed the suitability of current avalanche forecasting methods for operational use in APC, and used available avalanche records and meteorological data for the development of a regression method for assessing avalanche danger in the High Tatras.

The effects of terrain, snowpack and weather parameters on snow avalanches in the Low Tatras are discussed in M.Sc. thesis by Seres [88].

Foreign sources

The oldest publications usually describe the effects of an avalanche. Coaz in 19th century [18] looked through the avalanche formation in connection with weather (e.g. pressure patterns).

Further, this review focuses on several avalanche forecasting methods, potentially applicable in Slovakia, which have been developed in Alps and North America since 1970s, when research in Slovakia begun falling behind due to communist ideology and isolation. Modern forecasting is moving away from conventional methods toward partially computerized systems. [59]

Avalanche handbook by McClung and Schaerer [59] is a “bible” for everyone concerned with snow avalanches, providing a thorough introduction to avalanche theory: starting with weather systems, snowpack analysis and terrain features, through avalanche forecasting and prediction, search and rescue, control with explosives, etc.

Time series analysis applied on avalanche forecasting can be found in Salway [81] and Moyse [82]. These papers were inspiring for the development of a regression model for the High Tatra Mts. [104] and for the selection of variables associated with avalanching.
Discriminant analysis was introduced by several authors: [13] Bovis (1977), [22] Drozdovskaya (1979), [72] Obled and Good (1980). A few decades later, one-way analysis of variance and canonical discriminant analysis are used by Floyer and McClung [30] to identify the principal variables that allow discrimination between avalanche and non-avalanche time periods. The prediction rates increased above 70%, after the region was divided on several homogeneous sub-regions, each with its individual subset of principal variables. Improvement of the method could be achieved by a combination with the method of nearest neighbours, and using hourly data as input.
Method of nearest neighbours was successfully applied for avalanche forecasting by Buser [15]. There are several applications around the world based on this method, with some improvements, or in combination with other methods: NXD-REG developed at SLF [33], model CORNICE in Scotland [79], and Avalanche Forecast System based exclusively on hourly data from AWS in British Columbia .
Classification and regression trees and ***neural networks*** become popular in 1990s: Davis [20], Jones [42], Kronholm [48], and others. The methods cope well with non-monotonic relationships (e.g. providing, hypothetically, that highest avalanche activity was associated with moderate winds, and lower activity with light and strong winds). The best neural network by Gregory and Philippe [32] was composed of 4 layers of neurons, the last one producing probability of an avalanche on slopes of Weissfluhjoch peak. Only 7 most important variables were used as input to the network, and in 90 cases out of 100 the network correctly predicted an avalanche day.
Diploma thesis by Nairz [70] presents a complex review of modern avalanche forecasting methods. More details are included in section 3.3.

Hägeli and McClung [37] discussed scale issues of currently used avalanche forecasting methods, revealing four main problems: (a) the inability of weather monitoring networks to capture small scale phenomena (e.g. snowdrift, surface hoar formation); (b) the insufficient spatial resolution of snow profile measurements with regard to their natural variability; (c) the poor resolution of stability measurements; and (d) the contradictions between input and output scales in avalanche forecasting models.
Verification of avalanche forecast is the main subject of Italian publications by Pedrazzoli et al. [74] and Soratroi [95].
Model SNOWPACK [9], being developed for the Swiss avalanche warning, simulates the evolution of the snow cover based on meteorological input data. It solves the mass- and energy balance equations using a Finite Element numerical scheme.
Dissertation by Laternser [53] takes in hand snow characteristics, temporal trend and spatial distribution of avalanche activity, and suggests a revision of the traditional snow-climatological regions of the Swiss Alps (resulting from cluster analysis).
Hebertson and Jenkins [38] used dendroecology analysis for the dating of the occurrence of large avalanches in period 1928-1996. Climate elements responsible for significant avalanche winters were found by *logistic regression* and *classification trees*. Mean new snow height in January turned out to be significant for the probability of large avalanche occurrence in transitional climate.
Mock and Birkeland [69] discussed relationship between climatic patterns at larger spatial scales and snow avalanche responses. Some promising and potential relationships exist between avalanche activity and the Pacific–North American teleconnection pattern, the Pacific decadal oscillation, and ENSO (El Niño).

Bariffi [6] illustrated how GIS can be used for inclusion of topographical factors that influence the avalanche risk.

Maggioni and Gruber [55] performed a statistical analysis of avalanche releases on well-documented avalanche paths in the region of Davos, where an almost complete database of avalanche events over the last 50 years exists. The principal topographic parameters used for the definition of release zones were slope, confinement, aspect and distance to the next ridge.

McCollister et al. [60] presented a probabilistic method that allows avalanche forecasters to better utilize historical data by incorporating a GIS with a modified meteorological *nearest neighbours* approach. They analyzed the effect of new snowfall, wind speed, and wind direction on the spatial patterns of avalanche activity. Patterns exist at the slide path scale, and for groups of adjacent slide paths, but not for either the entire region as a whole or when slide paths are grouped by aspect. Specific topography around a given path, and not simply aspect, is more important when relating wind direction to avalanche activity.

2. Data

There are two main information sources used for the purposes of this study: SHMI and APC.
The data from SHMI come from climatological and precipitation database. Unfortunately, some data are still available only in paper archive. Nevertheless, quality control is inevitable for this study even though multiple revisions are being systematically performed on the records, especially on climatological records. The precipitation datasets, from the past contain only values greater than zero, so that it is hard to distinguish between missing and zero values. More details on QC can be found in sections 3.1 and 5.1.
Avalanche related data were obtained from various datasets maintained in the APC. All paper datasets are being digitized step by step and they are planned to be stored in a unified database system. Primarily the digitized avalanche records and avalanche slopes with parameters were obtained from the APC. Avalanche records are being revised on the fly during the winter season and again when feeding into the database.
The APC manages meteorological stations mainly for operational avalanche forecasting. Regrettably, only small portion of these measurements are available digitized, since they were sent usually via telephone in the past. Starting in the winter of 2001/02, the measurements and observations are being filled into database via web-based forms on daily basis. The personnel has become trained enough to perform professional observations. Since the winter of 2006/07, the APC personnel have started the processing of snow profiles by a software and since 2007/08 also the regional avalanche centres are sending the digitized observations via the Internet to the APC centre [4]. The number of profiles significantly increased, too. Some occasional snow profiles from the past are available only on papers. Nowadays, the profiles are carried out occasionally during tours in various spots, but they are to be performed regularly on some selected slopes.
Automatic weather stations (AWS) produce large datasets that can be used as an input for avalanche forecasting models with hourly time resolution. The data from 5 AWSs have been used primarily for the current weather monitoring since the winter of 2007/08 and they have not yet been revised.
Geographical factors are mentioned only marginally, because it is a task beyond the scope of the dissertation. Digitizing of avalanche slopes and implementation of GIS would be a challenging task for another study in cartography or geoinformatics.

Following sections describe the most important elements suitable for avalanche forecasting divided into 3 classes:

1. Geographic – mostly quasi-static parameters changing rather slowly in time
2. Meteorological – observations and measurements from stations
3. Snowpack and stability – ramsonde, snow profiles, stability tests

2.1 Geographical data

There are 6 significant avalanche mountain ranges in Slovakia: the Western, High, Belianske and Low Tatra[1] Mountains, Small and Big Fatra. Only a few avalanches occur rather seldom in Oravská Magura, Chočské vrchy and Strážovské vrchy.
Concerning the mapping of avalanche slopes and tracks in Slovakia, Kňazovický [43], [44] and Milan [67] are the main trailblazers in Slovakia. As a result of their effort, the Cadastre of avalanche terrains and their topographic characteristics was created. Some data about locality,

[1] The name Tatry comes from Slavic term *trtri*, i.e. reefs or snow hills

type of avalanche, dimensions and level of danger on a map of avalanche slopes were comprehensively elaborated by Pacanovský [73].
The current avalanche cadastre in APC consists basically of maps with a scale of 1:10 000, which were created by a team headed by L. Milan in early 1980s. These maps have been updated since then, and about three dozens of new slopes were added to the cadastre. At the present time, not all avalanche slopes can be found on these maps, for the reason that some atypical ones have appeared just recently as a consequence of inappropriate forest management. Despite the small size of these new avalanche terrains, some of them pose a considerable danger for the people living near there.

2.1.1 Avalanche slopes classification

This subsection introduces readers to the geographic background, necessary to understand the classification of avalanche slopes made by Milan [67] and maintained by APC personnel.
The mapping of avalanche terrains was based on:

- Interpretation of aerial photographs with a scale of 1:14 000
- Terrain reconnaissance by on-foot patrols both in summer and winter
- Research of old written records in addition to information taken from local inhabitants, mountaineers and experts

The following parameters were assigned to the slopes:

- Avalanche occurrence frequency:
  - I. Yellow – at least once in 6 years
  - II. Red – once in 6 – 30 years
  - III. Black – once in 30 or more years
- Geomorphology features:
  - α Slopes with cliff terrain or with a system of gravitational trenches, rock walls, stony steps, talus cones with slope angles above 30°
  - β Morphologically well-expressed steep avalanche gullies with homogeneous or more dissected concave zones with distinct avalanche track
  - γ Less steep homogeneous slopes (including the convex ones) with rougher surface, without tree vegetation
- Threat and damage levels:
  - A. Threat of roads, touristic pathways and passageways, dwellings, buildings and other human objects, including human lives
  - B. Damage of forest, dwarf pine and other vegetation
  - C. Above the zone of dwarf pine, without any damage to alpine vegetation

All compact and mainly the plain slopes that were not segmented vertically with incline 25° or more situated above the tree-line were classified as avalanche terrains. Slope boundaries were drawn with full line and the trigger zone was highlighted by hatching, following the fall line. Very narrow slopes not possible to project on the map as areas were drawn as arrows.
Slope inclines of the zones of origin, transition and deposition were assessed regarding the contour lines. These numbers are sometimes not precise and it would be better to reassess the values using a GIS. Current DEMs allow to calculate more precisely and objectively various parameters, such as the **prevailing slope orientation**, **altitude**, **maximum track length**, **maximum trigger width**, etc. It is also useful to have an information on local **vegetation**, and **terrain roughness** (see Tab. 1).
Exemplar use of GIS as a platform for the collection, analysis and displaying of various parameters related to avalanching was done by Bariffi [6].

Tab. 1: Availability of significant geographic parameters and characteristics in Slovakia. GIS = parameter can be determined from a DEM; SLPDB = already available in electronic database; M = assigned by Milan [67] and updated by APC.

Geographic factor (equivalent in Slovak)	Source
Slope orientation (expozícia svahu)	M/SLPDB/GIS
Morphology (členitosť)	M/SLPDB
Threat type (typ ohrozenia)	M/SLPDB
Slope angle/incline (sklon svahu)	M/GIS
Altitude (nadmorská výška)	M/GIS
Trigger zone width (šírka pásma odtrhu)	M/GIS
Slope maximum length (dĺžka svahu)	GIS
Terrain roughness (drsnosť povrchu)	GIS
Vegetation – forest, meadow, rock, with outcrops, boulders (les, lúka, skalný povrch, voľné kamene a skaly)	GIS
Convex or concave (konvexnosť a konkávnosť)	GIS

At present, the SLPDB database contains avalanche slopes for each avalanche mountain range. The slopes are grouped into so-called *main valleys* for easier processing. The valleys as well as slopes are numbered, rising in an anti-clockwise direction (see Fig. 1). If a “new” avalanche slope is discovered, then it is drawn to the map with the lowest free number. More detailed segmentation within a single slope was realized by lowercase alphabetic indices (a-z), which were assigned to marked channels that differed from the prevailing character of the slope terrain and these are usually the zones with higher frequency of avalanches.

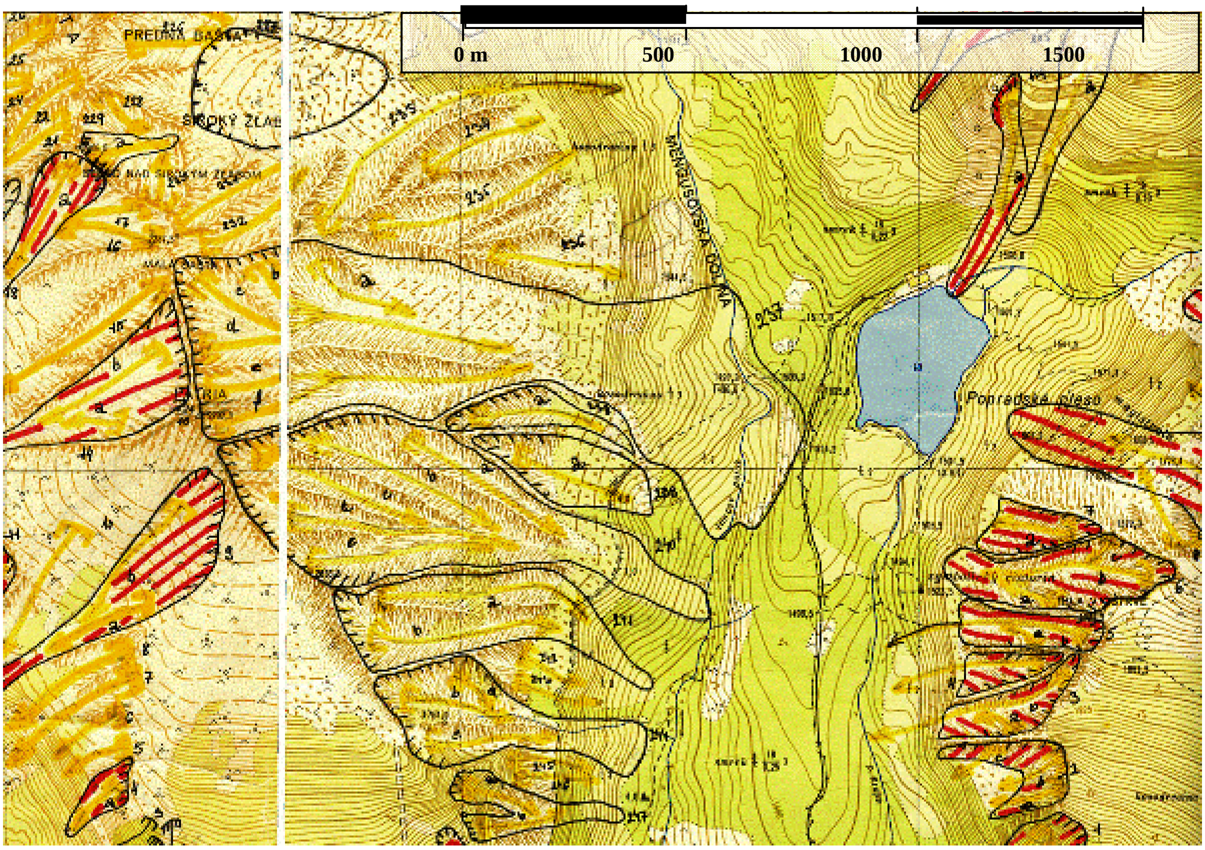


Fig. 1: Sample map from avalanche cadastre – Mengusovská dolina, HT. Each slope in the main valley is identified by a number. Within a slope several tracks are identified by an alphabetic index. Typical frequency (return period) can be distinguished by colour (black, red, yellow).

2.2 Meteorological data

The list of used meteorological stations is in Appendix A and a map in Appendix B. All available meteorological factors that influence avalanche occurrence and are interesting for climate change of snow conditions (see Tab. 2) were selected regarding both the experiences of APC avalanche forecasters and published foreign studies.

Tab. 2: Selected meteorological variables with units and frequency of measurements at mountainous stations in Slovakia. MST = mean solar time.

Symbol	Meteorological element	Unit	Frequency
SD	Snow depth	cm	Daily total 07-07 MST
NS	New snow height	cm	Daily total 07-07 MST
R	Precipitation amount	mm	Daily total 07-07 MST
PT	Precipitation type (prevailing)	10 types (Tab. 3)	Daily, 07-07 MST
SWE	Snow water equivalent	mm	weekly[2]
PI	Precipitation intensity	mm/h	Continuous on AWS
SI	Snowfall intensity	cm/h	Continuous on AWS
SS	Snow surface condition	11 types (Tab. 4)	Daily at 07 MST
T	Air temperature	°C	07, 14, 21 MST
Tx	Maximum daily temperature	°C	Daily maximum
Tn	Minimum daily temperature	°C	Daily minimum
RH	Relative humidity	%	07, 14, 21 MST
N	Cloudiness	oktas or tenths	07, 14, 21 MST
SunD	Sunshine duration	h	Daily total
GR	Global solar radiation	W/m^2	Daily totals
Wd	Wind direction	8 or 16 directions	07, 14, 21 MST
Ws	Wind speed	m/s	07, 14, 21 MST
WG	Wind gust speed	m/s	Daily maximum
Press	Air pressure	hPa	07, 14, 21 MST

Tab. 3: Precipitation types reported by observers in Slovak INTER report (see [92]) grouped into four basic types.

Precipitation type	Code	Description
✳ Solid	7	Only snow
◇ Mixed	1	Mixed or variation of solid and liquid
	3	From solid to liquid
	4	From liquid to solid
● Liquid	2	Freezing
	5	Drizzle or drizzle with rain
	6	Only rain
< Not studied >	8	Only liquid or solid showers
	0	Precipitation in vicinity
	9	Hail or hail with rain

[2] SWE measured on Mondays, if total snow cover depth is 4 cm or more. See Snow water equivalent, p.32.

The data of the Czechoslovak classification of synoptic situations (patterns) has been available since 1.1.1946. The most widely used classification comprises 28 types. It was developed by a team led by J. Brádka on the basis of Hess-Brezowský and Multanovský classification [94].

The *maximum wind gust* recorded for given day was excluded at the beginning of stepwise variable selection, due to low number of records. The longest series at Lomnický štít was available only since 1993. Moreover, its statistical structure is not suitable for regression methods as the average wind speed.
Precipitation intensity from ombrograph records were not available in the database.
The *state of the ground* with snow and some *meteorological phenomena* (rain with snow, freezing rain, glaze, rime, blowing or drifting snow) were occasionally used during detailed analysis, when information on snow pack structure was important (e.g. for the assessment of avalanche indices – see section 2.4.1).
Some meteorological variables important in avalanche prediction are measured only shortly, irregularly or not at all: snow surface temperature, depth of snow on storm board, density of new snow, settlement of new snow.
In the autumn of 2003, an ultrasonic snow depth sensor was installed for testing purposes on the pioneer mountainous *automatic weather station* (AWS) in Jasná. Few years later, another 5 special AWS designed mainly for avalanche forecasting were installed in the year 2007/08. These stations are equipped with a webcam, sensors and devices for measuring air temperature and humidity, wind speed and direction, snow depth, precipitation, sunshine duration, snow surface temperature and temperatures in 5 fixed heights above ground (in winter for snow temperature profile). Four of 5 AWSs needed a reconstruction after 2 years of operation, due to the damaged masts caused by avalanche blast waves and extreme icing with strong wind.
Also the data from SHMI AWSs were not processed, because they are available only since 1996. However, the data may enable the development of avalanche forecasts with hourly time resolution in future. This task will need a little different approach.

The elementary meteorological variables are internally numbered (e.g. ***V17***), so that it is easier to refer to them:

V1	T_7	**V6**	Ws_7	**V12**	RH_7	**V28**	*NS*
V2	T_{14}	**V7**	Wd_7	**V13**	RH_{14}	**V29**	*SD*
V3	T_{21}	**V8**	Ws_{14}	**V14**	RH_{21}	**V30**	*SWE*
V4	T_x	**V9**	Wd_{14}	**V15**	N_7	**V31**	*R*
V5	T_n	**V10**	Ws_{21}	**V16**	N_{14}		
		V11	Wd_{21}	**V17**	N_{21}		
V35	*SunD*	**V36**	*WG*	**V37**	*Press*	**V38**	*GR*

2.2.1 Elaborate variables

Beside the basic meteorological variables, also some nonlinear, mixed and cumulative variables were defined in order to improve the step-wise regression model. These elaborate variables were taken from or inspired mainly by Salway [81], Vojtek [104], and Baggi and Schweizer [5].

The variables are internally numbered (e.g. ***V18***), so that it is easier to refer to them.

V18 $\tilde{T}^2 = (T_x - T_n)^2$ - squared temperature amplitude

V19 $\overline{T_{x+}} = \begin{cases} 0 \ldots T_x \le 0°C \\ T_x \ldots T_x > 0°C \end{cases}$ - positive maximum air temperature

V20 $W^2 :\equiv \left(\frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3} \right)^2$ - squared wind speed (a measure of kinetic energy for snow transport)

V21 $\mathrm{logW} :\equiv \ln\left(\frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3} + 1 \right)$ - natural logarithm of average wind speed

Wind direction is a significant variable, because it is a signal of any change in synoptic situation. The problem of numeric discontinuity around north directions (e.g. an abrupt numeric change from 350° to 10°) was solved by introduction of *wind orthogonal projections*, i.e. north *WNproj* and west *WWproj* components:

V22-4 $WNproj_i = Ws_i \cdot \cos\left(\frac{2\pi}{360} Wd_i \right)$ **V25-7** $WWproj_i = Ws_i \cdot \left(-\sin\left(\frac{2\pi}{360} Wd_i \right) \right)$,

where i = {7, 14, 21} MST

These variables are an alternative to *snowdrift index* that is already measured by a special device in some countries.

V32 $\mathrm{SDR} = SD \cdot R$

V33 $\rho^{\mathrm{NS}} = \frac{R}{NS}$

V34 $\rho_{\mathrm{o/n}} = \frac{\frac{\mathrm{SWE}}{\mathrm{SD}}}{\frac{\mathrm{R}}{\mathrm{R+NS}}}$

V39 $colday = \begin{cases} \sum 0 \ldots T_{\max} \ge 0°C \\ \sum n \ldots T_{\max} < 0°C \end{cases}$ - number of previous consecutive days with the maximum temperature below freezing

V40 $melday = \begin{cases} \sum 0 \ldots \overline{T} \le 0°C \\ \sum n \ldots \overline{T} > 0°C \end{cases}$ - number of previous consecutive days with the mean temperature above freezing

V41 $\mathrm{SetRat} = \frac{[\mathrm{SD}]_{-1} - ([\mathrm{SD}] - [\mathrm{NS}])}{[\mathrm{SD}]}$ - settlement rate

V42 $NSlogW = [NS] \cdot \ln\left(\frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3}+1\right)$

V43 $NSW = [NS] \cdot \frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3}$

V44 $NSW2 = [NS] \cdot \left(\frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3}\right)^2$

V45 $NSW3 = [NS] \cdot \left(\frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3}\right)^3$

V46 $SDRRH = [SD] \cdot [R] \cdot \frac{[RH_7]+[RH_{14}]+[RH_{21}]}{3}$

V47 $SDRRHT_n = [SD] \cdot [R] \cdot \frac{[RH_7]+[RH_{14}]+[RH_{21}]}{3} \cdot [T_n]$

V48 $SDRRHT_x = [SD] \cdot [R] \cdot \frac{[RH_7]+[RH_{14}]+[RH_{21}]}{3} \cdot [T_x]$

V49 $RT_x = [R] \cdot [T_x]$

V50 $RT_n = [R] \cdot [T_n]$

V51 $R1T_x = [R]_{-1} \cdot [T_x]$

V52 $R1T_n = [R]_{-1} \cdot [T_n]$

V53 $NSTamp = [NS]_{-1} \cdot \left(T_x - [T_n]_{-1}\right)$

V54 $TTR = \left([T_x]_{-1} - T_7\right) \cdot R_{-1} \cdot \left([T_7]_{-1} - T_7\right)$

V55 $COHES :\equiv \sqrt{\sum_i \left(NS^{-(i+1)} \cdot \left(T_x^{-(i+1)} + T_n^{-i}\right) - \sum_{i=0}^{n} \frac{NS^{-(i+1)} \cdot \left(T_x^{-(i+1)} + T_n^{-i}\right)}{n} \right)^2}$,

where $n = 2$ and $i > 1$

V56 $NS3 = \sum_{i=0}^{2} NS_{-i}$

V57 $NS4 = \sum_{i=0}^{3} NS_{-i}$

V58 $NS5 = \sum_{i=0}^{4} NS_{-i}$

V59 $SDRRH :\equiv \sqrt[3]{[SD] \cdot [R] \cdot \frac{[RH_7]+[RH_{14}]+[RH_{21}]}{3}}$

V60 $NS2W :\equiv \left([NS]_{-1} + [NS]\right) \cdot \frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3}$

V61 $NS3W = \left([NS]_{-2} + [NS]_{-1} + [NS]\right) \cdot \frac{[Ws_7]+[Ws_{14}]+[Ws_{21}]}{3}$

V62 $\Delta Press := \equiv \frac{Press - Press_{-1}}{Press}$

In view of the fact that favourable conditions for avalanche release form several days before the event, each variable V1-V62 was shifted back in time. Given that 7 days were chosen as sufficient limit, as a result, more than 400 variables were available for a single station if all basic elements were measured. By convention, a value of variable V1 measured 3 days ago is referred as 3V1.

2.3 Snowpack and stability

While weather variables can be characteristic for a significant part of a mountain range, snowpack characteristics seems to be more local and only representative for a smaller area [37]. Therefore, various snowpack observations (Tab. 5) are currently made and new techniques (such as stability tests in Tab. 6) are being introduced to get tighter relationship with avalanche activity. The type of snowpack surface (Tab. 4) is one of special meteorological observations performed at the APC stations.

Tab. 4: Snowpack surface types reported by observers from the APC stations or nearby slopes.

Code		Description
1	**Dry**	Powder snow (ski sink easily)
2		Consolidated or settled
3		Wind-packed slab (deep sounds during walk)
4		Ice crust (walk without climbing-irons possible, foot sink through crust)
5		Ice layer, glaze (walk on climbing-irons necessary)
6		Frozen firn
7		Surface hoar
8		Graupel
9	**Wet**	Moist (no water flows from snowball when pressed)
10		Wet (water flows)
11		Clog snow, melting firn

An example of snow profile can be found in Appendix F. Ramsonde is a part of the measurement.

Tab. 5: Significant elements from complex snow profile observation.

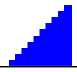
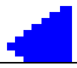
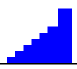
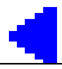
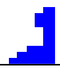
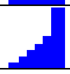
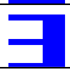
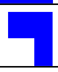
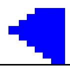
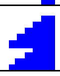
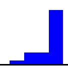
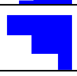
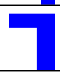
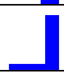
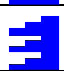
Symbol	Element	Unit
ρ	Snow density	g/cm^3
PD	Penetration depth	cm
K	Ram hardness	$kg.m/s^2$
TP	Temperature profile	°C
GS	Grain size	mm
GT	Grain form (type)	10 basic types

Tab. 6: Some stability tests used more or less in Slovakia to assess the avalanche danger in terrain.

Stability test	Equivalent in Slovak
Test skiing	Test zlyžovaním
Test with explosives	Test odstrelom
Rutschblock test	Zosuvný blok (Blokový test sklzu)
Shovel shear test	Test sklzu lopatkou
Compression (tap) test	Poklepový test
Stuffblock test	Test spustením závažia
Tilt board test	Test naklonením doštičky

New method for the verification of avalanche danger level was developed in Italian Alps by AINEVA association [95] and [74]. Avalanche danger level is a result of four different assessments. One approach is based on combination of the amount of snow and the type of snow profile (see Tab. 7).

Tab. 7: Snow profiles classification by AINEVA. Abbreviations stand for snowpack stability levels: S – good stability, M – moderate stability, W – weak stability, VW – very weak stability. Colours represent the avalanche danger level.

Snow profile		Snow depth					
		30 cm	60 cm	90 cm	120 cm	150 cm	180 cm
1		S	S	S	S	S	S
2		M	M	M	M	S	S
3		S	S	S	S	M	M
4		W	W	W	M	M	M
5		S	S	M	M	W	W
6		M	M	M	W	W	W
7		S	S	M	M	W	W
8		S	M	M	W	W	W
9		M	W	W	W	W	W
10		W	W	W	W	M	M
11		M	W	VW	W	M	M
12		S	M	W	W	VW	VW
13		M	W	VW	W	W	M
14		W	VW	VW	VW	VW	VW
15		M	W	VW	VW	VW	VW
16		W	W	VW	VW	VW	W

2.4 Avalanche data

The oldest mentions of avalanches point out that avalanches have always represented significant problem for forests, buildings, infrastructure and visitors of Slovakian mountains. Fortunately, some authors searched for these rather sporadic records and collected them: Bohuš [12] completed avalanche records published by Andráši [2].
The oldest records can be found in annuals of the Hungarian-Carpathian Association, founded in 1873 to deal with guidance, rescue and prevention in mountains of Austro-Hungarian empire.
The first known avalanche record describes ground avalanche from 1850 in the High Tatras:

> *In 1850, ground avalanche released from Tupá into Zlomiská valley, toward the Popradské pleso lake. It carried along well-grown groups of Swiss Pines and buried a few Tatra Chamois. [2]*

The second record describes an avalanche a quarter of century later:

> *In 1874, an avalanche that triggered from the west slopes of Velická kopa (Granátové steny), buried the mountain cottage near Velické pleso lake. [2]*

The fifth record includes the day of occurrence, and even the track length:

> *1.3.1908: M. Zaruski and R. Kordys triggered an avalanche during the descend on ski from Polish Ridge into Svišťová dolina valley. Track length was 266 m. Nobody was injured thanks to experiences of the two mountaineers caught. [12]*

The selection of interesting avalanche records from the historical records inserted into SLPDB database by the author follows:

Peculiar avalanche records

26.7.1936 – Austrian student (13 years old) perished under the Čierny štít peak. He released a massive snow table when traversing, and was buried in depth.

25.7.1942 – Firn released under the feet of I. Fábry, when descending from the Štrbský štít peak and traversing SW slope above the Okrúhle pleso tarn. He was drifted down to the lakefront.

13.4.1946 – an avalanche was released due to the shooting of signal rockets during military exercise. The day after, two separate avalanches occurred on the same path within one hour.

Winter 1954/55 – the Chata pod Rysmi cottage was hit by avalanches twice.

July 1969 – avalanches occurred in High Tatra Mts. during summer !

6.-10.9.1971 – unusual temperature drop with snowfall created conditions for numerous avalanche releases in the Western and the High Tatras. Some avalanches rich in snow were of sizes that do not occur even during a whole winter. Their lengths were 600-800 m, with debris heights of 3-5 m.

21.-22.3.1980 – many (60-70) small avalanches sufficient to endanger a man. Most of the full depth avalanches released early in the morning of March 22nd.

Winter 1984/85 – a big number of avalanche accidents during December and January. Very low temperatures and great temperature gradient caused development of persistent weak layers within the snowpack, despite its below-average quantity

5.4.1985 – the flowing of avalanche in the Žiarska dolina lasted for 4 minutes

1st half of June 2005 – a rapid temperature fall with snowfall caused moderate avalanche danger with numerous small avalanches in Western and High Tatras.

5.-11.8.2005 – very cold weather with heavy rainfall and above 1800 mASL with snowfall, unusual in August. Snow depth in the HT Mts. was about 45 cm, but due to the snow drift, the depth was in places (north slopes mainly) up to 80 cm. The soil was relatively warm and the snow was not well bonded to it. This resulted in numerous sluffs and small avalanches up to 450 m.

25.3.2009 11:00 – the largest avalanche ever recorded triggered in the Žiarska dolina valley. It was composed of 7 powder snow avalanches and estimated volume of released snow mass could be placed on one football field to the height of 370 m (Eiffel tower is 324 m high) [63].

After the World War II, some basic avalanche parameters were collected from questionnaires disseminated among tourists and climbers. The systematic registration of avalanche accidents began in 1960's by TANAP guides and Mountain Rescue Service. However, this archive contains usually the avalanches associated with a damage, injuries or casualties.
Another progress came in 1981 with the Cadastre of avalanche terrains and their topographic characteristics [67] that supported significant increase in the number of recorded avalanches (see Fig. 2), which were reported by occasional APC patrols, cottagers and volunteers.

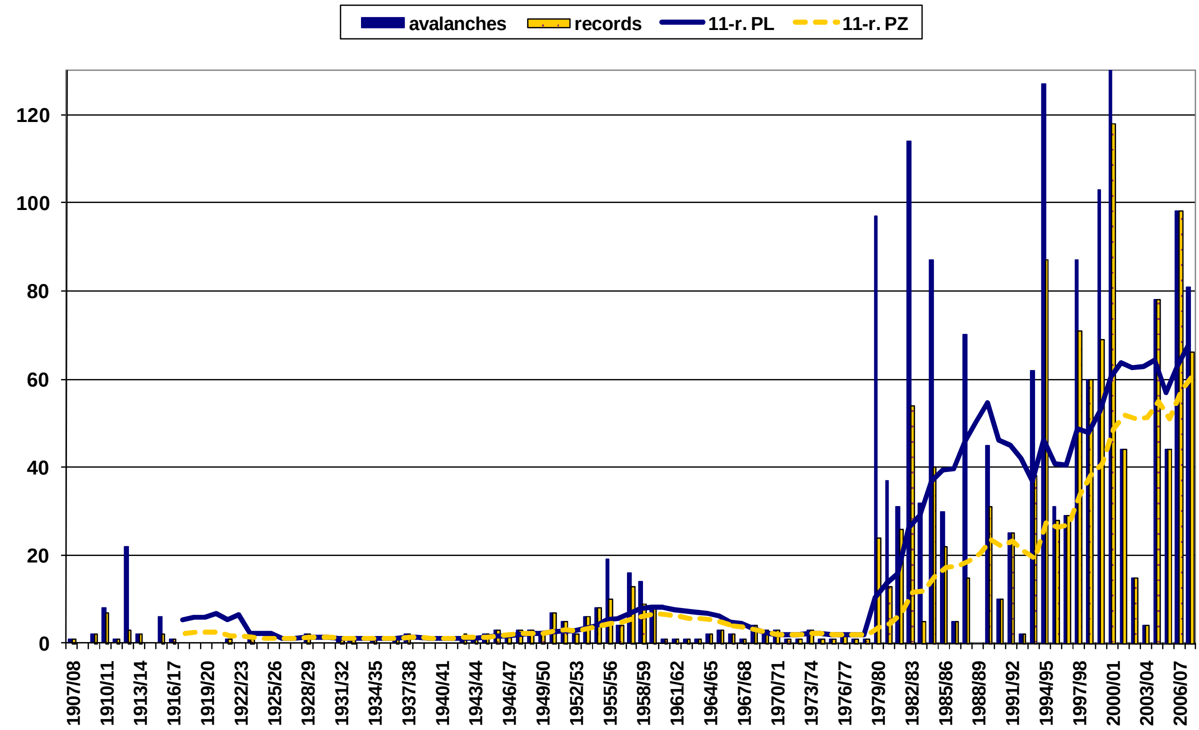


Fig. 2: The number of avalanches and records in the High Tatra Mts. with 11-year running averages increased rapidly in 1979/80. Data taken from SLPDB database.

The registration of avalanches got easier with implementation of electronic avalanches database in 1990s, and this enabled regular and systematic processing. Data flows from/to APC and automation of their processing were analyzed by Vyparina [111].
The avalanche records since 1991 were loaded from FoxPro (under MS DOS) into SLPDB (Microsoft Access 2000 database), which offers a better graphical user interface and the amount of data is sufficient for some of numerical forecasting methods. The data model was also changed a little to enable „many-to-many" relationship between avalanches and slopes. If an avalanche stroke more slopes, the old data model enabled to assign it only to a single slope. The new data model (see Fig. 3) comprises principally of three main tables: **`avalanches(laviny)`**, **`slopes(svahy)`** and **`avalanche_slope(lavina_svah)`**. The latter table assigns a time event (i.e. avalanche at specific time or interval identified by unique **`IDLavina`**) with a space where the event took place (one or several slopes, **`IDSvah`**). The table **`laviny`** contains date, time or time interval of avalanche occurrence and its parameters. The table **`svahy`** contains parameters of avalanche slopes grouped into valleys and ranges.

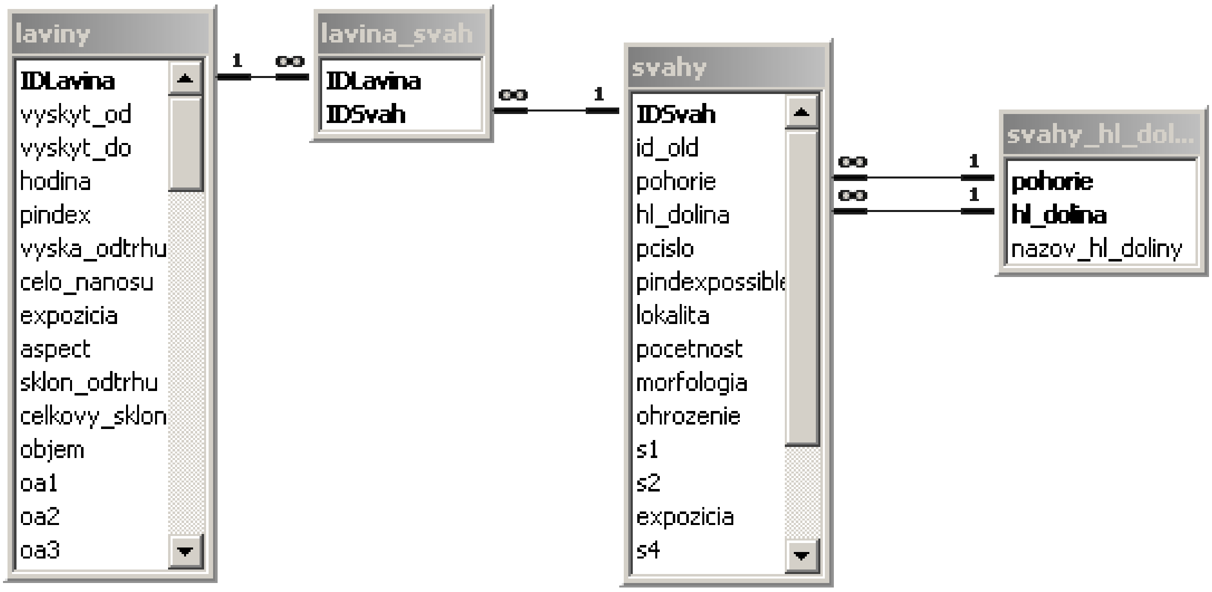


Fig. 3: Relationships among the core tables in SLPDB.

There are also another tables according to the needs of APC, and obviously, various forms for easy data entry (Fig. 4).

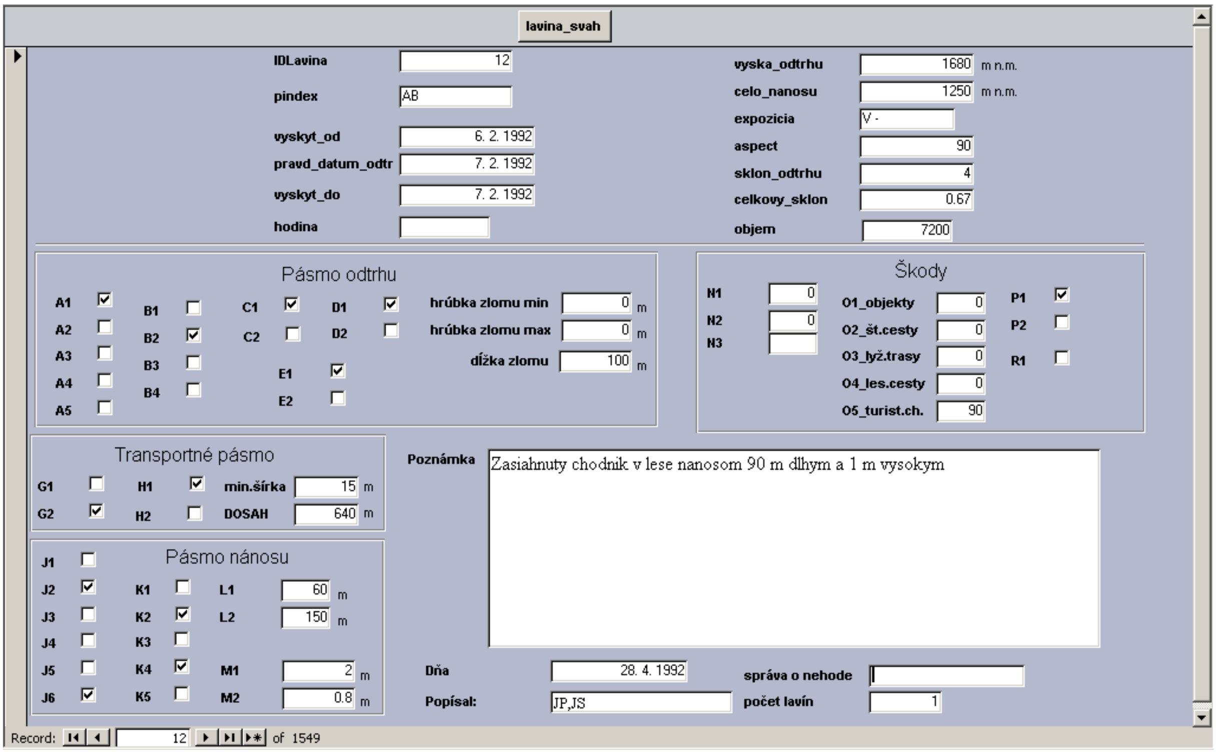


Fig. 4: Form designed for avalanche parameters entry.

2.4.1 Variables Characterizing Avalanche Activity

Some basic variables characterizing daily avalanche activity in the High Tatras were introduced in diploma thesis [104] (winters 1994/95 – 1999/00). Some of the definitions required to be slightly modified here:

- **Forecasted avalanche danger level** [Y_f] – a real forecast of avalanche danger level (see Appendix C) issued by APC
- **Tendency** - [$Y_{+/-}$] – a tendency of avalanche danger (1-increase, 0-stagnation, 2-decrease)
- **Boolean variable** [$Y_{I/O}$] – is 1 if at least one avalanche was recorded; equals 0 if no avalanche was recorded (including surrounding mountain ranges)
- **Snow avalanche water content** [Y_{swc}] –
    - equals 1 if the trigger (usually of dry avalanche) was caused primarily by large portions of fresh snow
    - equals 3 if the trigger (of wet snow avalanche) was caused mainly by increased temperature or solar radiation (increased snow water content)
    - equals 2 in case of combined effects (dry, moist, wet avalanches)
    - equals 0 if no avalanche was recorded (including surrounding mountain ranges)
- **Number of avalanches** [Y_N] – count of all recorded avalanches; it is 0 if no avalanche was recorded (including surrounding mountain ranges)
- **Maximum avalanche track length** [Y_{dx}] – maximum length in meters of all recorded avalanches.[3] The longer dimension (width or length) was taken for slab avalanches. In some cases the value differs (by no more than 30%) from really measured value, especially if extremely long avalanches were recorded in neighbouring Western Tatras.
- **Harm index** [Y_i] – values between 1 = no harm, and 10 = catastrophic avalanche. Damage on forest, buildings or paths was considered.
- **Verified avalanche danger level** [Y_Ω] – forecasted Y_f that was corrected if the forecast was not successful. Assessed with precision of half-degree, e.g. may equal to 2.5 if avalanche danger is 2 in the morning and 3 in the afternoon.

All the above mentioned variables introduced in late 1990s had to be estimated backward for a given day by an expert. The aim was to gain a data sample with sufficient quantity of serious avalanche days, i.e. danger level 3 and higher was in preference (see *Tab. 21*). Various data sources were utilized during this estimation, including even the NCEP reanalysis of 500 hPa pressure field maps, available since 1948 [5*].

[3] Salway [81] defines relative terminus as a ratio of actual avalanche length to maximum possible avalanche path length on a given slope.

3. Methods

3.1 Quality checking and homogeneity

Long homogeneous time series (where variations are caused only by variations of weather and climate) are inevitable for any climate change study. Even though the data obtained from SHMI databases undergo multiple revisions, some errors and inconsistencies were revealed, mainly in precipitation database. Some automated quality checking (QC) rules were applied on datasets and, whenever possible, the missing/erroneous data were completed/corrected usually taking data from surrounding stations (reference series standardized to average and standard deviation of candidate station). Afterwards, the longest time series of precipitation, total snow depth, new snow height and mean daily temperature were homogenized in order to eliminate non-climatological biases. QC in climatology is a „never-ending story"...

3.1.1 Missing/erroneous records

Oldest records in SHMI precipitation database contain a value only if it was not null. Therefore the periods of missing measurements might be incorrectly interpreted as periods without precipitation (drought periods). It was desirable to eliminate these null records either by completing the precipitation data with zero values or by replacing the missing values, in case of shorter breaks (i.e. a few successive days) with values from suitable reference series. Unfortunately, longer breaks (i.e. a few months/years) cause significant loss of information, so that only the longer part of the time series can be used for climatological purposes. Otherwise, such interpolation would lead to distorted interpretation without improved information value.
Without treating outliers, homogenization and successive analysis may render misleading results [100].
Examples of common errors in data may be: misplaced decimal, added digit, reversal of sign or digits during data entry (e.g. 7 and 1), careless sampling, reading/writing by observer, etc. Sometimes it can be confusing, when new snow depth measured 'this morning' is written to yesterday's date. Merging databases from various providers may thus lead to consistency errors, e.g. if snow depths are written to the day after/before the 'observation day'. Comparisons with neighbouring stations are here of crucial importance.

QC rules

Simple QC rules were applied on precipitation data. The suspect records were subsequently revised and corrected, if necessary:

$SD < NS_{-1}$ (total snow cover less than new snow; both measured at the same time)
$SD\text{-}SD_{-1} > NS_{-1}$ AND R-1 > 0 (increase of snow depth between successive days higher than new snow)
NS = 0 cm & PT = 7 (only snow) & R > 5 mm
(NS_{-1} = 0 OR R_{-1} = 0) AND $SD\text{-}SD_{-1} > 0$ (snow cover depth increase without any precipitation)

The null values were replaced by zeroes according to the following rules:
IF $R_{-1} = 0$ AND $SD\text{-}SD_{-1} \leq 0$ THEN INSERT $NS_{-1} = 0$
IF $R_{-1} > 0$ AND $SD\text{-}SD_{-1} \leq 0$ AND PT_{-1} = 5 or 6 (drizzle or rain) THEN INSERT $NS_{-1} = 0$

Total snow cover can be estimated from other meteorological elements. However, no snowpack model was used for quality checking.
New snow height can be estimated from its density and precipitation measured in gauge. The following table can be used for rough estimation of new snow density, using mean term temperature T_t:

Tt [°C]	≤ -2	-1	-0.5..0	0..+0.5	+1	≥+2	Average (all records)
rhoNS [kg/m^3]	95	125	140	180	230	210	100
1 mm of precipitation corresponding to NS [cm]	1.1	0.8	0.7	0.6	0.4	0.5	1

Some quality checking rules on SWE were adopted from [87], while others were developed for further purposes of this work. SWE values measured weekly were compared with estimated SWE values (two methods were used: [71], [83]), and the outliers were especially scrutinized.
SWE has been measured and recorded in most cases on Mondays since 1971, however, at some stations the frequency of measurement had been every 10 days mainly before the mid 1960s. Occasionally, there were also records for other days of week.

Monday SWE record was flagged as missing/erroneous when $SD \geq 4$ cm and $SWE \leq 0.01 \cdot SD$.

The record was flagged suspect when:

1. $SWE < 0$ mm or $SWE > 300$ mm... global limit check

2. $SWE_0 \leq 0.1 \cdot SWE_{-1}$ or $SWE_0 \geq 10 \cdot SWE_{-1}$ ... maximum interdiurnal change

3. $SWE_0 < SD_0$ or $SWE_0 > 70 \cdot SD_0$ ... density of total snow cover should be from 10 to 700 kg/m^3

4. $SWE_{-1} - 0.35 \cdot \overline{T_{0+}} + R^*_{-1} \leq 0$ ... estimated SWE_0 value is 0 cm or less

   , where $R^*_{-1} = \begin{cases} 0 \ldots R_{-1} > 0 \wedge NS_{-1} = 0 \wedge SD \leq 10cm \\ else \\ R_{-1} \end{cases}$

   It was assumed that when liquid precipitation (only rain) falls on snow cover, which is 10 cm or less deep, the rainfall completely flows away (R^*_{-1} = 0) and does not contribute to SWE. Rough melting of snow cover is obtained by multiplying the positive mean daily temperature $\overline{T_{0+}}$ with coefficient -0.35 [cm/°C]. Refer to 'temperature index degree-day method' in [61].

5. $\dfrac{\left| SWE_0 - SWE_{-1} + 0.35 \cdot \overline{T_{0+}} - R^*_{-1} \right|}{SWE_{-1} - 0.35 \cdot \overline{T_{0+}} + R^*_{-1}} \leq 0.25$ absolute value of relative change should be less than 25 %.

6. $SWE_0\text{-}SWE_{-7} > \sum_{i=-6}^{0} R_{i-1}$ increase in SWE value during a week greater than weekly precipitation amount is suspect, assuming that precipitation measurements were not underestimated. More false alarms are generated at stations where considerable amount of solid precipitation is systematically lost from precipitation gauge.

7. $SD_0 > SD_{-7} \wedge SWE_0 < SWE_{-7}$ ... increase of SD and decrease of SWE

8. $\frac{SD_0}{SD_{-7}} > 1.1 \cdot \frac{SWE_0}{SWE_{-7}}$ ... increase/decrease of SD and suspicious/inadequate decrease of SWE, respectively

9. $\overline{W_s} > 7$ m/s and $\left|SWE_0 - SWE_{-1} - R_{-1}\right| > 500$ ... day-to-day change of SWE is 5 cm or more than estimated variation caused by redistribution of snow by drifting/blowing

All suspect records were verified by human expert to judge whether the value is valid or erroneous. If an erroneous value occurred, then both the preceding and the following values were checked in detail, because unreliable observers sometimes preferred estimating instead of real measuring of SWE value. Whenever it was plausible, the missing and erroneous values on Mondays were estimated and completed, in order to obtain the best weekly SWE time series as input for the CHMI method [71]. The estimation of missing/erroneous values was based on a combination of two independent methods [71] and [87] fit on valid measurements.

Assuming that snow water equivalent is measured professionally, we can define a measure of precipitation gauge catchment ability as a ratio of weekly precipitation total (if any occurred within the week) to the snow water equivalent weekly increase:

$$Q_i^{SWER7} = \frac{\sum_{j=i}^{i-7} R_{j-1}}{SWE_{\mathrm{i}}\text{-}SWE_{\mathrm{i-7}}}$$

Finally, the measurement quality coefficient Q^{SWER7} for a given station was defined as an average of the weekly ratios, fulfilling the following conditions:

$$\sum_{j=i}^{i-7} R_{j-1} \geq 1 \text{ and } SWE_{\mathrm{i}} > SWE_{\mathrm{i-7}}$$

Nevertheless, for a given station, the QSWER7 indicates the quality of measurement, either of the precipitation in winter or the snow water equivalent.

QC rules

Dry avalanches

An error is reported if the following conditions are fulfilled:

$$Y_{swc} = 1 \text{ AND } \frac{\sum_{j=i}^{i-3} R}{\sum_{j=i}^{i-3} NS} > 3.5$$

In other words, dry avalanche probably does not occur if 3-day fresh snow average density is higher than 350 kg/m^3. *NS* and *R* are taken from a set of representative stations located within altitudinal range of avalanche occurrence (e.g. 1100-2600 mASL in the HT Mts.).

$Y_{swc} = 1$ AND $\overline{T}_{nx} > 0°C$

$\overline{T}_{nx}$ is an area average of minmax temperatures computed from the stations Štrbské Pleso, Skalnaté pleso and Lomnický štít. The average altitude (~1900 mASL) well represents typical starting zones for the HT Mts.

Moist avalanches

$Y_{swc} = 2$ AND ($\overline{T}_{nx} > +6°C$ OR $\overline{T}_{nx} < -10°C$)

Wet avalanches

$Y_{swc} = 3$ AND $\overline{T}_{nx} < -4.5°C$

The relationship between $\mathbf{Y_{swc}}$ and water content in snow fallen for the previous 3 days is clearly visible in Tab. 8.

Tab. 8: The ratio of new snow to total precipitation (3-day sums) is a measure of snow density (1979/80-2003/04). Q1 = first quartile, Q3 = third quartile.

Y_{swc}	Days	[NS_{sum3d} / R_{sum3d}]		
		Q1	Median	Q3
1	218	9.5 %	11.2 %	13.6 %
2	114	7.2 %	9.4 %	10.7 %
3	142	5.1 %	6.8 %	8.5 %

3.1.2 Homogenization

In the view of further climate trends analysis, the following criteria were concerned for stations selection:

1. Stations located at high altitudes,
2. the longest series with minimum number of missing/erroneous data,
3. both precipitation and temperature data available.

Metadata

Some potential inhomogeneities can be detected directly from metadata, if available. These include station/measurement movement, device exchange or recalibration, change of observer, measurement method or environment, etc. Recently, introduction of snow guns might have changed micro-climate and had significant influence on winter measurements: increased humidity and precipitation due to drifting and blowing snow, higher albedo, etc. Significance of inhomogeneity becomes apparent when compared with neighbouring stations. However, metadata are often incomplete and some essential influences causing a discontinuity might be missing.

Whether there was metadata available or not, the following relative homogeneity tests were performed on monthly and yearly data using AnClim software [99]:

- various modifications of SNHT (single normal homogeneity test) by Alexandersson [1]
- Easterling & Peterson [24]
- Bivariate test by Maronna & Yohai [56]
- Vincent method [102]

These tests are performed on merged time series, created as difference/ratio between time series from inspected ***candidate*** station and ***reference*** series – usually a composite of surrounding stations. The technique of creating reference series is very important. If metadata files of good quality exists, the detected inhomogeneities can be easily verified and corrected.

Reference time series

Reference series should represent given climatological region, and can be calculated as weighted average from the nearest stations. The weights are usually a function of distance or correlations (see Fig. 5). Peterson and Easterling [75] suggested calculating the correlations from the series of first differences, because it eliminates the influence of eventual steps on the correlation coefficient.

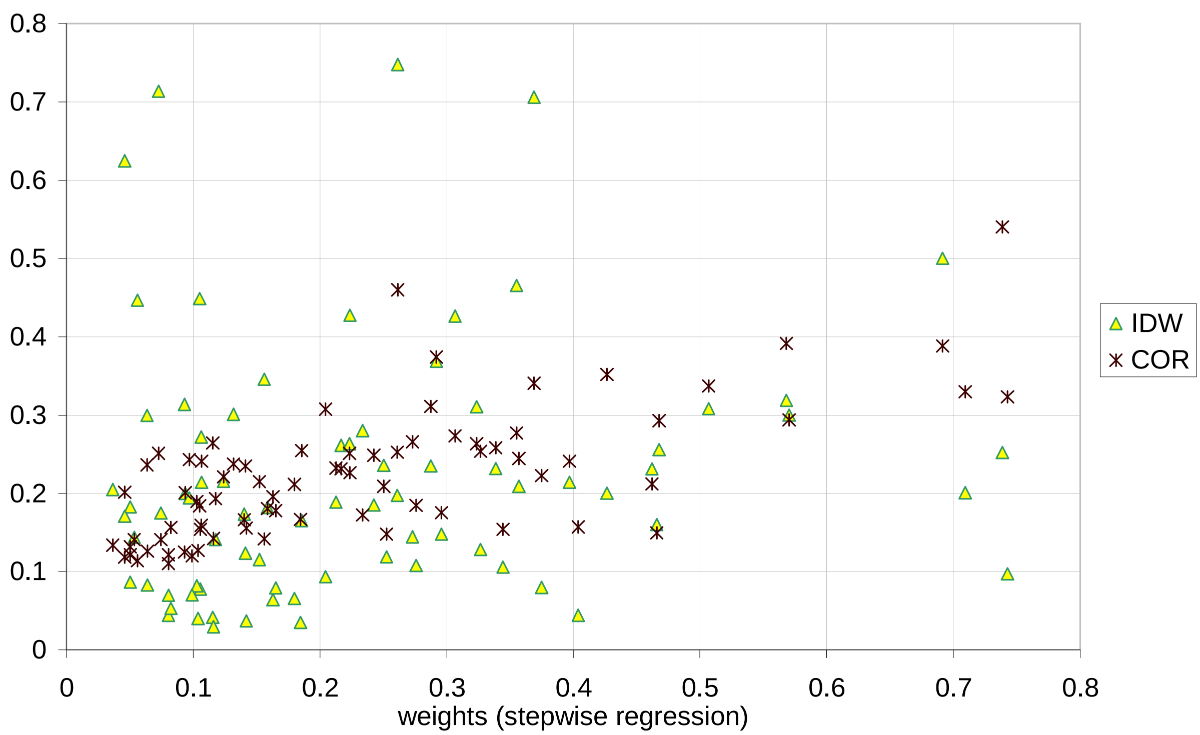


Fig. 5: Relationship between weights obtained from stepwise regression method and inverse distance (IDW) and Spearman rank correlations (COR) weights. All weights were standardized so that the sum of weights for a given reference precipitation series was equal to 1. There is a poor relationship between IDW and stepwise regression weights.

The neighbouring stations with observing period at least of the same length as candidate station were picked from the union of up to ten nearest stations (by horizontal distance) and stations with correlations (calculated from the series of first differences) exceeding 0.65. Mean distance among the studied stations was around 80 km. If less than 3 stations passed through the above mentioned criteria, then additional independent, though shorter, reference series was created.
The daily reference time series were created as the best linear combination of neighbouring series obtained from stepwise regression. In case of precipitation and snow series, only records with values greater than zero were included into correlation and regression procedures, and only positive coefficients were used in linear combination.
When a neighbouring station creating a reference series was suspect of having a potential discontinuity within the same decade as the candidate series, then another reference series was used for testing. The influence of eventual inhomogeneities in reference series was thus reduced by using preferably homogeneous neighbouring stations in the second (and eventually in the third) round of homogeneity testing. The typical number of neighbouring stations creating a reference series was 3 to 7.

Some reference series were finally standardized to average and standard deviation of candidate station:

$$Y_R = E_C + \frac{D_C}{D_R}(Y_R - E_R)$$

, where E_C, E_R are mean values , and D_C, D_R are standard deviations of candidate/reference series. Since both series must have normal distribution, this standardization was applied only on temperature data. Afterwards, these series were used for missing data completion.
Snow and precipitation reference series were not standardized.

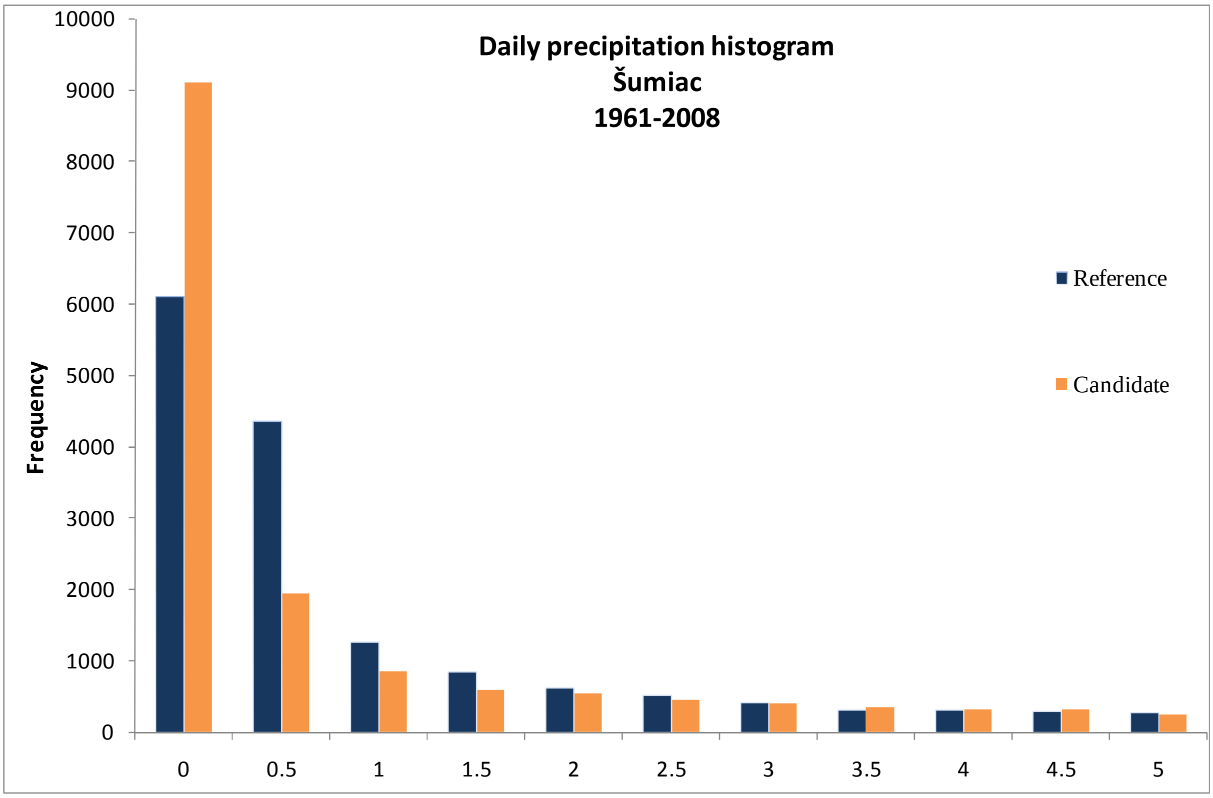


Fig. 6: Histograms for daily precipitation amounts in mm; station Šumiac and its best reference series. Note the differences on the left part - the x-axis is cut at 5 mm intentionally.

The reference series created by a combination of more stations have different distribution than the candidate station (see histogram above). Zero cases occur less frequently in such reference series, because they cover greater area than single station. These reference series must be adjusted if we intend to use them for missing data completion. Otherwise, some analysis where distribution of the lowest precipitation values is important might be negatively affected.

Approving and adjusting inhomogeneities

Potential inhomogeneities detected by tests should be confirmed by metadata.

The inhomogeneity recorded in metadata was approved if at least 2 different homogeneity tests fulfilled all the following criteria:

1. only significant steps detected in monthly [1-12] or yearly [Y] series are considered
2. step was detected at least for two different time series (monthly or yearly)
3. maximum error of +/- 2 years in detected inhomogeneities was tolerated for tests

When metadata were not available, then at least 3 different tests must fulfil the above mentioned criteria.

There are several methods used for adjusting at presence. It is necessary to realize the aim and consequences on characteristics that we are going to calculate from adjusted series.

Adjustments in this work were performed on daily data, using a method of percentiles described by Štěpánek et al. in [100], also called “q-q method”. Adjustment coefficients were calculated using 5 years around the inhomogeneity, and they were applied only for those months where the correlation coefficient between adjusted and reference series was changed by -0.005 or more.

Snow depth series can be considered as partly cumulative variable, and such series are also called stationary in statistics. When only certain month is adjusted and others remain unchanged, there are artificially created steps in snow depth series in the first and the last day of the month.

Therefore the adjustment was performed on the series of first differences, and snow depth series were recreated back by an integration from these adjusted series.

After the first inhomogeneity is adjusted, the whole process is repeated until there is no significant inhomogeneity detected.

3.2 Snow climatology

The change of snow climate may positively or negatively affect the energy and hydrological balance, local ecosystems, tourism and other human activities in future. This work focuses on climate trends of some selected snow characteristics, mostly for the period 1961-2008. Regular observations of snow began in 1921 after the foundation of MET-service in Czechoslovakia. Another increase of snow observing stations is connected with a boom of winter sports in 1960s. Given that the precipitation database offers data starting from 1981, the stations can be divided into 3 groups, depending on the length of snow depth series (see Fig. 7).

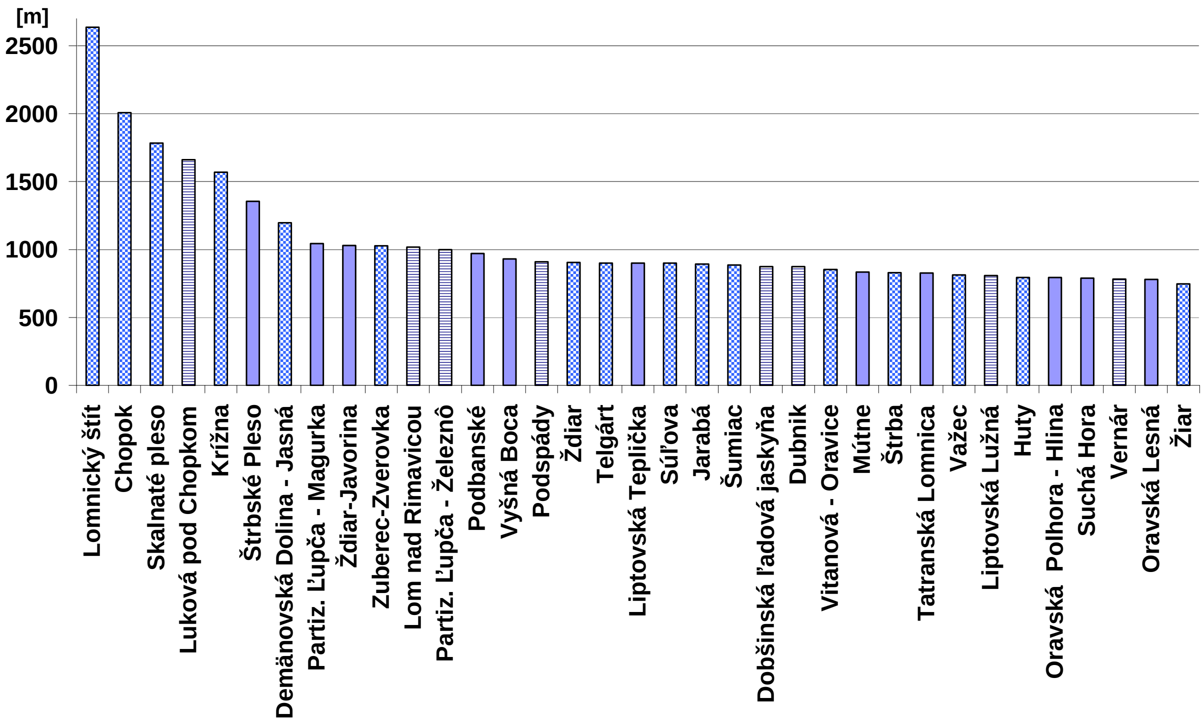


Fig. 7: Meteorological stations sorted by altitude can be divided into 3 groups, depending on the beginning of snow depth observation: since 1981 (lining); since 1961 (chessboard); and the longest since 1921 (full).

There are various characteristics used in snow climatology nowadays:

- Seasonal[4] sum/average/maximum snow depth in cm ($\sum SD, \overline{SD}, SD_x$)
- The first (B1, …, B50) and the last (E1, …, E50) date with snow cover of 1, 20, 30, 50 cm and more
- The longest continuous snow cover duration of 1, 20, 30, 50 cm and more (D1, …, D50)
- The number of days with snow cover of 1, 10, 20, 30, 50, 100 cm and more (NSD1, …, NSD100)
- The number of snowfall days of 1, 10, 20, 30, 50, 100 cm and more (NNS1, …, NNS100)
- Snow depth reached in the minimum during 100 days (SD100D), i.e. 100-th value in list of daily snow depths sorted decreasingly
- The fractions of solid/mixed/liquid precipitation

[4] Seasonal in this work means mostly from July to June

The time series shorter than 20 winter seasons or with many missing records were excluded from trend analyses.
The climate trends are taken as a b-coefficient from linear regression model:
$y = a + b \cdot x$, where x represents time. The trends are usually rescaled per 10-year period for climatological purposes. The T-test was applied on b-coefficients to consider the significance of the trend on 95% level.

3.2.1 Snow water equivalent

Two methods were used to estimate daily SWE values from weekly measurements:

1. The method published by Němec et al. [71] uses the following input variables:
   - Daily precipitation total (fallen during previous 24 hours)
   - New snow height (fallen during previous 24 hours)
   - Total snow depth
   - Water vapour tension (pressure)

2. The simpler regression method by Samelson & Wilks [83] estimates the square root of SWE by simple regression of four predictors:
   - Daily precipitation total (fallen during previous 24 hours)
   - New snow height (fallen during previous 24 hours)
   - Square root of total snow depth
   - Number of previous consecutive days with the maximum temperature below freezing

The sum of squared differences between estimated and measured values for the simpler method [83] was about twice of that for the CHMI method [71]. That is why the CHMI algorithm was preferred for estimation. Anyway, the simple regression method was helpful for errors checking.

Fitting calculated SWE
The SWE_{CHMI} daily values obtained by iteration method were subsequently fit to the weekly measurements SWE_w using the following procedure:

1. The weekly differences (on Mondays) were calculated: $\Delta SWE_w = SWE_{CHMI} - SWE_w$
2. Simple linear interpolation between two successive ΔSWE_w differences was used to obtain daily differences ΔSWE_d for other days of the week
3. Daily differences were applied on SWE values calculated by CHMI method:
   $SWE_f = SWE_{CHMI} - \Delta SWE_d$

3.3 Avalanche forecasting

Daily avalanche forecast issued by APC is based on information collected from various sources; primarily on meteorological measurements and observations, recent avalanche activity, snow profiles and eventually on snow stability tests performed on selected slopes. Meteorological stations concerned here are provided by SHMI, MRS and IMGW.
The structure as well as the content of avalanche bulletin has been changing since the beginning, principally due to harmonization with other avalanche services associated within EAWS. The daily forecast is issued in the morning until 9 AM, and it is exceptionally corrected if necessary. Substantial information for each of 5 mountain ranges (HT, LT, WT, SF, BF) includes avalanche danger level, its expected tendency towards the following day and

character of expected avalanche activity and its topographical specification. The description of meteorological conditions with focus on snow cover is added in a paragraph.
Avalanche forecast is issued usually from November to April, and according to the situation at any time during the year (note *Tab. 22*). If the danger exceeds level 3 of the International avalanche danger scale (see Appendix C), then warnings are issued also via public media.

Statistical methods used for avalanche forecasting are based on sufficient amount of data, which were digitized backward for various purposes of this thesis. The largest dataset containing daily weather and avalanche data is now available for the HT mountains.
Forecasting methods can be divided into groups according to the several points of view. Conventional forecasting is intuitive method, which relies almost entirely on the experience of the forecaster. Despite the progress in computer-aided numerical techniques, the conventional forecasting seem to be still the most successful. [70]. The disadvantage of conventional forecasting is the lack of objectivity and the length of time it takes people to learn techniques that are based largely on experience. In addition, there is an uneven quality and uncertainty about results that are based largely on human intelligence, intuition, experience and local knowledge. [59]
The methods can be divided as follows:

1. Conventional (synoptic) avalanche forecasting
2. Numerical (statistical) methods (based on sufficient amount of data):
   - Discriminant analysis
   - Nearest neighbour method
   - Time series analysis
   - Regression methods
   - Neural networks
   - Classification trees
3. Deterministic (physically based) methods (expert systems based on rules and relations)

Each model can be modified according to the needs of end-user. As a result of diploma thesis [104], it was proved that regression parameters should be calculated separately for wet and dry avalanches. Therefore the whole dataset was divided into 4 sets, depending on the type of avalanches fallen (dry, wet and moist/combined) and the rest consisting of non-avalanche days.
The successfulness of the forecasting of avalanche and non-avalanche periods increases when the whole area is divided into several homogeneous sub-regions. Subsequently, suitable variables can be selected and parameters of the model calculated for each sub-region [30]. McClung [59] divides forecasting models to regional and local. The regional ones correspond to areas of 100 km^2 (meso-scale to synoptic scale) and heavily relies on meteorological data. Local forecasting is usually more heavily based on snowpack data and stability observations than regional forecasting. This thesis focuses on the HT Mts. with total area about 250 km^2.

Numerical method provides an output, which can be one of the following (or a combination):
- the volume or track length of the largest expected avalanche,
- the number of avalanches,
- the probability of the trigger.

Avalanche danger can be assessed as a combination of these outputs. The forecasted *avalanche danger level* Y_f (defined in section 2.4.1) was selected as the best output variable for the regression method, after consultations with the chief of the APC (J. Peťo). Although

the *number of avalanches* is interesting output, the level of danger and harmful effects are better expressed by the above-mentioned variable. Especially in spring the number of avalanches culminates, but their length is not always so dangerous nor harmful. The *maximum expected track length* Y_{dx} is also suitable variable, but not so suitable for regression because of its variability. It should be used in combination with another variable because its interpretation during non-avalanche days might be confusing.
The *Boolean variable* $Y_{I/O}$ is suitable primarily for the method of nearest neighbours.

3.3.1 Conventional avalanche forecasting

Conventional avalanche forecasting is a synthesis of all available information regarding the current avalanche activity, based on experiences of at least two consulting avalanche experts. This method seem to be the most successful, since an expert takes into consideration also outputs from existing numerical models. Real avalanche expert will probably never be replaced by numerical models or by even more complex *expert systems*, because he/she holds in his/her brain all complicated relations and is capable to select the substantial factors in atypical situations (e.g. long-term and persistent weak layer variably distributed in space since the beginning of winter).
Some basic principles were outlined by LaChapelle in 1970 [50] and a decade later in [51]. Also the time-scale of the forecast was described: 1-3 day forecast relies primarily on precipitation, longer forecast is based on expected temperature, and an outlook for 2 weeks to 3 months is based on persistent instable layers in snowpack (e.g. depth hoar). McClung and Schaerer [59] noticed that the depth hoar can be created at the beginning of winter, when the first snowfall settled as thin layer on relatively warm ground is followed by long freezing period. Gradients greater than -10°C/m creates favourable conditions for the development of weak layer, which can persist for long time.
On the other hand, experiences alone may not be enough, especially if they are subjective or distorted. That is why the development of objective, even not always so precise methods is valuable. Several mountaineers, being careless about measurements and warnings, have paid for their belief of “having a nose for avalanches” with their lives.

Patrick Nairz [70] has collected experiences noted by several authors, which are valuable for conventional forecasting as well as for creation of an avalanche forecasting model. A brief review of the knowledge follows:

Precipitation and snowfall

„The depth of new snow gives a good measure of the quantity of snow likely to be released. As the depth of new snow increases above 30 cm or so, the probability of widespread avalanches of significant size tends to increase.“
„An accumulation rate of 3 cm/h or more sustained for several hours is likely to produce major avalanches.“
(Mellor M. (1968): Avalanches. U.S. Army Cold Research and Engineering Laboratory, 111-A3d.)

„First there is the depth of old snow on the slope. If there are 60 cm or more, that is generally sufficient to cover ground obstructions so that it becomes easier for new snow to slide over them; furthermore, the deeper the snow, the more ammunition it supplies to the avalanche.“
„30 cm is regarded as the minimum generally necessary to produce by itself an avalanche of dangerous proportions.“
(Atwater M.M. (1954): Snow Avalanches. Scientific American, January 1954.)

„A certain minimum depth, in the order of 70 cm is required for the Roger Pass area, to cover the rocks and vegetation in the slide paths before the avalanche season is established.“
(Schaerer P.A. (1962): The avalanche hazard evaluation and prediction at Rogers Pass, National Research Council of Canada, Tech. Paper No.142.)

„Access road in the Žiarska dolina valley is seriously endangered by avalanches (slab and powder dry), when the sum of new snow heights reaches 65 cm or more, after snowstorm.“
[77]

Similar rough rules of thumb can be used for other areas where avalanches endanger any buildings, roads, railways, ski-lifts, etc.

Wind

„Prolonged wind strengths of 25 km/h in the west area and 40 km/h for the centre and east area are critical. Rogers Pass region.“ [86]

Air humidity

„A value of 85% or over causes wind packing."
(Seligman (1936): Snow structure and ski fields: being an account of snow and ice forms met with in nature and study on avalanches and snowcraft. Macmillan, London)

„Relative humidity of 80% and over, in combination with wind speeds of 25 km/h causes the formation of slab avalanches.“
[86]

Settlement

„In new snow a settlement ratio less than 15% indicates that little consolidation is taking place; above 30%, stabilization is proceeding rapidly. Over a long period ordinary snow layers shrink up to 90%, but the slab layers may shrink no more than 60%."
(Atwater M.M. (1954): Snow Avalanches. Scientific American, January 1954.)

„In general, new snow settlement in excess of 15-20% indicates a trend toward stabilization. There is one situation in which settlement is not a stabilizing factor. An underlying snow layer may settle away from a stiffer layer above, even to the point of leaving an air gap when the latter is strong enough to be selfsupporting.“
(USDOAFS (United States Department of Agriculture Forest Service) (1968): Snow avalanches, a handbook of forecasting and control measures. Agricultural Handbook No.194.)

Air temperature and water content

„Temperature directly influences the snow type. Dry snow normally falls at –4°C and below. Temperatures above –2°C promote rapid settlement and metamorphism... A sudden drop increases the tension, particularly in slab. The gradual warming of the temperature in the spring leads to cumulative deterioration of the snow and to heavy, wet avalanches.“
„...dry snow types normally average 5-8% water, but when the proportion of water in such snow exceeds 10%, we have a clear warning that its weight may be increasing faster than its cohesion.“
(Atwater M. M. (1954): Snow Avalanches. Scientific American, January 1954.)

Geographical factors

L. Milan in [67] wrote highly on the importance of geographical factors. Holý [39] analyzed theoretically the influence of topographical conditions on avalanche formation in study area (profile of the Chopok massif). General knowledge can be found in the avalanche handbook [59].

Elevation influences the amount of snowfall and due to lower temperature it takes longer time for the snow cover to stabilize at higher elevations.
Slope orientation/aspect determines exposure to the prevailing winds and incoming solar radiation. More intense insolation of southern slopes results in more frequent occurrence of small-sized loose-snow avalanches and in spring full-depth avalanches. Since the prevailing winds in the Western Carpathians is northwest, the snow is deposited mainly on south- and east-oriented channels. Statistically, the greatest number of avalanches is recorded on south-eastern slopes in Tatra mountains [106]. Example of meso-scale effects can be found in the HT Mountains, where during certain synoptic situations the amounts of new snow at Ždiar-Javorina (north-east part) are considerably different from the rest of stations (mostly on southern slopes) [104]. In general, the effect of wind is very variable due to topography, and there is no simple rule on wind loading on certain orientations after a snowstorm. Focusing on smaller scales, according to the study from Jackson Hole (Wyoming) [60], specific topography around a given path, not simply aspect, is more important when relating wind direction to avalanche activity. For example, the effects of ridges funnelling wind and groups of trees acting as snow fences are more likely the most proximate reasons for selective wind loading at the slide path scale when considering the ultimate effect of wind direction.

Anthropogenous factors

We must take into consideration also the fact, that the slope which skiers visit more frequently are usually more stable than surrounding slopes with intact snow cover (Wiesinger T., EAWS meeting in Davos 2005).

3.3.2 Principal component analysis and discriminant analysis

PCA is an orthogonal linear transformation that transforms the data to a new coordinate system such that the greatest variance by any projection of the data comes to lie on the first coordinate (the 1st principal component), the second greatest variance on the second coordinate, etc. The 1st principal component, in other words, is the eigenvector with the largest eigenvalue. The method can be used for displaying of the problem in a low-dimensional data space, as much of the variance as possible (using a linear transformation) is moved into the first few dimensions. The remaining dimensions may be dropped with minimal loss of information. PCA was invented by Karl Pearson (1901) and generalized by Hotelling (1933). More can be found e.g. in [16].
For instance, PCA can be applied to visualize the avalanche and non-avalanche days in orthogonal coordinates (first 2-3 principal components), so that days with similar weather are grouped in some patterns.
Subsequently a suitable one-dimensional distribution functions can be fitted on both data groups for each coordinate. Let’s explain the problem in 2-D space: If a lower and upper threshold is defined for the distribution, then an ellipse for each group can be sketched. Avalanche and non-avalanche days are thus “trapped” within avalanche or non-avalanche ellipses. The today’s weather can be then displayed as a single point in data space, and some criteria can be defined to decide whether it is closer to the avalanche or non-avalanche group. More details on application of discriminant analysis for avalanche forecasting can be found in [13][22][31][72].

3.3.3 Stepwise regression

Stepwise multiple regression is used here for selection of the best set of variables that are related to predicted variable (e.g. avalanche danger level). The choice of the best predictive variables is carried out by a sequence of *F-tests* and *multiple partial correlations* are used.
There are 3 possible approaches:
Forward selection[5] involves starting with no variables in the model, trying out the variables one by one and including them if they are statistically significant.
Backward elimination starts with model including all candidate variables. These are step-wisely tested one by one for statistical significance and eliminated if they are not significant.
Both stepping direction is a combination of forward and backward approach. For further details, see [58]. All calculations were done by S-Plus software.

The dataset was divided into 2 groups:

1. Records older than 1st July 2002 – for selection of the best variables and for calculation of parameters (regression coefficients)
2. Records dating from 1st July 2002 – for testing and verification of models, represents circa 25% of all data

Second division into three groups was based on the avalanche variable Y_{SWC}, which was created to distinguish the basic mechanisms of avalanche formation as well as resulting types (dry, moist/mixed, wet).
In view of the fact that some variables (e.g. snow depth, SWE, temperature) are seasonally dependent, another alternative division was suggested: models for each month were developed. Because of the lack of sufficient amount of data, also one neighbouring month was used for the calculation of coefficients. For example, the name of model obtained from January-February data can be identified by suffix “JF”.
Variety of models were obtained for each dataset and subsequently they were verified on winters 2003-2009.

3.3.4 Nearest-neighbour method

The method of nearest neighbours (NNB) is statistical method, where user controls the process of avalanche forecast. For example, ten days *most similar to a given situation* are selected from a period of 20 years. These ten days serve as a basis for decisions, as well as enabling a control of the accuracy of past avalanche records. [15] The forecaster can determine not only the probability of avalanche triggering, but also an overview of the given meteorological situation in the frame of historical records.

Essential assumption of the NNB method is that that similar events are likely to happen under similar conditions. Based on weather variables, the model identifies the most similar days in the whole dataset and returns the records and avalanche activity parameters associated with those days. These records help the forecaster to make the final decision. Some of the models suggest a combination of avalanche parameters to calculate the probability of avalanching.
While the principle is quite simple, the problem is with the definition of *the nearest* neighbour. In our case, the definition must be derived from suitable set of meteorological

[5] The method was formulated in **FRIEDMAN J.H., STUETZLE W.** (1981): Projection pursuit regression. *Journal of the American Statistical Association 76*. (p.817-823).

variables that are closely related to avalanche activity. These variables will be selected by stepwise regression.
Recent applications of the NNB method were inspiring for this section, for their interesting approach of optimization and verification. This implementations were led by Gassner and Brabec [33] in Switzerland, by Purves [79] in Scotland, and by Cordy [19] in British Columbia, Canada.
Once we have a set of best meteorological variables, we can put them into a matrix. For every day we have a k-tuple of independent elements, what allows us to use a metric such as *Euclidean* or *Mahalanobis* [15]. The distance between individual days can be measured by the following formula:

$$\Delta d = \sum_j \Delta x_j^{\ 2}\ .$$

, where x_j are meteorological variables standardized by subtracting the overall mean and dividing the result by the standard deviation.
In order to compare different batches of data, especially when dealing with unimodal (single-humped) distributions, it is practical to use any symmetry-producing transformation. The most commonly used are the *Box-Cox transformations*:

$$T(x) = \begin{cases} \dfrac{x^\lambda - 1}{\lambda} \dots\dots\dots \lambda \neq 0 \\ \ln(x) \dots\dots\dots \lambda = 0 \end{cases}$$

Power transformations with $\lambda > 1$ helps produce symmetry when applied to negatively skewed data. [112]
The Hinkley[6] d_λ is used to decide among power transformations by trial and error, by computing its value for each of a number of different choices for λ. That choice of λ producing the smallest d_λ is then adopted to transform the data.

$$d_\lambda = \frac{|mean - median|}{spread}$$

Optimization
A priori probability for avalanche occurrence on given day can be defined as *n/N*, where *n* is the number of avalanche days selected from *N* nearest neighbours. However, Buser recommended to mark the forecasted day as avalanche day if at least 3 out of 10 days were connected with avalanche activity. Thus, the warning level is driven by critical proportion of positive neighbours and the optimal threshold might differ from region to region.

The method can be improved by introduction of weighing vector c_j into the definition of distance between days:

$$\Delta d = \sum_j c_j \Delta x_j^{\ 2}$$

The weights should be set in a manner that the most important variables have the greatest weights. Pearson correlation coefficients can be used:

[6] Hinkley D. (1977): On quick choice of power transformation. Appl. Stat. 26, p.67-69

$$c_j = \frac{|r_j|}{\sqrt{\sum_k r_k^{\,2}}}$$, and the weights can be normalized by

their maximum $c_j = \frac{|r_j|}{\sqrt{\sum_k r_k^{\,2}}} \cdot \frac{1}{\max\{x_j\}}$ or average $c_j = \frac{|r_j|}{\sqrt{\sum_k r_k^{\,2}}} \cdot \frac{1}{\bar{x}_j}$.

For example, normalization by maximum is suitable for sunshine duration, and average can be used for total snow depth [15]. Purves et al. [79] used genetic algorithms for objective determination of weights.
Quite a few variables are seasonal, and this may exclude some suitable nearest neighbours. For instance, certain threshold snow depth must be achieved for avalanches to trigger. Once this value is exceeded, there might be not necessary to make big difference between settled stable snow of 1 m or 2 m deep. Hence, the days with snow depth below this threshold may be excluded from historical dataset. The influence of seasonality can be eliminated by creation of model for each month or for each custom season.

A comprehensive scheme including all important steps in order follows:

Data preparation, QC & completion
(original, derived and mixed variables)
Preliminary analysis – histograms, box-plots, scatterplot matrices

Selection of the best input variables into model
(step-wise regression)

Suitable transformations & normalisation
(Box-Cox, logarithmic, by maximum/average)

The definition of distance metric for the nearest neighbour method.
Optionally introduce weights (genetic algorithms, correlations, expert ...).

Selection of optimum number of neighbours.
Optimum threshold for avalanche and non-avalanche days.

In case of sufficient amount of historical records the NNB method gives satisfying results. Even if the probability of avalanching is not sometimes ascertained appropriately, the avalanche forecaster is supplied with similar situations from the past. Concurrently, the beginner learns to distinguish the conditions of various types of avalanche formation and acquires empirical experiences more quickly. The weights can be adjusted at any time later after the experienced forecaster identifies situations when the model is less successful.
Geographical distribution of avalanche activity can be displayed together with the nearest neighbours, if there is a digital model of avalanche slopes for GIS. This is not the case in Slovakia at present, so only the orientation and the altitude can be displayed, e.g. on radial charts. Introduction of GIS would offer to better identify the influence of various synoptic

patterns on the distribution of avalanche activity. Experience shows, that there are two basic different situations, depending on the location of cyclone bringing snowfall – from N/NW and from the Mediterranean (south).

3.3.5 Verification

The overall performance of an avalanche model, which forecasts avalanche and non-avalanche days, is usually presented in contingency tables (see Tab. 9).

Tab. 9: Contingency table for avalanche prediction.

		Observation/Reality	
		Avalanche	Non-avalanche
Forecast	Avalanche	**H**its	**F**alse
	Non-avalanche	**M**issed	**C**orrect negative

Let H denote "hits", i.e. all correct yes-forecasts - the event is predicted to occur and it does occur, F false alarms, i.e. all incorrect yes-forecasts, M missed forecasts (all incorrect no-forecasts that the event would not occur) and C all correct no-forecasts. Assume altogether N forecasts of this type with H+F+M+C=N. A perfect forecast sample is when F and M are zero.

The following fitness metrics are used in this thesis:

The ***proportion of correct*** PC=(H+C)/N, gives the fraction of all the forecasts that were correct. Usually it is very misleading because it credits correct "yes" and "no" forecasts equally and it is strongly influenced by the more common category (typically the "no" event).

The ***probability of detection*** POD=H/(H+M), also known as ***hit rate*** (HR), measures the fraction of observed events that were correctly forecast.

The ***frequency bias*** BIAS=(H+F)/(H+M), ratio of the yes forecast frequency to the yes observation frequency; a measure of overforecasting/underforecasting.

The ***True Skill Score*** $TSS = \frac{H}{H+M} - \frac{F}{F+C}$, a measure of success of categorical forecasts.

The ***Unweighted average accuracy*** $UAA = \frac{1}{2} \cdot \left(\frac{H}{H+M} + \frac{C}{F+C} \right)$ gives equal weights to avalanche and non-avalanche hit rates.

Regarding the avalanche danger, there are 5 levels to be forecasted. For that reason, the definitions were generalized as following:

The ***proportion of correct*** PC*=(H1+H2+H3+H4+H5)/N, where H1,...,H5 are correctly forecasted avalanche danger levels (degree 1 to 5), i.e. the difference between the forecasted and the real value is less than 0.5.

Hit rates for individual danger levels: HR1*=F1/O1, a ratio of the number of forecasted (F1) and observed (O1) avalanche danger level 1. Similarly for other avalanche danger levels.

The ***proportion of incorrect danger*** PNCD=FM/N, where FM is the sum of all days where forecasted value differs from the true (really assessed and verified) by 1.5 degree or more.

3.3.6 Visualization of actual avalanche danger on maps

The output of regional avalanche model is usually one number for given day. This actual avalanche danger can be visualized on maps, taking into account also some topographic parameters. Up to now, some inspiring studies in Slovakia has been dedicated to the static

identification of avalanche trigger areas. With some modifications, the method using basic operations with map layers can be applied for the visualization of current avalanche activity on daily basis.
Hreško [40] developed a formula for identification of avalanche trigger areas based on morphometric indices and terrain roughness:

$$P\left(I_{geo}\right) = (S + A + E + F) \cdot R$$

where: $P(I_{geo})$ = geographical probability of avalanche initiation
S = slope incline factor
A = altitude/elevation factor
E = aspect factor
F = factor of slope shape (based on profile curvature – convex, linear, concave)
R = roughness factor

Barka et al. [7], [8] proposed a modified model, taking slope factor as multiplier and suggested better parameterization of individual factors:

$$P\left(I^{*}_{geo}\right) = \left(A + E + F\right) \cdot S \cdot R$$

Moreover, Barka [8] tried to supplement the trigger areas by avalanche paths, derived from simple model of maximum runout distance.

Comments, ideas and suggestions

Although the geographical factors are beyond the scope of the thesis, some comments, ideas and suggestions follow. Once a digital map layer of avalanche terrains and paths exists, it can be used along with other map layers to visualize the actual avalanche danger on a map.
A map layer of avalanche paths can be created, considering the long-term average frequency of avalanche occurrence f_A, which is available in avalanche cadastre (see *Tab. 10*).

Tab. 10: Categories of avalanche occurrence frequency and their percentage in the High Tatra mountains, as obtained from avalanche cadastre.

Frequency of avalanches per year	Percentage of slopes (High Tatras)
$f_A \geq 1/6$	55 %
$1/6 > f_A > 1/30$	20 %
$f_A \leq 1/30$	25 %

Just for imagination, the maximum frequency of detected avalanches reached 15 in 20 years on single slope in the Mengusovská dolina, HT Mts.

S factor. Slope incline is the primary terrain factor. Snow sluffs occur frequently in small amounts on slopes with 60°-90° [59]. Dry snow avalanches initiate where a portion of slope has an incline ≥ 25°. Minimum incline for wet snow avalanches and slush flows is 10°.
A factor. The snow depth as well as avalanche danger is not always increasing with altitude – especially when the strong wind drifts the snow downward to the upper forest boundary. An altitude itself thus has no straightforward influence on snow avalanche hazard. The factor could be replaced by snow depth map layer.
E factor. Dry- and wet-snow avalanches sometimes trigger in groups on slopes with similar aspect. McCollister et al. [60] proved that dependence on aspect is not simple because of large variability of winds within mountain range. Detailed regionalization is needed for mountain range – sometimes it is possible to limit dangerous sector of aspects in given valley. Although

most avalanches trigger on south-east slopes in the High Tatra Mountains, no aspect should be preferred in general. Implementation of results from snow stability tests *SI* performed on suitably selected model slopes with various aspects could be more suitable.

F factor. It is hard to say whether convex or concave areas are more avalanche-prone. This factor might be redundant.

R factor. The roughness factor (see Tab. 11) changes as snow cover depth increases. Dwarf-pine prevents avalanche from releasing only until it is fully buried under the snow. This factor as a function of snow depth should be used instead of constant roughness map layer.

Tab. 11: Roughness factor set by reclassification of vegetation types suggested by Barka.

Roughness factor	Vegetation type
0.5	Forest (coniferous, deciduous, mixed)[7]
1.2	Open forest with dwarf-pine rough stony debris and slope covered by lesser blocks
1.4	Deciduous shrubwood
1.5	Open forest
1.6	Dwarf-pine and slope with juts of parent rock under 50 cm
2	Grass areas with sporadic dwarf-pine and small size slope debris
3	Compact grass areas and rock plates

[7] Healthy mixed forest is more stable than coniferous or deciduous monoculture. Avalanches may glide easily on substrate of leaves from trees.

4. Dissertation objectives

The main objectives of the dissertation were briefly stated in the year 2002 and subsequently these objectives were discussed in details in the project of dissertation [107]. Here are summarized the principal objectives again:

1. Overview of the research from literature
   - snow climatology in mountainous regions
   - numerical avalanche forecasting

2. Selection of stations and quality control of necessary meteorological and avalanche data
   - Missing/erroneous data completion/correction
   - Homogenization of daily snow depth and precipitation time series

3. Create a database for the avalanche warning service
   - Digitize historical avalanche records from the paper archives
   - Quality control of avalanche data

4. Snow climate characteristics and trends
   - Dependence on altitude
   - Changes in fractions of solid, mixed and liquid precipitation
   - Changes in seasonal regime

5. Develop an avalanche forecasting model/tool
   - Collect and select all possible data sources
   - Relationship between serious avalanche events and synoptic situations
   - Improve the quasi-linear regression model
   - Apply the nearest neighbour method
   - Verification and comparison of models

5. Results and discussion

This chapter contains the main results using the methods described in Chapter 3 and following the objectives stated in Chapter 4.

5.1 Quality & Homogeneity

This section comprises results acquired from homogeneity testing and adjusting, which fulfils the second objective of this thesis. Using AnClim software [99], some representative temperature, precipitation, new and total snow depth series (yearly and monthly) were tested for homogeneity. Yearly snow depth series were constructed as seasonal sums from July to June. Finally, 14 stations were selected for testing, while temperature measurements were available only on 10 of them.

5.1.1 Missing data

Tab. 12 summarizes missing months that were interpolated for later use. Stations with more than 12 months missing were not used for the creation of reference series.

Tab. 12: The list of stations selected for homogenization with periods available and the number of missing/erroneous months.

Station	**Period** (81-08 means 1981-2008)				**Missing/erroneous months**			
	T	**R**	**NS**	**SD**	**T**	**R**	**NS**	**SD**
Demänovská Dolina - Jasná	N/A	81-08	81-08	51-08	N/A	0	0	8
Chopok	55-08	55-08	55-08	55-08	0	0	0.0	0.0
Jarabá	N/A	61-05	61-04	61-05	N/A	63	29	29
Krížna	63-00	63-00	63-00	63-00	0	109	40	9
Liptovská Teplička	N/A	81-08	81-08	21-08	N/A	0	0	0
Liptovský Hrádok	N/A	51-08	51-08	51-08	N/A	0	0	0
Lomnický štít	51-08	51-08	51-08	51-08	0	0	0.0	0.0
Luková	N/A	81-08	81-08	81-08	N/A	0	3	3
Mútne	N/A	81-08	81-08	21-08	N/A	1	0.1	0
Oravská Lesná	61-08	51-08	51-08	21-08	0	0.0	0.4	0.6
Oravská Polhora - Hlina	N/A	81-08	81-08	21-08	N/A	38	19	19
Partiz. Ľupča - Magurka	N/A	81-08	81-08	21-08	N/A	16	4	4
Podbanské	61-08	61-08	61-08	21-08	0	2	3	1
Skalnaté pleso	61-08	61-08	61-08	61-08	0	0.3	3	5
Suchá Hora	N/A	81-08	81-08	21-08	N/A	N/A	0	0
Štrbské Pleso	51-08	51-08	51-08	21-08	0	0	0	0.0
Šumiac	N/A	61-08	61-08	61-08	N/A	26	11.5	11.5
Tatranská Lomnica	61-08	51-08	61-08	21-08	0	12	10	10
Telgárt	51-08	51-08	51-08	51-08	0	0	0	0
Vyšná Boca	N/A	81-08	81-08	21-08	N/A	32	26	26
Ždiar-Javorina	61-08	61-08	61-08	21-08	0	1	0.1	0.0

5.1.2 Temperature

Monthly and yearly series of mean temperatures of 10 representative stations from 1961 were tested. Lomnický štít, Štrbské Pleso and Telgárt have data from 1951, Chopok from 1955, and Krížna only between 1964-2000. Monthly series were constructed as average of mean daily temperatures.

Tab. 13: Summary of significant inhomogeneities detected by various tests and metadata in mean daily temperature yearly [Y] and monthly [1-12] series. **H** denotes homogeneous series, date in brackets is possible step, but not approved. Column Step flags **I**ncrease or **D**ecrease after the date of inhomogeneity.

Station METADATA	**SNHT***	**Bivariate**	**E&P**	**Vincent**	**Approved**	**Step**
Ždiar-Javorina	[Y,5,10]1978, [3,8,9]1979, [Y,7,10]1984	[3]1977, [8,10]1978, [9]1979	[Y,4,5,6,10] 1975, [9]1979	[Y,8,10] 1978, [9]1979, [7,10]1984	**1.7.1978**	D
Reference 2	[Y,3,5,10] 1978, [8,9]1979, [7,11]1982	[8,10]1978, [Y,9]1979, [7,11]1982	[8,9]1974, [Y,4,6]1975, [10]1978, [11]1979	[8,10]1978, [Y,9]1979		
station moved in July 1978						
Lomnický štít	[1,2]1980, [Y,12]2000	-	[1,2]1975, [Y,12]2000	-	**H**	-
Reference 2	[6,8]1977	-	[1,2]1975	-		
homogeneous, changed thermometer in 31.7.2001						
Skalnaté pleso	[2,10]1972, [Y,6,7]2001	[Y,7]2001, [6]2002	[Y]2001, [6]2002	[Y]2001, [6]2002	**H** (1.7.2001)	(I)
Reference 2	[2,7]1999, [Y]2001	[Y,7]2001	[4,5]1996, [Y,8]2001	[Y,7,8] 2001		
provider changed, observation take-over by professional meteorologists since 1.9.1962						
Tatranská Lomnica	[9,10]1990, [Y,8]1992, [5,6]1993	[Y,8]1992, [5,6]1993, [7,12]1994	[5,6]1993, [7,9]1994	[Y,8]1992, [5,6]1993, [7,12]1994	**8.7.1993**	I
Reference 2	[9,10]1990, [6]1994, [8,10]2005	[Y,9]1988, [6]1994	[Y,2]1988, [Y,6,7]1994	[Y]1988, [1,7]1989, [6]1994		
station moved 8.7.1993						
Štrbské Pleso 1	[Y,7]1961, [3,10]1962, [3,10,12]1973, [10,12]1974	[Y]1961, [6,7,10] 1962	[Y]1961	[Y]1961, [6,7,10] 1962	**1.1.1961**	I
Reference 2	[Y,6]1961, [7,10]1962	[Y]1961, [10]1962, [6,7]1963	[Y,10]1961	[Y]1961, [10]1962, [6,7]1963		
station moved - since 1.1.1961 near spa building Kriváň-Hviezdoslav						

Station METADATA	SNHT*	Bivariate	E&P	Vincent	Approved	Step
Štrbské Pleso 2	[9,12]1992, [Y,2,4,7,8] 1993, [7,8,9]2006	[5,10]1991, [9]1992, [Y,2,3,4,6, 7,8]1993	[10]1992, [2,4,6,7,8,9] 1993, [1,3,11]1994	[9]1992, [Y,2,3,4, 7,8]1993	**2.12.1992**	D
Reference 2	[Y,1,2,4,7, 8,9]1993, [5,6,7,8, 9,12]2006	[2,3,11]1992, [Y,1,4,7, 8,9]1993	[Y,1,5,6,7, 9,10]1993, [5,6,7,11]2004	[2,3,11]1992, [Y,1,4,7, 8,9]1993		
station moved - since 2.12.1992 near spa building Helios						
Podbanské	[Y]1970, [6,8]1976, [5,7,9]1977, [1,11]2007	[Y]1970, [4]1971, [6]1976, [5,7]1977	[4]1971, [7]1977	[Y]1970, [4]1971, [6]1976, [5,7]1977	**H** (1.6.1978)	(I)
Reference 2	[4]1978, [Y,5,8,9]1979	[Y]1978, [4,8]1979, [5,6]1990	[Y]1968, [3]1978, [Y]1979	[Y]1978, [4,5,8]1979		
station moved 28.8.1963						
Chopok	[Y]1989, [2,4,9]1990	[2,3]1988, [Y,5]1989	[1,2,5]1989	[2,3]1988, [Y,5]1989	**H** (1.1.1989)	(I)
Reference 2	[Y,1]1989	[3,4]1988	[1,5]1989	[4,8]1988		
homogeneous						
Oravská Lesná	[6,9]1999	-	[9]1999	[Y,9]2000	**H** (1.9.1999)	(I)
Reference 2	[6]2000, [7]2001	[6]1986, [7]1987	[Y,3]2002	[6]1986, [7]1987		
station moved 20 m north-eastward due to planned house build-up 15.11.1989						
Telgárt	[Y,6]1975, [4,12]1979, [7,12]1981	[Y,10]1976	[5,8]1968, [Y,10,12] 1976	[Y,10]1976	1.11.1975	-
Reference 2	[Y,7]1975, [10]1976	[7]1974, [Y]1976	[Y]1976	[Y]1976		
Reference 3	[4,10,11]1963, [7]1974, [Y]1975, [10]1976	[7]1974, [Y]1975, [10]1976	[7]1974, [Y,9]1975	[7,9]1974, [Y]1975, [10]1976		
homogeneous						
Krížna	[3,12]1974, [6,7]1978	[Y,7]1979	[Y,6,8]1979	[Y,7]1979	**H** (1.9.1978)	(D)
Reference 2	[Y,5,7]1967, [6,7,9]1978, [Y,2,4]1987, [1,4,5,10] 1998	[6]1978, [7]1979	[4,6,7]1971	[6]1978, [7]1979, [Y,5]1987		
low quality of measurements						

Test results for Telgárt strongly indicate an inhomogeneity around season 1975/76, according to the criteria outlined in section 3.1.2. Finally, the inhomogeneity was not approved, because it is not well-founded in metadata and does not exhibit significant adjustment factor.

5.1.3 Precipitation

Monthly and yearly precipitation series of 14 representative stations starting mostly in 1961 were tested. Lomnický štít, Štrbské Pleso and Telgárt, Oravská Lesná, Liptovský Hrádok have data from 1951, Chopok from 1955, and Krížna only from 1964-2000.

Tab. 14: Summary of significant inhomogeneities detected by various tests and metadata in precipitation yearly [Y] and monthly [1-12] series. **H** denotes homogeneous series. Column Step flags **I**ncrease or **D**ecrease after the approved inhomogeneity.

Station METADATA	**SNHT***	**Bivariate**	**E&P**	**Vincent**	**Approved**	**Step**
Ždiar-Javorina	[Y]1965	[9]1963	-	H	H	-
Reference 2	[10]2005, [12]2006	[9,10]2007	[10]2005	H		
homogeneous						
Lomnický štít	[Y,4]1991, [3,6]1992	[Y,4]1991, [3]1992	[4]1991, [3]1992	[Y,4]1991, [3]1992	1.4.1991	I
Reference 2	[1]1989, [Y,4]1991 [3]1992	[Y,4]1991 [3]1992	[Y,4]1991, [3]1992, [11]2005	[5]1990, [Y,4]1991, [3]1992		
possible change in evaluation method						
Skalnaté pleso	[Y]1962, [3]1963, [3]1964	[11]1962, [3]1963	[5,7]1972	[11]1964	H	-
Reference 2	[7]1967, [2]1968	[11]1962	[2]1998, [9]1999	-		
provider changed, observation take-over by professional meteorologists since 1.9.1962						
Tatranská Lomnica	[11]1990, [12]1973	[11]1990	[Y,2]1973	[2,3]1992	H (8.7.1993)	(I)
Reference 2	[Y]1985, [11]1986	[12]1983	[3,10]1987	-		
station moved 8.7.1993						
Štrbské Pleso 1	[Y]1960	[Y]1961	[Y]1963	[Y]1961	H (1.1.1961)	(I)
Reference 2	[9]1957	[9]1957	-	-		
station moved - since 1.1.1961 near spa building Kriváň-Hviezdoslav						
Štrbské Pleso 2	[Y,7]1978, [1]1994	[6]1967	[Y]1993, [1]1994	[Y]1993	**2.12.1992**	I
Reference 2	[Y]1992	[Y]1992, [1,3]1994	[Y]1992, [1]1994	[Y]1992		
station moved - since 2.12.1992 near spa building Helios						
Podbanské	[Y,2]1963	[2]1963	[6]1967	H	H (28.8.1963)	(I)
Reference 2	[2,5]1963	[2]1963	[6,10]1995	[3]1964		
station moved 28.8.1963						
Liptovský Hrádok	[Y]1994	-	[Y]1995	H	H (19.9.1995)	(I)
Reference 2	[3]1975	[3]1974	-	[3]1974		
station moved 10 m southward 19.9.1995						

Station METADATA	SNHT*	Bivariate	E&P	Vincent	Approved	Step
Chopok	[5,11]1958, [Y,1,6]1961, [Y]1987	[11]1958, [1]1961, [Y,3]1987 [2]1988	[Y,3]1987, [2]1988	[9,11]1958, [3]1987	H (1.3.1987)	(-)
Reference 2	[Y]1986, [1]1988, [2]1989	[3]1986, [1]1989	[1,3]1981, [Y]1987	-		
Homogeneous						
Demänovská Dolina - Jasná	[7,11]1994, [Y]1995	[Y]1995	-	H	H (1.3.1994)	(I)
Reference 2	[7,11]1994, [Y]1995	[Y]1995	[7]1997	-		
observer changed 1.3.1994						
Oravská Lesná	[Y]1989, [4]1991, [11,12]1957	-	[Y,7]1988	[12]2004	H	-
Reference 2	[4]1962, [4,11]1963, [Y]1964	[11]1963	[1]1983	H		
station moved 20 m north-eastward due to planned house build-up 15.11.1989						
Telgárt	-	-	-	H	H	-
homogeneous						
Šumiac	[12]1974, [2]1975, [2,3,11]1976	[2]1975	[11]1976	[8]1974, [Y]1979, [11]1978	H	-
Reference 2	[Y]1995, [8]1996, [2]1975, [11]1977	[2]1975	[11]1990, [1,8]1992, [12]1991	[Y]1979, [11]1978		
station moved 1.11.1990, observer changed 1.12.1992						
Jarabá	[Y,1,2,5,12]1986	[1,8]1986	[1,3,5]1986	[6]1985	H	-
Reference 2	[3]1965	[11]1962	[Y,9]1966	[11]1974		
station moved 1.10.1990, many missing data						
Krížna	[Y,4]1967, [1,4]1966	[Y,6]1967	[1,4,11]1969	H	H (1968)	-
Reference 2	[4]1966, [Y,1]1967, [11]1968	[Y,6]1967	[Y,9]1970, [10]1979, [11]1978, [12]1977	H		
low quality of measurements						

The vast majority of steps result in increased precipitation totals after the inhomogeneity (note column Step in Tab. 14). Generally, increasing trends of the precipitation might be partly caused by the improvement of gauges and measurement method. Moreover, the stations were usually relocated to an environment where better catchment of precipitation was expected. These facts are very important for climate trend analyses.

False significant step was firstly detected at Lomnický štít station in 7.10.1959, when precipitation gauges moved 3 m higher on upper terrace. This inhomogeneity proved to be insignificant after the station Štrbské pleso (with possible step on 1.1.1961) was removed from neighbouring stations creating the reference series.
Significant increase of precipitation at Lomnický štít might be caused by a scientific conference held in 1990s in Stará Lesná, where measurement methods at this peak station was criticised. (P. Faško, personal communication) Probably some improvement on the precipitation gauge or its environment was made.

5.1.4 New snow height

Monthly and yearly new snow height series of 13 representative stations starting mostly in 1961 were tested. Lomnický štít, Štrbské Pleso and Telgárt, Oravská Lesná, Liptovský Hrádok have data from 1951, Chopok from 1955, and Krížna only from 1964 to 2000. Some data available only in paper archive were not processed, for example new snow height in Štrbské Pleso was observed since 1927.

Tab. 15: Summary of significant inhomogeneities detected by various tests and metadata in new snow height yearly [Y] and monthly [1-12] series. **H** denotes homogeneous series. Column Step flags **I**ncrease or **D**ecrease after the approved inhomogeneity.

Station METADATA	**SNHT***	**Bivariate**	**E&P**	**Approved**	**Step**
Ždiar-Javorina	[2]1989, [5]1991, [10,12]2007	-	[11,12]1966	H	-
Reference 2	[Y,2,3]1972	-	[3]1974, [4]1976		
homogeneous					
Lomnický štít	[1,4]1989, [1]1991	[Y]1994, [2]1995	[Y,1]1989	H (1.4.1991)	(I)
Reference 2	[1]1962, [4]1963, [4,10]1964, [3]1991, [11]1993	[Y,4]1994, [2]1995	[1]1988, [3]1991		
changed evaluation method ?					
Skalnaté pleso	[Y]1972, [Y]1969	-	[Y]1972, [1]1974	H	-
Reference 2	[2,3]1972, [Y]1975, [3]1976	[Y,1]2005	[4,5]1976		
provider changed, observation take-over by professionals since 1.9.1962					
Tatranská Lomnica	[12]1972, [Y]1973, [3]1974, [Y,4]1994	[Y,2,12] 1972, [3]1974	[Y,3,12]1973, [3]1991, [Y]1992	1.1.1973 (8.7.1993)	D (-)
Reference 2	[3]1972, [Y,2]1973, [4]1992, [4]1993	[2,12]1972, [Y]1973, [3]1974, [1]1975	[Y,2,3,11,12]1973, [10]1990, [1]1994		
station moved 8.7.1993					
Štrbské Pleso	[3]1971, [3]1972, [Y,1]1992	[1]2005, [12]2008	[4,10]1976,[12]1970, [Y]1993	H (2.12.1992)	(I)
Reference 2	[1,11]1990, [4]1993	[2]1964, [Y]1965	[2]1967, [12]1971		
station relocations: 1.1.1961 and 2.12.1992					

Station METADATA	SNHT*	Bivariate	E&P	Approved	Step
Podbanské	[Y]1965, [2]1966	[Y]2000	[Y]1975	H	-
Reference 2	[Y]1979, [9]1997, [Y]1998	[Y]1998	[Y,1]1979, [Y]1995, [3]1993		
station moved 28.8.1963					
Liptovský Hrádok	[Y,11]1981, [Y]2007, [10]2006, [4]2005	[5,11]1963	[3,12]1977, [4]1979, [Y]1981	H	-
Reference 2	[11]1963, [10]1966	[11]1962, [12]1963	[10]1973, [4]1975, [Y]1993		
station moved 10 m southward 19.9.1995					
Chopok	[5,11]1992, [4]1979, [Y]1980	-	[Y]1969, [2]1973, [10]1974, [Y]1980	H	-
Reference 2	[Y]1972, [10]1970, [Y]1993, [11]1992	-	[Y]1969, [11]1971, [Y]1980		
homogeneous					
Demänovská Dolina - Jasná	[1,3,11]1991, [Y]1992, [1,3]1993	-	[Y]1993	H (1.3.1994)	(I)
Reference 2	[Y]1987, [Y]1995, [11]1992, [4]1993	-	[Y]1987, [11]1988		
observer changed 1.3.1994					
Oravská Lesná	[Y]1993, [10]1969, [3]1967		[Y]1980	H	-
Reference 2	[Y,2,3]1966	[Y]1966	[Y,3]1966, [4]1967		
station moved 20 m north-eastward due to planned house build-up 15.11.1989					
Telgárt	[1]1965, [12]1966, [3]1967, [Y]1994	[2]1965, [3]1966, [Y]1967	[1]1966, [3]1967, [Y]1997	H (1.4.1966)	(D)
Reference 2	[Y,3]1966, [Y,12]1982	[Y,3]1966, [11]1981	[Y,1,3]1966		
homogeneous					
Šumiac	[Y,12]1993,[10]1965	-	[4,10]1966, [Y]1980	H	-
Reference 2	[11]1977, [Y]1979	-	[3,4]1968, [2]1970		
station moved 1.11.1990, observer changed 1.12.1992					
Krížna	[2,3]1973, [Y]1993, [4]1992	-	-	-	-
Reference 2	[4]1966, [2,12]1967, [Y]1995	[11]1967	[1]1993		
about 2 % months missing					

Vincent test showed to be not suitable for NS and SD homogeneity testing.
The year 1972 was extremely poor in new snow – this might cause a few-years shift in detected inhomogeneities, e.g. see Tatranská Lomnica.

5.1.5 Snow depth

Monthly and yearly snow depth series of 20 representative stations starting in 1921 were tested. Lomnický štít, Liptovský Hrádok, Demänovská dolina - Jasná and Telgárt have data from 1951, Chopok from 1955, Skalnaté pleso and Šumiac from 1961 and Krížna only from 1964 to 2000. Due to its lucrative elevation (1661 mASL), also the snow depth series from Luková pod Chopkom station was added to homogenization, though it started only in 1981.

Tab. 16: Summary of significant inhomogeneities detected by various tests and metadata in new snow height yearly [Y] and monthly [1-12] series. **H** denotes homogeneous series. Column Step flags **I**ncrease or **D**ecrease after the approved inhomogeneity.

Station METADATA	**SNHT***	**Bivariate**	**E&P**	**Approved**	**Step**
Ždiar-Javorina	[3]1974, [Y,1,2]1988,[1]1989	[12]1987, [2,3]1999	[12]1936, [Y]1937, [1]1988	H	-
Reference 2	[5]1936, [12]1971, [Y]1972, [3]1974	[Y,3]1973, [Y]1995	[12]1936, [Y,2]1938, [10]2004, [4]2006		
homogeneous					
Lomnický štít	[Y,2,3,4]2000	[1]2000, [1]2002	[Y,2,3]2000, [1]2001	H	-
Reference 2	[Y,2]1988,[10]2000	[2,3]1998	[4,5,6]1998, [10]1999		
Reference 3	[Y,2,3]1988, [12]2006, [1,3]2007	[1,12]2006, [Y,3]2007	[5,6]1990		
changed evaluation method ?					
Skalnaté pleso	[Y,1,2]1963, [Y,2,3,4]1978	[1,2]1963, [Y,3]1978	[3]1978, [Y,2]1985	H (1.9.1962)	(D)
Reference 2	[1]1963	[1,2]1963	[1,10]1991		
provider changed, observation take-over by professionals since 1.9.1962					
Tatr. Lomnica	[Y,2]1994	[Y]1994	[4]1992, [Y]1994	8.7.1993 (1.1.1973)	D (D)
Reference 2	[Y,2]1994	[Y,2]1994	[2]1994		
Reference 3	[10]1992, [Y,2]1994	[3]1972, [Y]1973	[Y]1973		
station moved 8.7.1993					
Lipt. Teplička	[3]1933	-	[2]1968, [11]1969	H	-
Reference 2	[Y,3]1937	[Y,2]1925	[11,12]1949		
no metadata					
Štrbské Pleso	[11]1961, [Y]1993, [1]1991	[4]1992	[11]1964, [Y]1993	H (2.12.1992)	(-)
Reference 2	[10]1963, [4]1992	-	[1]1990, [2]1993		
station relocations: 1.1.1961 and 2.12.1992					
Vyšná Boca	-	-	[10]1944, [1]1946	H	-
Reference 2	[Y,12]1934	-	[Y,12]1934		
no metadata					

Station METADATA	**SNHT***	**Bivariate**	**E&P**	**Approved**	**Step**
Podbanské	[Y,2,3,4]1926, [12,2,3]1940	[Y,2,3,4]1926	[2,3,12]1940, [1]1941	1.2.1926	(D)
Reference 2	[Y,3,4]1926	[Y,2]1924	[10]1926,[2,3,4]1927, [1,12]1941		
Reference 3	[Y,1,2,3,4]1926	[2,4]1925, [Y,3]1926	[12]1926, [Y,2,3,4]1927		
station moved 28.8.1963, no metadata before 1955					
Liptovský Hrádok	[11]1962	-	-	H	-
Reference 2	[3]1996	-	-		
station moved 10 m southward 19.9.1995					
Chopok	[3,4,5]1986	[10]1986	[3]1985, [5]1986	H	-
Reference 2	[5]1986	-	[12]1961, [1]1963		
homogeneous					
Luková	[Y,4,5]2004	[Y,4]2004	[2,5]2004	1.8.2003	(D)
Reference 2	[Y,4]2004	[Y,3,4]2004	[Y,2,3,4,5]2004		
relocation + changed environment on nearby ski slopes (snowdrift changed)					
Demänovská Dolina - Jasná	[Y,3]1995	-	[Y,2,3]1995	1.3.1994	-
Reference 2	[Y,1]1995		[1,11]1995		
Reference 3	[Y,3]1995	[3]1995	[Y,3]1995		
new observer since 1.3.1994					
Partizánska Ľupča - Magurka	[Y,1,2]1952, [5]1953	[Y,1,2]1952	[Y,2]1952, [1]1953	1.2.1952	I
Reference 2	[2]1952, [Y,1]1953	[Y,1,2,3] 1952	[2]1952, [Y,1]1953		
no metadata					
Oravská Lesná	[1]1925, [Y,2,3]1943	[Y,1,2]1925, [10]1942	[1]1928, [2]1944, [Y]1945	H (1.1.1926) (1.1.1943)	(D) (D)
Reference 2	[1]1925, [2]1926, [10]1941, [4]1943	[Y,1,2]1925	[10]1926, [10]1942, [1]1945		
Reference 3	[Y,2]1926, [4]1945	[Y,2,3]1925	[1,2]1927, [Y]1929, [4,5]1943		
professional station established since 1.1.1943					
Mútne	-	[Y,1,2]1924	[10,12]1927	H	-
Reference 2	[2,10]1926, [Y,2]1969	[Y,2]1969	[10]1926, [2]1969		
no metadata					
Oravská Polhora - Hlina	[Y,3]1929, [Y,2,4]1998	[Y]1998, [3]1999	[3]1997, [1,2]1998	1.3.1997	-
Reference 2	[3]1997, [Y,4]1998	[3]1999, [Y,2]1998	[Y,2,3,12]1943		
no metadata					
Suchá Hora	[3]1953, [Y,2]1955	-	[3]1953, [Y]1955	H	-
Reference 2	[Y]1998	-	[11,12]1926		
no metadata					

Station METADATA	SNHT*	Bivariate	E&P	Approved	Step
Telgárt	[Y]1967, [1]1968	[Y,11]1967, [1]1968	[Y,1]1968	(1.2.1967)	(D)
Reference 2	[Y,2]1967	[Y,2]1967, [1]1968	[Y,2]1967		
Reference 3 homogeneous	[1]1989, [Y]1992	[Y,1]1968	[11]1969, [Y,2]1992		
Šumiac	[1]1980, [2]1981, [Y]1983	[3]1983	[Y,2,12]1980	H	-
Reference 2 station moved 1.11.1990, observer changed 1.12.1992	[Y]1982	-	[Y,1]1979		
Krížna	[1]1990	[11]1967	[Y,1,2]1991	H (1.1.1991)	(D)
Reference 2 about 2 % months missing	[1]1991	[11]1967	[Y,1,3,10]1991		

Note: According to the metadata, the station in Oravská Lesná was re-established in 1st January 1943. However, some of the tests suggested year 1944 or 1945 as a first year with inhomogeneity. The period before 1943 has higher average than the period after, but the winter season of 1943/44 was extremely rich in snow and this might brought about one- or two-year shift. Anyway, this year was not finally approved as inhomogeneity.

5.1.6 Adjusting

Since the snowfall is a function of temperature and precipitation, the inhomogeneities should be consistent. Refer to Tab. 17, where the resulting summary of detected inhomogeneities can be found. There is also indicated an increase/decrease/no step after a possible discontinuity. The dates in brackets are possible inhomogeneities that were not adjusted. Approved discontinuities to be adjusted are highlighted with the most probable reason.

Inhomogeneities were caused by the following reasons: 11 station relocations, 2 observer changes, 1 change in observation method, 1 change in environment, 5 unknown occasions. Jasná and Luková stations are located in a ski resort where systems for making technical snow were installed. This additional snow causes local cooling so that it is easier also for natural snow to deposit.

Štrbské Pleso, as a representative mountain station with metadata of good quality, is a good example. The first relocation (1.1.1961) preserved the slope orientation but the elevation was raised by 25 m. As we may expect, an increase in precipitation at higher altitude was confirmed. Surprisingly, the temperature generally increased after the relocation due to local environment and climate effects. The new site was more often exposed to warm southern winds. Consequently, the general increase in precipitation was a little compensated by higher temperature (which means decrease in solid fraction of total precipitation). That is why the tests did not marked the year as significant step.

Current location (since 2.12.1992) is nearly at the same altitude but is better sheltered from warm southern flows. Moreover, notice that due to this significant inhomogeneity the temperature decreased and precipitation increased after the relocation. Again, according to the approval procedure (refer to page 35), no significant inhomogeneity was detected in new snow nor in snow depth. Despite the fact that the tests suggest only insignificant or no inhomogeneity, this one was finally approved.

Tab. 17: Summary of detected/possible inhomogeneities that **were** (weren't) adjusted in time series of air temperature (T), precipitation totals (R), new snow height (NS) and snow depth (SD). H=homogeneous series, N/A=not available.. Arrows represent increase/decrease after the inhomogeneity. Inhomogeneity reasons: L=relocation, O=observer, M= method, E=environment, U=unknown reason.

Station	**T**			**R**			**NS**			**SD**		
Ždiar-Javorina	**1.7.1978**	▼	L	H			H			H		
Lomnický štít	H			**1.4.1991**	▲	M	(1.4.1991)	▲		H		
Skalnaté pleso	(1.7.2001)	▲		H			H			(1.9.1962)	▼	
Tatr. Lomnica 1	H			H			**1.1.1973**	▼	U	(1.1.1973)	▼	
Tatr. Lomnica 2	**8.7.1993**	▲	L	***8.7.1993***	▲	L	**8.7.1993**	---	L	**8.7.1993**	▼	L
Štrbské Pleso 1	**1.1.1961**	▲	L	(1.1.1961)	▲		H			H		
Štrbské Pleso 2	**2.12.1992**	▼	L	**2.12.1992**	▲	L	***2.12.1992***	▲	L	***2.12.1992***	---	L
Podbanské	(1.6.1978)	▲		(28.8.1963)	▲		H			**1.2.1926**	▼	U
Liptovský Hrádok	N/A			(19.9.1995)	▲		H			H		
Chopok	(1.1.1989)	▲		(1.3.1987)	---		H			H		
Luková	N/A			N/A			N/A			**1.8.2003**	▼	LE
Jasná	N/A			(1.3.1994)	▲		***1.3.1994***	▲	O	**1.3.1994**	---	O
Magurka	N/A			N/A			N/A			**1.2.1952**	▲	U
Oravská Lesná	(1.9.1999)	▲		H			H			H (1.1.1926) (1.1.1943)	 ▼ ▼	
Hlina	N/A			N/A			N/A			**1.3.1997**	---	U
Telgárt	**1.11.1975**	---	U	H			(1.4.1966)	▼		(1.10.1966)	▼	
Krížna	(1.9.1978)	▼		(1968)	---		H			(1.1.1991)	▼	
Mútne	N/A			N/A			N/A			H		
Jarabá	N/A			H			N/A			(1.1.1981)		
Šumiac	N/A			H			H			(1.1.1981)		
Vyšná Boca	N/A			H			H			H		

5.1.7 Discussion

Homogenization is not simple task. Especially in case of snow cover data, where the spatial variability is greater than that of precipitation. A change in snow regime due to inhomogeneity is hardly visible also on time graphs of monthly/annual totals, because they are too small in comparison with natural climatic interannual variability. The approval of detected inhomogeneities was therefore set up rather strictly, with the accent put on significance and metadata.

Although the test results were processed using the criteria described on page 35, the final decision remained subjective. For example, the observation at Skalnaté pleso station was not professional in first two years. The change of station provider might be a significant change, even though the tests did not proved it. It is generally problem in both detecting and adjusting those inhomogeneities, which divide the time series into very short parts. Also the precise date of inhomogeneity without metadata can be only estimated in terms of years, even if we use more than one reference series.

We must be careful especially on discontinuities detected near 1951 and 1961, when the whole station network was reorganized, methods of measurement were unified and regular monthly revision begun. The methods and instruments for precipitation measurement since 1921 were quite homogeneous (M. Lapin, personal communication). Another station network reorganization during 1990s is related to introduction of automatic weather stations and division of Czechoslovakia.

The reference series of high quality are crucially important for homogenization. There are only few time series available since 1921 for construction of the first-class reference series. Also, it is difficult to create NS and SD reference series without having neighbours of higher altitude. The situations when it snows at higher station, but rains on all its neighbours are frequent usually in spring-to-autumn months. Despite this, we considered such reference series as sufficient enough for the purpose of inhomogeneities detection. During the homogeneity testing of NS and SD series, some monthly series were not considered, if they (or their reference series) contained more than 50% null values in the whole period. For example, probability of no new snow occurrence is less than 30% in August on the Lomnický štít. However, both July and August were not considered for this station, because its closest neighbours have probability of no new snow occurrence more than 50% in these months.
Unlike detecting, the adjusting of the NS and SD series of a peak station without an appropriate reference series would be very problematic. The correction coefficients for spring-to-autumn months couldn't be calculated correctly. The only solution is to prepare a better reference series, using also other meteorological elements (e.g. hourly ombrograph and temperature data) or use an output from a numerical weather prediction model.

The adjustment applied on data may be affected by the number of years (before and after certain inhomogeneity) used for the calculation of correction coefficients. Referring to Fig. 14 we may notice that a decade rich in snow can be followed by a decade poor in snow. Although this natural climatic variability is "filtered" by the use of merged series for the correction, somewhat similar unbalanced periods are present in merged series, too. In general, the more years are used for calculation of the adjusting coefficients the more credible the result is, providing these years belonged to a homogeneous subperiod.

Huge windstorm on 19th November 2004 remarkably changed the environment in the HT Mts. The foothills were seriously struck by a violent downslope wind. Despite this widespread forest calamity, the homogeneity of T, P, SD and NS seem not to be affected significantly at the selected stations.

5.2 Climate trends

Climate change is often discussed among people of various generations, but the human perception is influenced by subjective feelings. This section offers rather objective results of recent trends of various characteristics listed in section 3.2. Some of them can be compared with a little older trends published in [109].
The results are here shown mainly on homogenized (adjusted if necessary) data, but sometimes also results from unadjusted inhomogeneous data can be found in order to emphasize how particular inhomogeneities may influence climatological analysis.

Temperature

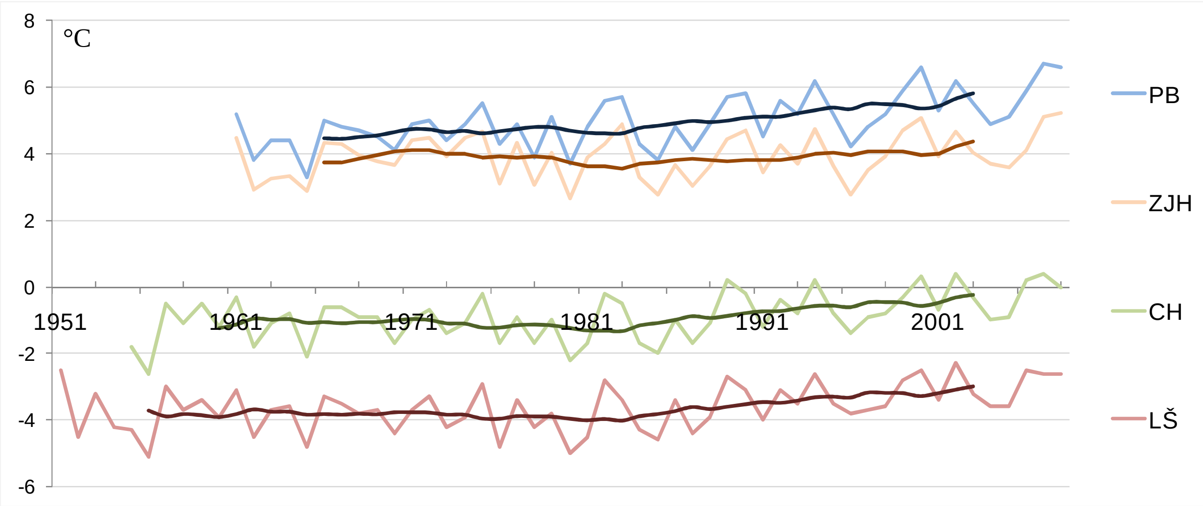


Fig. 8: Yearly averages of mean daily temperatures and 11-year running averages from the Podbanské, Ždiar-Javorina (adjusted), Chopok, and Lomnický štít stations.

There is a remarkable increase beginning in early 1980s, but the trends were calculated since 1951/61 up to 2008. The yearly averages of mean daily temperatures tend to increase up to 0.35°C/10yr (Podbanské). This warming is significant at all stations, except for Ždiar-Javorina with increase of 0.1°C/10yr.
However, there is a weak seasonal cooling (up to -0.06°C/10yr on average in September) or no trend in autumn months, while the most significant warming is most clearly pronounced in January (0.5°C/10yr), May (0.4°C/10yr) and July (0.35°C/10yr), if we consider average trends of homogeneous stations.

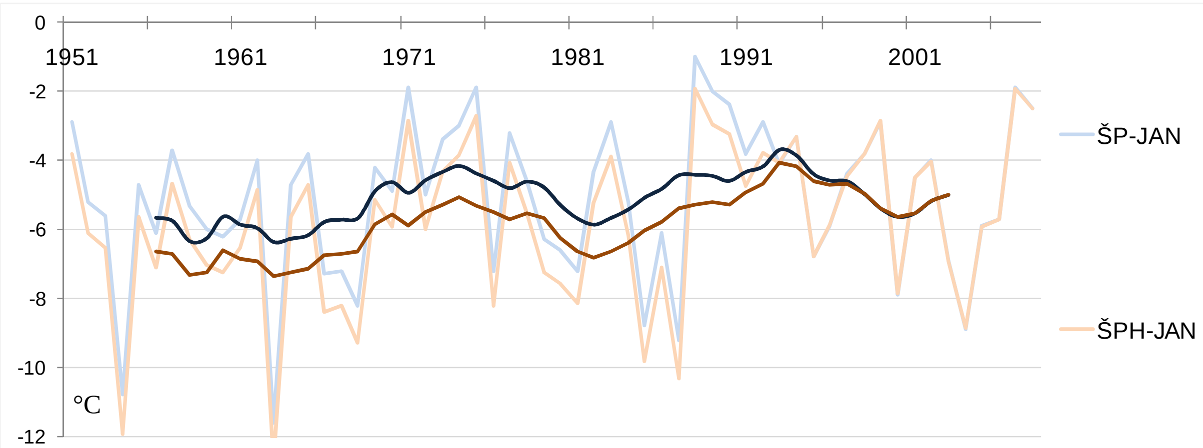


Fig. 9: January averages of mean daily temperatures and 11-year running averages from Štrbské Pleso, ŠP-JAN unadjusted and ŠPH-JAN adjusted.

The overall trend for January in Štrbské Pleso (see Fig. 9) was changed from 0.2°C/10yr to 0.4°C/10yr after homogenization.

Precipitation

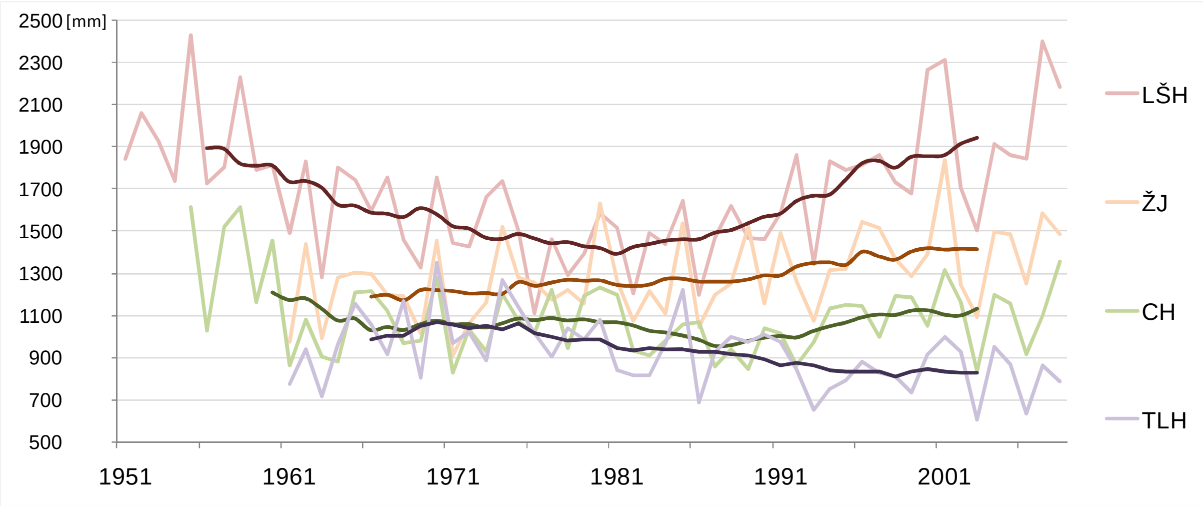


Fig. 10: Yearly sums of daily precipitation totals [mm] and 11-year running averages from the Lomnický štít (adjusted), Ždiar-Javorina, Chopok (adjusted) and Šumiac stations.

Generally, precipitation totals at most of stations tend to increase significantly since 1951/61 up to 2008. The greatest increase is 59mm/10yr (Ždiar-Javorina), or even 76mm/10yr (unadjusted Lomnický štít) if we considered also inhomogeneous data. The maximum reduction of yearly totals reaches -48 mm/10yr (adjusted Tatranská Lomnica) and –46 mm/10yr (Šumiac). Trends at Chopok are strongly dependent on period chosen for calculation: 1955-2008 decrease (-24 mm/10yr), and 1961-2008 increase (19 mm/10yr).
Trends by months revealed the highest rise in July and March (4 mm/10yr on average), while the drop in June and November was on average -3 and -1 mm/10yr. The typical distribution of precipitation throughout the year tends to change at the most in June-August period.

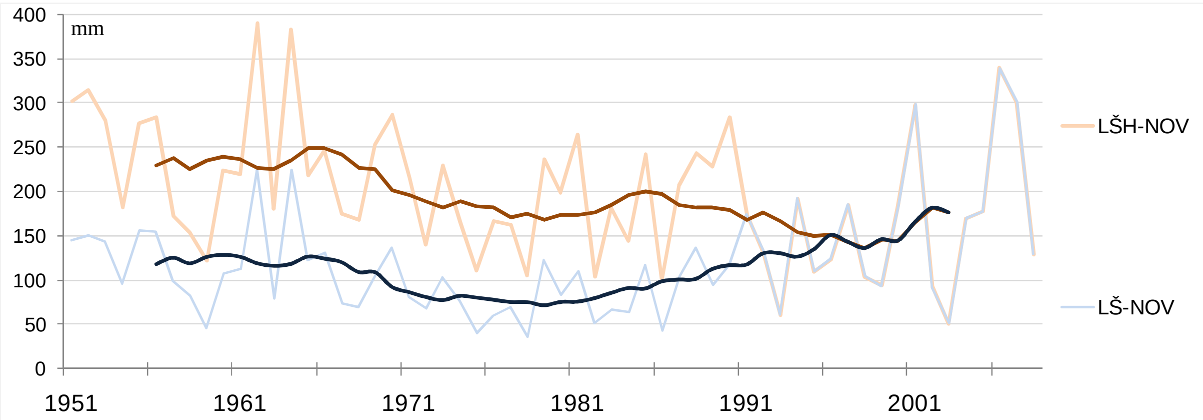


Fig. 11: November precipitation totals and 11-year running averages from Lomnický štít, LŠ-NOV unadjusted and LŠH-NOV adjusted.

Increasing trend of 10mm/10yr was changed to decrease of -16 mm/10yr due to adjusting at Lomnický štít in November (see Fig. 11).

New snow height

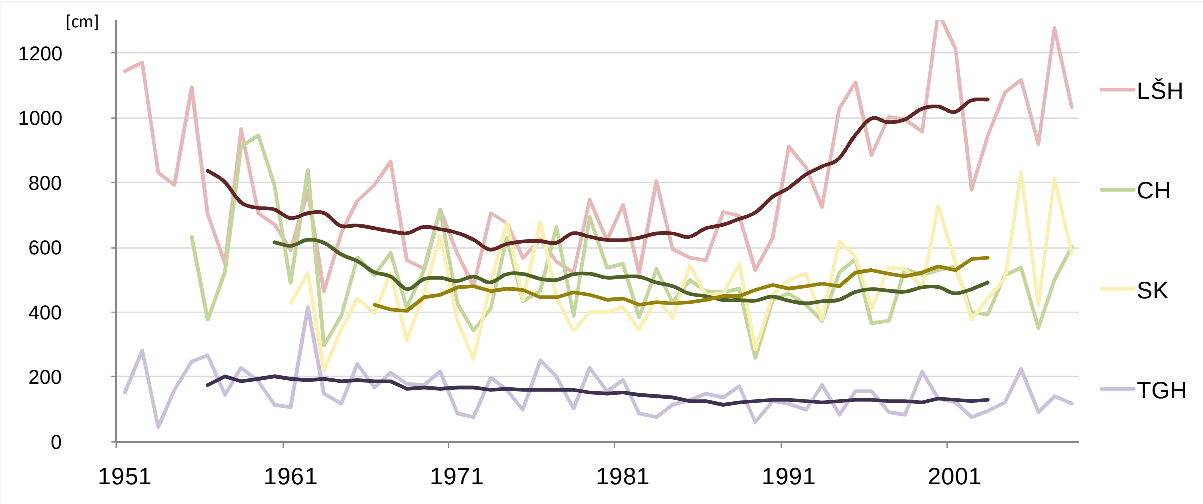


Fig. 12: Yearly sums of daily new snow heights [cm] and 11-year running averages from the Lomnický štít (adjusted), Chopok, Skalnaté pleso and Telgárt (adjusted) stations.

With the exceptions of the Chopok (-31 cm/10yr) and Telgárt (-14 cm/10yr) stations, which have shown a significant decrease and the Lomnický štít (49 cm/10yr), Skalnaté pleso (37 cm/10yr) and Tatranská Lomnica (16 cm/10yr) stations which have shown a significant increase, the remaining stations have recorded insignificantly increasing trends in yearly snowfall totals, in the period 1951/61-2008.
Trends by months revealed slight rise in March and November (3 and 2 cm/10yr on average), at the expense of December (-1 cm/10yr).

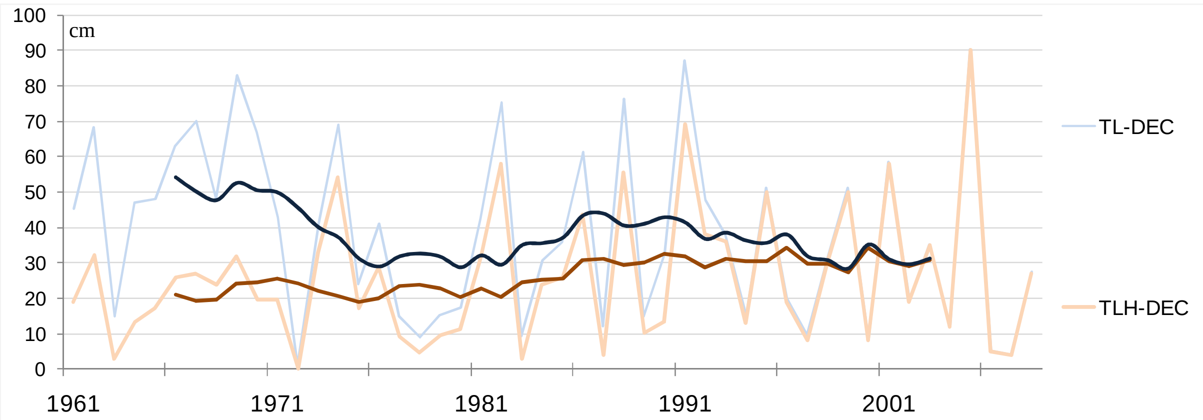


Fig. 13: December snowfall totals and 11-year running averages from Tatranská Lomnica, TL-DEC unadjusted and TL-DEC adjusted.

Snowfall reduction of -5 cm/10yr changed to increase of 3 cm/10yr due to adjusting on Tatranská Lomnica in December (see Fig. 13).

Snow depth

Seasonal average of daily snow depths was calculated for the period from July to June.
Considering the period 1921-2008, there is no significant trend in yearly average snow depths and the values varies from -0.35 cm/10yr (Oravská Lesná) to +0.43 cm/10yr (Ždiar-Javorina), and significant increase was only at the latter station in November and December.
If we take into consideration the period 1951/61-2008, then overall reduction of average snow depth was identified (up to -1.35 cm/10yr at Skalnaté pleso), except for Lomnický štít with

significant increase of 10.55 cm/10yr. This station tends to lose snow insignificantly in November and December (-6.8 cm/10yr) at the expense of quite significant increase from February to June with maximum rate of +49.7 cm/10yr in April. Other stations are losing snow a little from October to February, but in March the trend turns to increase at Chopok (the second highest station) and in April at stations above 1100 mASL.

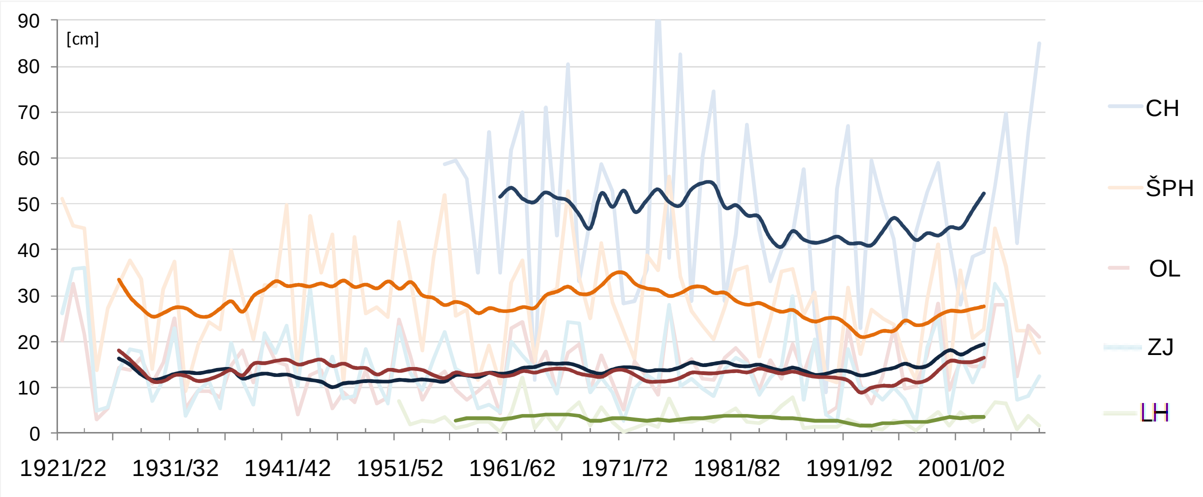


Fig. 14: Seasonal averages of daily snow depths [cm] and 11-year running averages from the Chopok, Štrbské Pleso (adjusted), Ždiar-Javorina, Oravská Lesná, and Liptovský Hrádok stations.

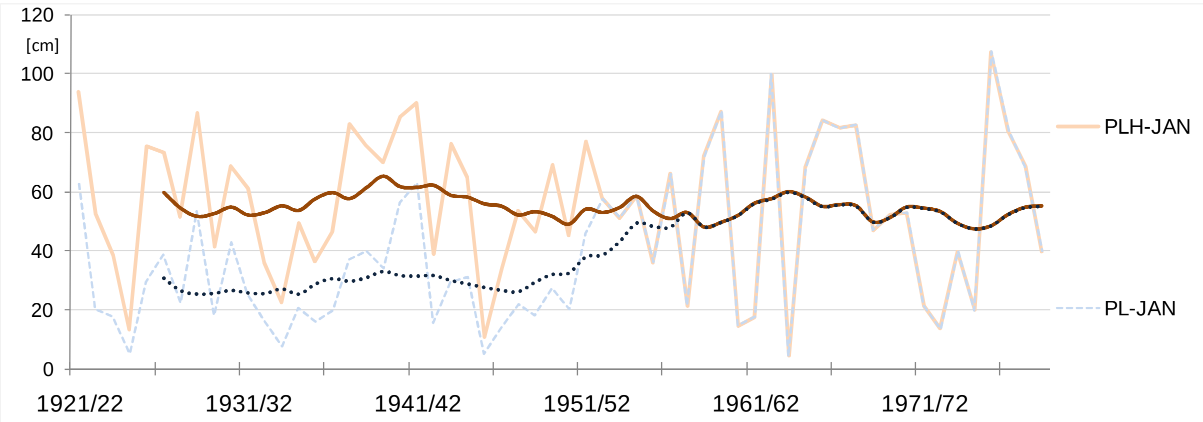


Fig. 15: January mean snow depths and 11-year running averages from Partizánska Ľupča – Magurka, PL-JAN unadjusted series (with inhomogeneity in February 1952) and PLH-JAN adjusted.

The greatest change in trend due to adjustment was connected with the inhomogeneity in 1.2.1952 at Partizánska Ľupča – Magurka station, where the increasing trend 0.78 cm/10yr turned to be 0 (no trend) in January average snow depth (see Fig. 15).

The average annual course of snow depth is changing remarkably mainly at the peak stations. The *annual maximum* is shifting to later dates: taking the period 1952(56)-81 and 1982-2009 we can see considerable shift from 3rd March to 15th April at Lomnický štít and from 17th March to 31st March at Chopok (Fig. 16).

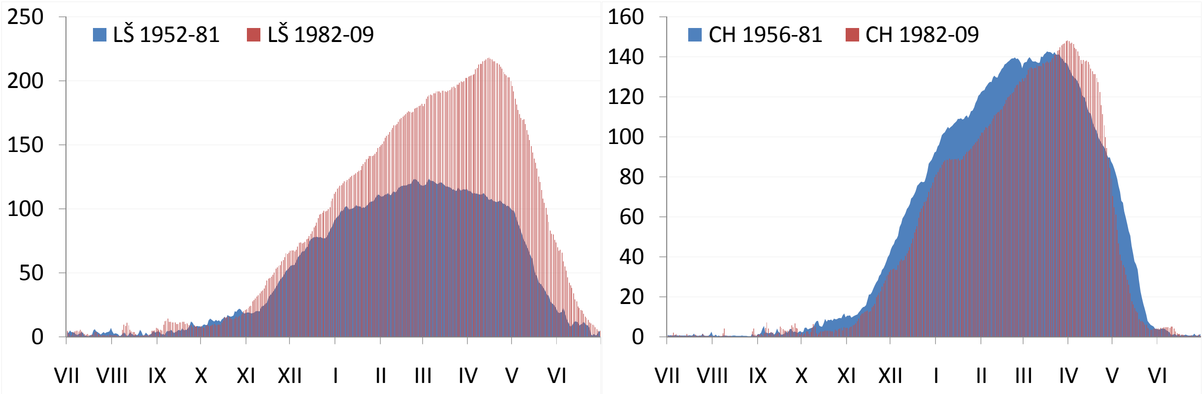


Fig. 16: Annual course of snow depth [cm] at the Lomnický štít (LŠ, 2635 m a.s.l.) and Chopok (CH, 2008 m a.s.l.) stations. Note the different shapes in two successive averaging periods and shifting of annual maxima.

Seeing the fact that snow cover is a function of precipitation and temperature, we can determine the trends in snow using a contour graph (see Fig. 17). In this case, the contours are based on the current long-term averages of temperature, precipitation and snow depth values from selected stations. When we apply the current trends of precipitation and temperature to estimate the values some 10 and 20 years in future, we expect that the station moves through the contours to another point, which corresponds to expected value of average snow depth. We can then compare these expected values with the ones calculated purely from snow depth time series (see Fig. 14). The consistency of T, R and SD trends can be checked easily.

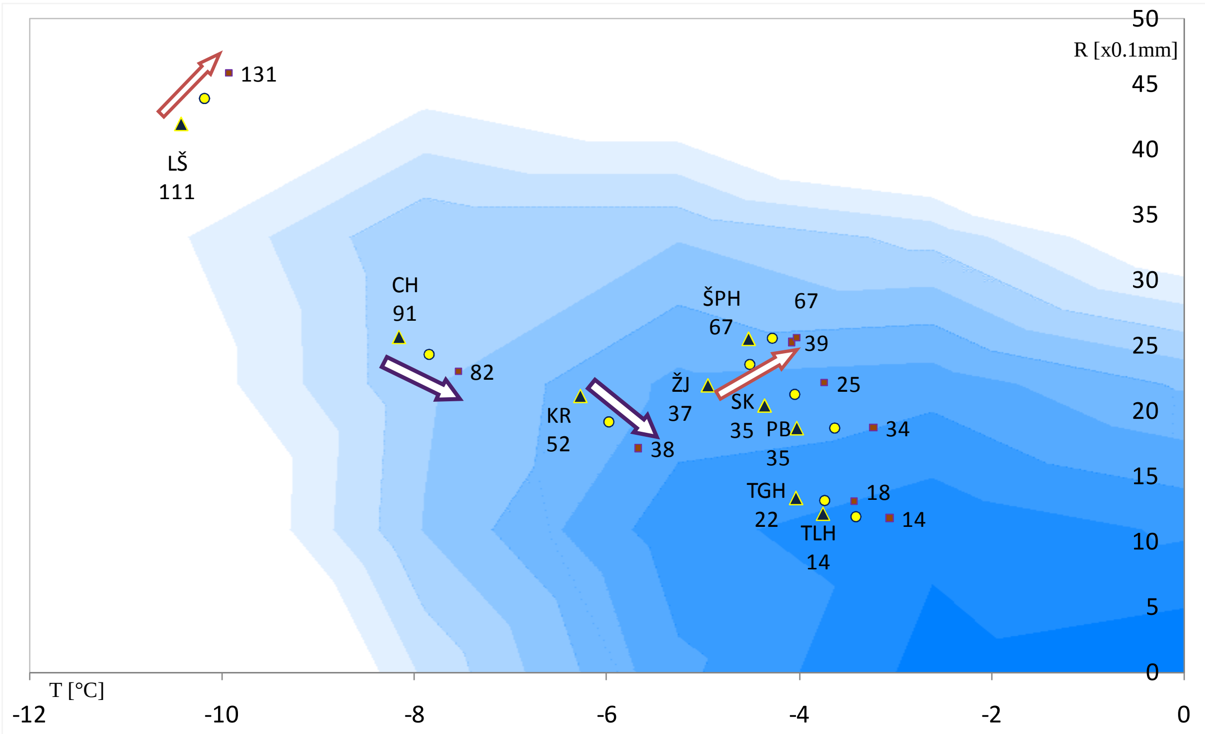


Fig. 17: Contour graph presents winter (DJF) daily average snow depth [cm] as a function of average DJF temperature [°C] and average DJF daily precipitation totals [tenths of mm]. The greater the snow depth, the brighter the contour is. Long-term average for each station is represented by triangles, labelled with average snow depth. Linear trends of temperature and precipitation were applied on each station, so that circles stands for expected values in 10-year and squares in 20-year horizon.

We can see that both methods give us consistent values of expected snow depths, except for some stations that do not fit to the contour graph. Skalnaté pleso (SK) moved to slightly higher value in contours, but using purely snow depth data we obtained significant decrease. Another station Ždiar-Javorina (ŽJ) moved nearly to the same point as Štrbské Pleso (ŠPH), but only a slight increase was detected purely from snow depth series. Possible explanation might be that also another effects play a significant role in snow changes, such as solar radiation, cloudiness or wind flows, which are all driven by different synoptic patterns. However, the contours enable us to identify stations with peculiar "behaviour".

Number of days with snow cover

Insignificant decrease in the number of days with snow cover of ***10 cm and more*** (***NSD10***) prevails at the selected stations. The diminution in the number of days is observed primarily in the Low Tatras: Šumiac (-6.2 days/10yr), Telgárt (-3.5 days/10yr), Jasná (-2.7 days/10yr) and Chopok (-2.6 days/10yr). However, there is increase in the High Tatras: Lomnický štít (8.8 days/10yr, significant), Skalnaté pleso (1.9 days/10yr), Ždiar-Javorina (1.2 days/10yr).
On average, the reduction is well-expressed in January, while increase is mainly in April and November.
Decrease in the number of days with snow cover of ***50 cm and more*** (***NSD50***) prevails at the selected stations, except for the highest station Lomnický štít with significant increase 10.4 days/10yr and Ždiar-Javorina 1.8 days/10yr. The diminution in the number of days is observed primarily at higher elevation stations such as Skalnaté pleso (-7.6 days/10yr), adjusted Štrbské Pleso (-2.6 days/10yr) and Chopok (-2.3 days/10yr).
Again, the reduction is well-expressed in January, while increase is only at few stations mainly in March or April. The highest station Lomnický štít has the greatest increase even in May (3.7 days/10yr).

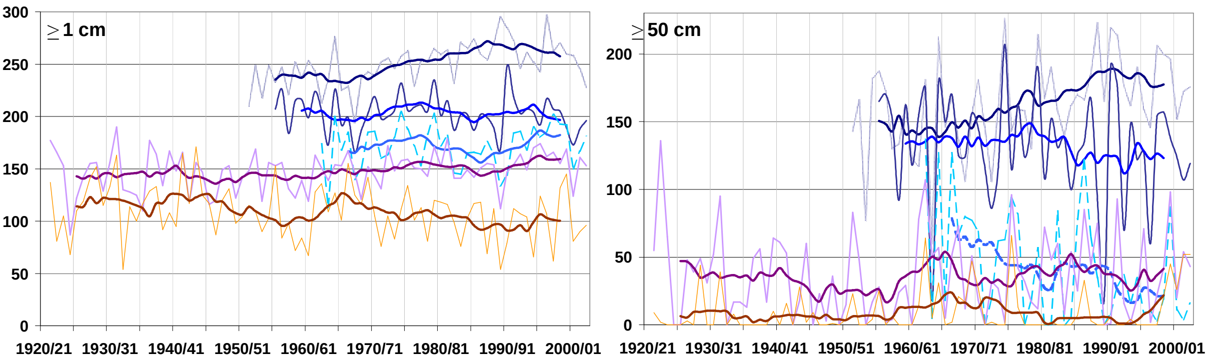


Fig. 18: Seasonal sums of the number of days with snow cover depth ≥ 1 cm and ≥ 50 cm with 9-year running average (top to bottom): Lomnický štít (2635 m), Chopok (2008 m), Skalnaté pleso (1783 m), Ždiar-Javorina (1030 m) and Liptovská Teplička (900 m).

Comparison between NSD10 and NSD50 shows that the decrease is more radical for NSD50, especially for the stations below 2000 m. On the other hand, the increase in NSD50 is stronger for the highest station.

First and last day with snow

The values for BSD and ESD are counted days starting from 1st July (BSD=1) and the latest possible date can be 30th June (ESD=365). Beginning and final dates are illustrated for SD thresholds of 10 cm and 50 cm.

Nearly all stations are inclined to postpone the first date with SD≥10 cm up to 2.5 days/10yr. Only the highest station tends to shift the beginning to earlier dates, at a rate of 4 days/10yr. The last day with SD≥10 cm tends to shift to earlier dates by -2.1 days/10yr, except for Lomnický štít, Oravská Polhora, Skalnaté pleso and Ždiar-Javorina with increase up to 2.2 days/10yr.
Similar trends are for higher SD thresholds, although fewer stations were considered in order to calculate the trends. BSD50 shifts to later dates mainly at Partizánska Ľupča-Magurka, Skalnaté pleso and Jasná (3.4 days/10yr), while the strongest opposing shift is at Lomnický štít (-4.9 days/10yr) and Ždiar-Javorina (-2.8 days/10yr). ESD50 are shifting to earlier dates at a maximum rate (-3.7 days/10yr) at Skalnaté pleso. Only two highest stations tend to shift the ESD50 to later dates: Lomnický štít (4.2 days/10yr) and Chopok (1 day/10yr).

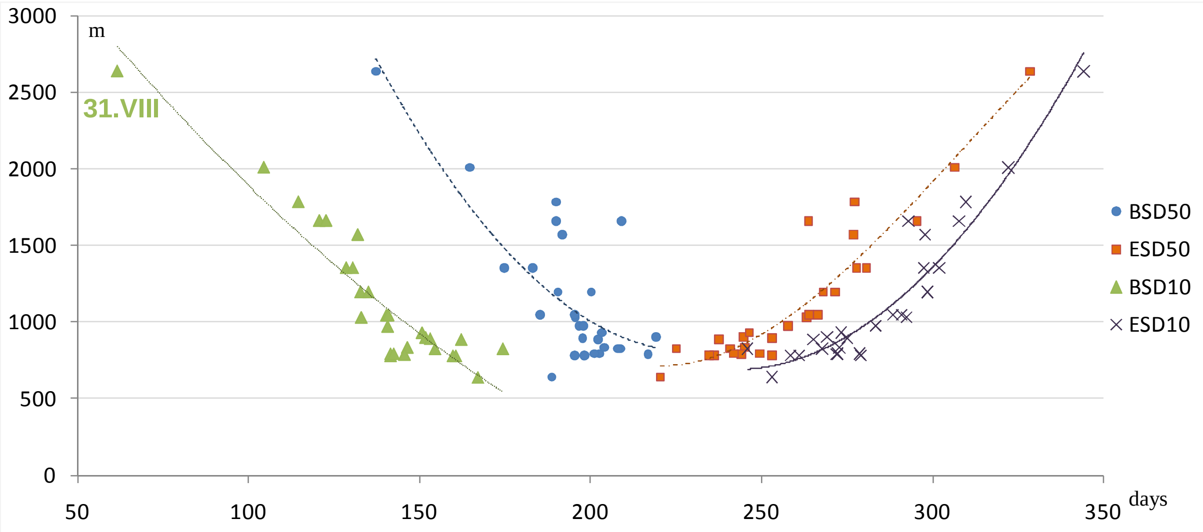


Fig. 19: The first and the last days with snow cover over 10 cm and 50 cm thresholds and the dependence on altitude, averaging period 1951/61-2008.

100-days-rule

Snow depth reached in the minimum during 100 days is a useful characteristic for ski resort developers.

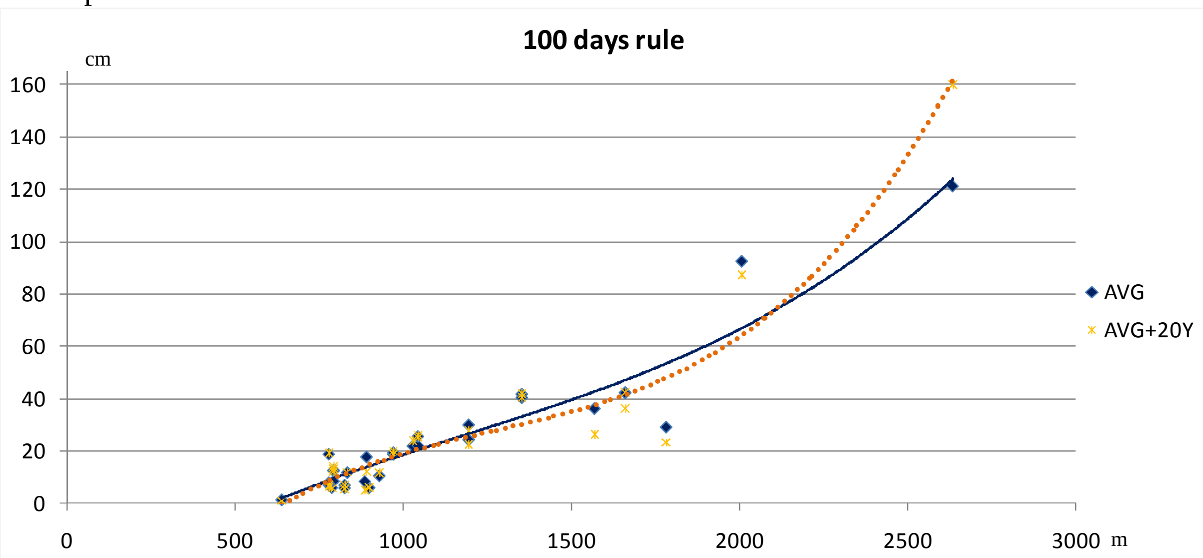


Fig. 20: The 100-days-rule characteristic and the dependence on altitude. The full line is a polynomial fit of the current average (AVG). The dotted line represents a change on the 20-year-horizon, if the trends are applied.

Although the decreasing trends prevail at most of the selected stations, there is no significant change in lower elevation stations. Taking into account the current trends, the shape of the curve (see Fig. 20) is to be changed mainly at elevations above the tree line. A further noticeable fact is that the minimum snow depth during 100 days reaches 20 cm or more only at elevations above 1000 mASL, on average. Based on absolute minima, the critical altitude with snow depth duration at least of 100 days is about 1300 mASL.

Precipitation type

The ratios of solid, mixed and liquid precipitation (refer to Tab. 3) to the precipitation total are quite sensitive characteristics. The trends were published in [109] and some refreshed graphs are presented here. Although the trends are a little different, no principal change since 2003 has been observed for both periods: December to February (Fig. 21) and November-April (Fig. 22).

Substantial decrease in solid precipitation is well visible at altitudes 1000-1500 mASL, mainly on account of increase in mixed forms. The solid fraction is decreasing slightly also at stations below 1000 mASL due to slight increase in both mixed and liquid ratios. There is a critical break-point altitude, above which the trends changes; i.e. the fraction of solid precipitation tends to stagnate or even increase during the winter. The altitude can be only estimated due to lack of stations. This level lies approximately in 1900 mASL on northern and in 2300 mASL on southern slopes.

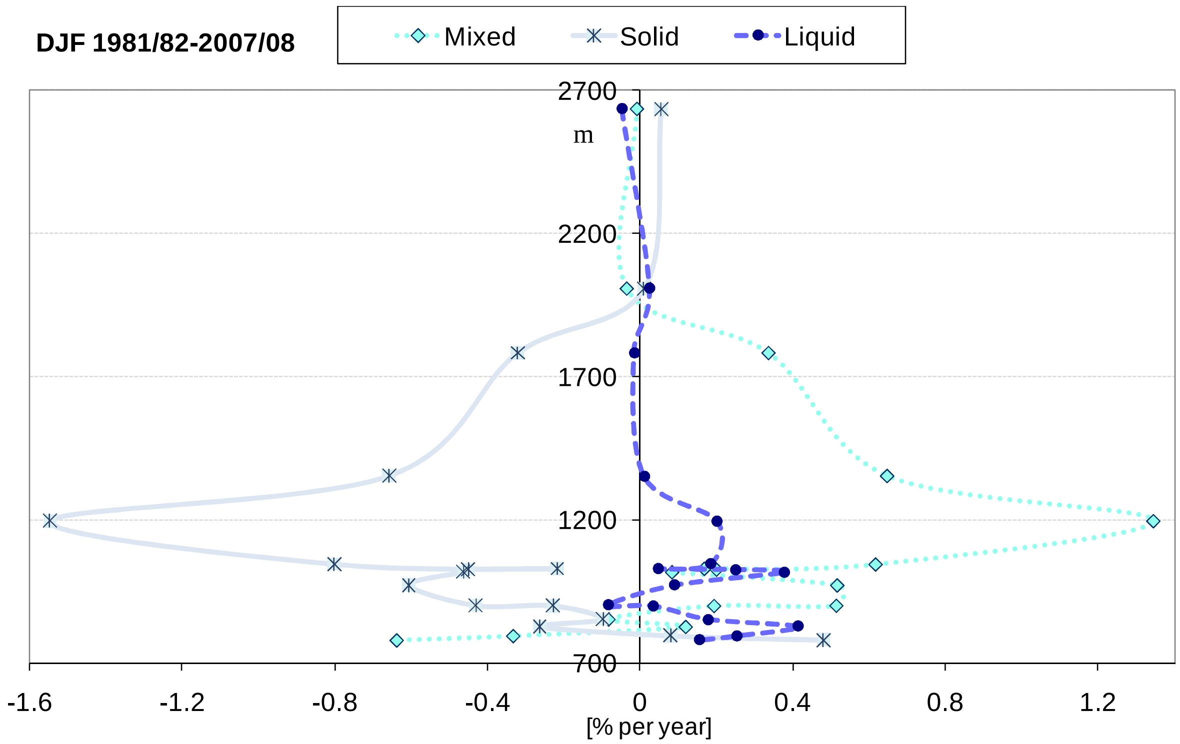


Fig. 21: Trends (1981/82–2007/08) of ratios of mixed, solid and liquid precipitation to the total precipitation amount in winter months (DJF) for selected meteorological stations above 700 m.

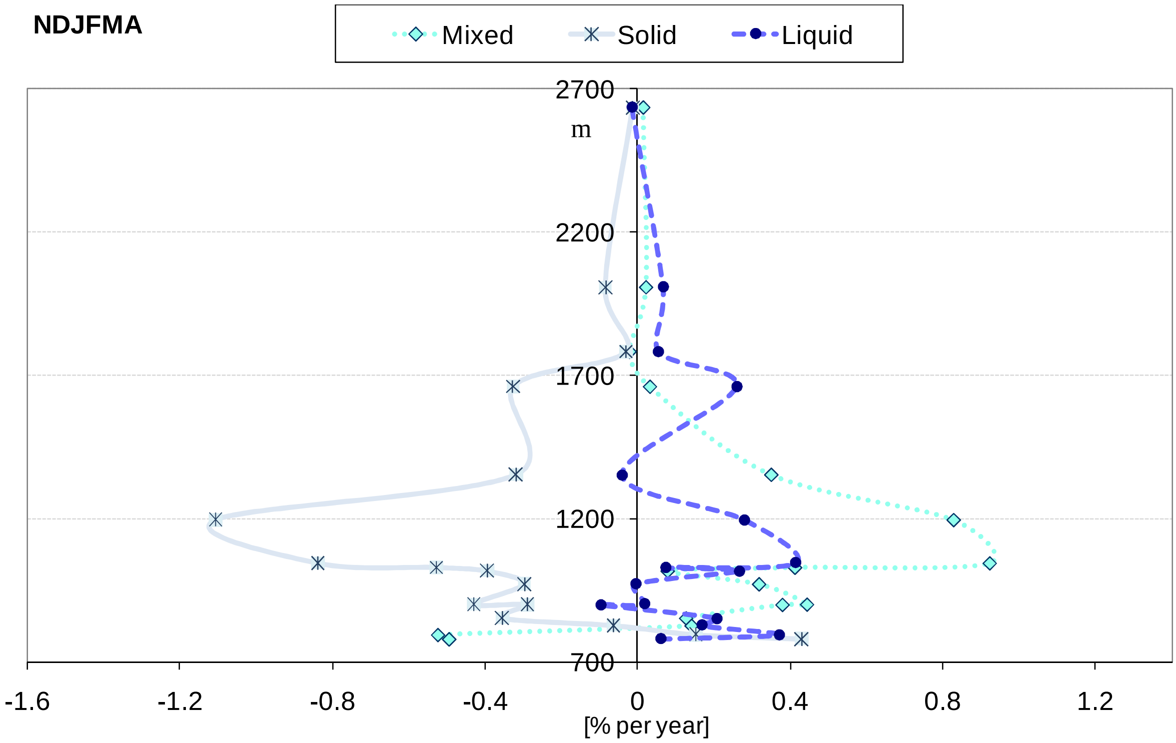


Fig. 22: Trends (1981/82–2007/08) of ratios of mixed, solid and liquid precipitation to the total precipitation amount from November to April (NDJFMA) for selected meteorological stations above 700 m.

Snow water equivalent

Using both SWE methods, the most remarkable outliers were identified and erroneous measurements were eventually corrected.

The usefulness of quality control rules, defined in section 3.1.1, is summarized in Tab. 18. Where fraction is written, the denominator is a sum of records flagged as suspect and the numerator is number or records acknowledged as erroneous by expert. No record was flagged with QC4 rule in selected sample.

Tab. 18: Number of days flagged as missing, erroneous, and suspect, and precipitation measurement quality coefficient for selected stations (1981/82-2005/06). Refer to Appendix A for abbreviated station names.

Abbr.	mis	err	Suspect							Q^{SWER7}	
			QC1	QC2	QC3	QC5	QC6	QC7	QC8	AVG	StDev
ŠP	11	7	297	3	1	260	1/167	3/38	6/121	1.9	6.3
PB	51	12	0	4	4	2/444	2/91	5/28	9/80	2.7	9.1
ŽJ	41	1	41	5	2	311	54	16	1/102	1.8	3.3
OL	22	12	58	5	0	225	2/88	11/22	12/72	2.9	11.4
TG	5	3	0	1	0	243	88	2/15	2/45	2.5	15.5
TL*	32	4	0	3	0	3/198	37	1/10	3/30	1.8	2.9

The rule QC6 revealed also the quality of winter precipitation measurement, in cases when significant precipitation amounts were systematically lost due to the inappropriate measurement. For example, the sum of weekly precipitation might be only 60 % of the weekly increase of SWE. Although the increase of SWE might be caused by another processes (income from melted water flow, water vapour flux, …), however, assuming that

SWE measurements are of good quality, the coefficient Q_{SWER7} is a good measure of the quality of precipitation measurement (refer to the definition on page 31).

Stations without any inhomogeneity in precipitation and snow data were used for trend analysis applied on SWE average monthly values (which were calculated from daily SWE data). Though only about 10% of all trends were significant, an overall increase was observed in period 1981/82-2005/06, ranging from Liptovský Hrádok (0.8 mm/10yr) to the greatest rate at Oravská Lesná (10 mm/10yr). Greatest increase is observed in March, while only minor decrease in May.
The winter season of 2005/06 was extremely rich for SWE. Various buildings in Central Europe collapsed due to extreme loads.

5.2.1 Discussion

By combination of precipitation and temperature trends, we may notice that insignificant decreasing trend in air temperature is accompanied by decreasing precipitation in November. As a result, the amount of snow tends to be reduced mainly due to decrease in precipitation in autumn months. This leads to delayed beginning of "white" winter, what is illustrated with BSD characteristics in Fig. 19.
A further argument in favour of milder winters (especially in lower elevations) in the near future is the significant increase of temperature in January, while precipitation amounts are without significant tendency in mid-winter months.
The most significant increase in winter precipitation is in March and April, when the temperature trends play a marginal role. The temperature is low enough to snow, especially at higher elevations, and this causes increase in snow amounts as well as delayed end of winter.

The atmosphere is capable to contain more water molecules if the air temperature continues rising. That is why global warming is connected with higher precipitation amounts. Despite the warming, the highest locations in Slovakia are for sufficiently long time under the freezing point, so that the amount of snow is growing. Changes in precipitation types are a valuable evidence of climatic change.
The credibility of precipitation and snow measurements at the highest peak station (Lomnický štít) is questionable. Nonetheless, referring to Fig. 10 and Fig. 12, we can notice the change clearly resembles rising trend during 1990s rather than an abrupt step at a specific year. Due to insufficient number of stations at altitudes above the tree line, the results might not be credible, but similar results were achieved also in the Alps [10], where negative trends turn at higher altitudes to positive, because milder winters are associated with higher precipitation levels than colder winters, but with more solid precipitation at elevations exceeding 1700 – 2000 mASL, and more liquid precipitation below.
Climate trends obtained from homogenized data may differ from the raw ones. For example, in case of snow cover depth, all unadjusted series showed general decrease, but after adjusting these trends became weaker or even positive.
General increase in average SWE values implies a greater extremes, which are a base for the evaluation of the loads on engineering structures. Revised maps of the probability of repeating published in [64] confirm general increase in extremes, although this might be caused by usage of shorter time series in previous maps. The trends in time series along with the length of the time series are important parameters to consider in extreme value statistics.

5.3 Analysis of avalanche danger

Creation of the SLPDB database has enabled to retrieve several interesting statistics. Conventional forecasting is partly based on threshold values of some important meteorological elements. Typical values of some meteorological elements for 5 avalanche danger levels can be found in Tab. 19.

Tab. 19: Typical values of meteorological elements related to avalanche danger levels, based on interquartile ranges.

Meteorological element	Station	1	2	3	4	5
Precipitation on the third day before [mm]	Lomnický štít	0 - 30	0 - 75	10 - 150	90 - 210	365 and more
New snow heights total for the previous 3 days [cm]	Ždiar - Javorina, Podbanské, Skalnaté pleso	0 - 30	5 - 40	10 - 50	30 - 60	50 and more
Average squared wind speed[8] on previous day $[m/s]^2$	Ždiar - Javorina	0 - 15	5 - 30	10 - 55	20 - 75	45 and more

Note the 30 cm threshold of new snow heights, which was mentioned by Atwater in 1954 as the minimum generally necessary to produce spontaneous avalanches of dangerous proportions (see Section 3.3.1).

Typical expected lengths of avalanche tracks during the days with certain avalanche danger levels can be found in Tab. 20. It is important to emphasize that the values are typical for the HT Mts., where the tracks are limited by topography to about 1500 m. The longest avalanches were recorded in the WT (Žiarska and Jamnická valleys) and in the BF (Turecká and Suchá valleys), with length over 2800 m and 2300 m, respectively.

Tab. 20: Typical maximum avalanche track lengths as recorded during various avalanche dangers in the HT Mts, based on interquartile ranges.

Avalanche danger level Y_{Ω}	Typical track length [m] Y_{dx}
1	50-250
2	200-350
3	250-500
4	500-900
5	1000 and more

8 Average squared wind speed obtained from values observed in 3 terms, 7, 14 and 21 MST as following:

$$W_s^2 = \left(\frac{W_{s7} + W_{s14} + W_{s21}}{3} \right)^2$$

The International avalanche danger scale has been fully adopted in Slovakia since the winter of 1994/95. Frequency of verified danger levels by months are presented in Tab. 21.

Tab. 21: Frequency of verified avalanche danger levels in months (1994/95-2008/09) from SLPDB database.

f_{AD}	Frequency						
	Nov	Dec	Jan	Feb	Mar	Apr	May
1	60%	48%	27%	17%	18%	34%	71%
2	25%	36%	49%	45%	40%	43%	27%
3	15%	15%	18%	31%	37%	20%	2%
4	0%	1%	5%	6%	4%	3%	0%
5	0%	0%	0%	0%	0%	0%	0%

Avalanche activity was recorded already in September in some years, namely between 6th and 10th in the year of 1971, when quite a few avalanches occurred, some of them with 600-800 m track lengths. Some avalanches were detected also in July 1969, and recently in 12th June 2005 and 2006. Numbers of recorded avalanches in mountain ranges by months for nearly 2 decades can be found in Tab. 22. Small portion of avalanches occur in September, but no avalanches are recorded in October as a result of prevailing dry weather caused by anticyclone.

Tab. 22: Number of avalanches by months in mountain ranges (1991/92-2007/08). Based on available avalanche records in SLPDB.

Month	Number of avalanches													
	HT	%	WT	%	LT	%	SF	%	BF	%	BT	%	Sum	%
IX	1	0	19	3	8	2	0	0	0	0	0	0	28	1
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
XI	20	2	31	5	36	7	11	3	6	2	19	18	123	4
XII	75	7	48	8	66	13	14	4	10	3	12	11	225	8
I	100	10	157	25	56	11	87	25	102	33	16	15	518	18
II	246	24	87	14	95	19	34	10	66	21	18	17	546	19
III	289	28	115	18	133	26	150	43	104	33	22	21	813	28
IV	261	26	163	26	118	23	51	15	24	8	17	16	634	22
V	14	1	1	0	0	0	0	0	0	0	0	0	15	1
VI	14	1	2	0	0	0	0	0	0	0	3	3	19	1
Sum	1020	100	623	100	512	100	347	100	312	100	107	100	2921	100

The average number of recorded avalanches is about 60 per winter in the HT, but the maximum of 130 was reached in 2000/01. However, the true number is difficult to estimate, as the monitoring is not perfect.

Regular avalanche occurrence in some popular places (Skalnaté pleso, Veľká Studená dolina, Chata pod sedlom Váhy) requires avalanche control and particular engineering works, in order to maintain the recreational value. [2]

Summary of avalanche slopes was published by Milan [67] in 1981. There were added 34 slopes since then, and the refreshed review is in Tab. 23.

Tab. 23: Avalanche terrains in mountain ranges of the Western Carpathians in Slovakia. Updated table taken from (Milan, 1981).

Mountain Range	Area [ha]	Avalanche slopes [number]	Portion of total area [%]
SF	21 365	207	6.2
BF	63 710	168	2.4
LT	164 560	670	3.5
WT	29 177	761	28.2
HT	25 367	1749	12.3
BT	6 691	160	9.0
CH	15 463	17	0.3
OM	25 832	1	0.06
Total	352 165	3733	5.8

The WT Mts. with the greatest portion of avalanche slopes is an avalanche Eldorado in Slovakia. The avalanche slopes in the HT Mts. are numerous but smaller.

Having a look at the seasonal course (see Fig. 23), the most of avalanche accidents occurred within the following weeks:

- 26.12. – 1.1. between Christmas Eve and New Year's Day,
- 27.2. – 5.3. "spring" holidays
- 14.2. – 20.2. "spring" holidays

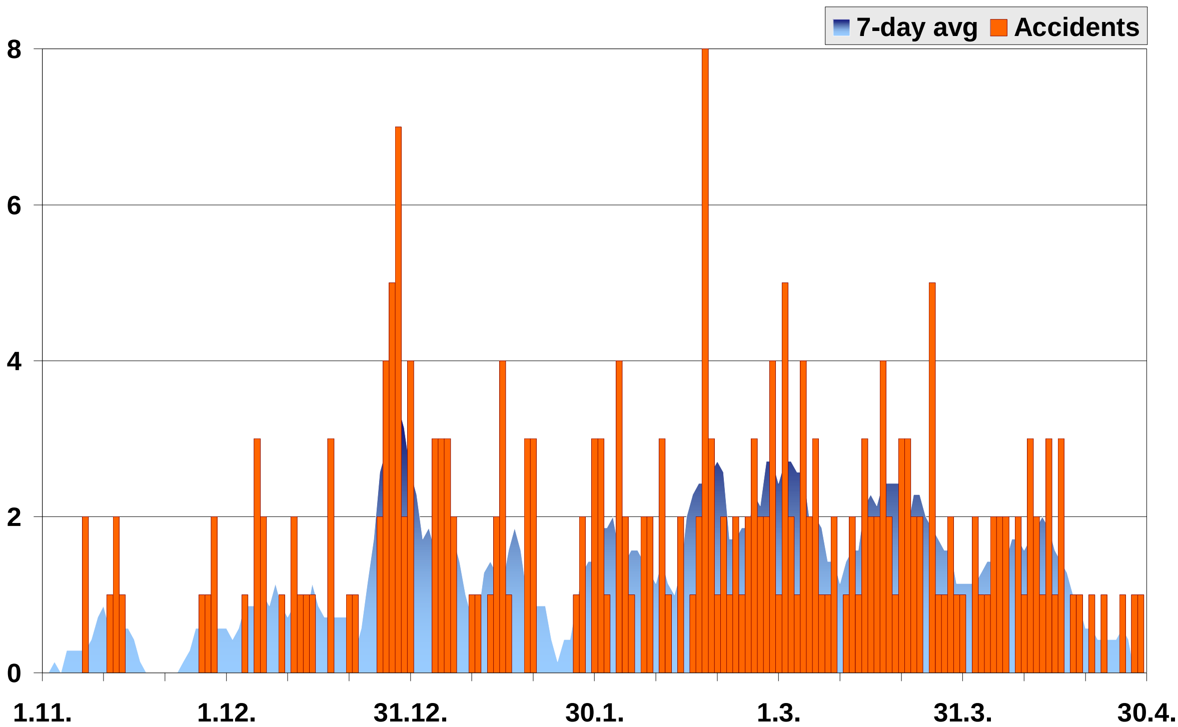


Fig. 23: Seasonal course of the number of avalanche accidents with 7-day running average.

5.3.1 Serious avalanche events and synoptic situations

Since the climate in the Western Carpathians is transitional (see Tab. 24), the avalanche formation can develop in various ways.

Tab. 24: Some yearly characteristics (obtained from 1961–2000) indicating transitional climate in the Western Carpathians: mean air temperature, total precipitation, sum of new snow, mean maximum snow depth, mean density of new snow (if ≥ 5 cm; calculated from 1981-2000), and mean density of total snow cover (if ≥ 5 cm).

Station	$\bar{T}$ **[°C]**	$\sum R$ **[mm]**	$\sum NS$ **[cm]**	$\overline{\max\{SD\}}$ **[cm]**	$\overline{\rho^{NS\geq 5cm}}$ **[kg/m³]**	$\overline{\rho^{SD\geq 5cm}}$ **[kg/m³]**
Lomnický štít (2635 m)	-3.9	1373	801	204	113	-
Chopok (2008 m)	-1.6	1030	477	179	97	-
Štrbské Pleso (1354 m)	2.8	992	421	116	78	258 *
Ždiar-Javorina (1030 m)	3.1	1260	363	83	82	253 *
Oravská Lesná (780 m)	3.7	1099	338	87	83	243 *

The aim of this section is to describe the synoptic patterns that are present during serious avalanche activity in the HT Mts. The period with serious avalanche activity was simply defined as consecutive days with avalanche danger levels 4 or 5. Avalanche danger levels (Y_Ω) were assessed backward by avalanche experts to increase the number of these relatively rare situations.
The Czech-Slovak classification of synoptic situations, available on the www.shmu.sk web-pages was used. It consists of 28 types, which are issued yearly in cooperation with Czech Hydrometeorological institute, in order to maintain its homogeneity.

Selected serious avalanche events took place between the years 1955-2008, and approximately one third of these events occurred in February. The most frequent synoptic types occurring on the days with avalanche danger levels 4 and 5 are the following:
NWC (25%), NEC (21%), NC (13%), EC (7%), WC (7%), B (7%), C (4%).

Taking into consideration also the 3 days preceding the serious avalanche danger days, the following results were returned:
NWC (24%), NEC (17%), NC (12%), WC (9%), B (6%), C (6%), EC (4%).

Achieved results correlate with situations rich for new snowfalls, published by Bochníček [11]: NWC, WC, B, NC, NEC, WCS, C, BP, VFZ, EC.

The most common chain sequences are the following:
1. Starting with B/WC > NWC > NC > NEC
2. Less frequent starting from south SWC > C > NEC/EC and finalizing with EA, when the danger slowly decreases

5.3.2 Peculiar avalanche records

This section was moved and merged into the Section 2.4 Avalanche data.

5.3.3 Stepwise regression

The general dataset G consisting of rows (older than 1st July 2002) with avalanche and meteorological variables was divided by variable Y_{swc} into following subsets:
D, if $Y_{swc} = \{0, 1\}$
M, if $Y_{swc} = \{0, 2\}$
W, if $Y_{swc} = \{0, 3\}$
The best stepwise regression models calculated from these datasets were selected and tested on the G dataset (records dating from 1st July 2002).
By convention, each model can be identified by its name, which begins with letter: D=dry, M = mixed/moist, W=wet and G=general (all types together); and continues with number of stations and input variables. For example, the model G7x19 means general model with 19 input variables selected from 7 stations.
Several statistics for the assessment of models performance can be found in Tab. 25. Ideal value for each HR* equals 1, and the models have evident problem with underforecasting of the danger level 3.

Tab. 25: Hit rates for individual avalanche danger levels, standard deviation between forecasts and observations, the number of tested days, the number of days used for calculation of model coefficients.

Model	HR1*	HR2*	HR3*	HR4*	HR5*	ST.DEV	Tested days	Calc. days
G7x19	0.5	1.5	0.7	0.8	3.0	0.47	1059	1716
G6x12	0.7	1.4	0.7	0.6	1.0	0.50	1060	2776
D7x44	0.9	1.4	0.5	1.3	N/A	0.44	504	1259
M7x54	0.8	1.4	0.6	1.8	N/A	0.49	496	1089
W7x39	0.9	1.4	0.5	1.5	N/A	0.49	503	1109
W7x17	0.8	1.5	0.4	0.5	N/A	0.46	503	1109
G7x51JF	0.5	1.3	0.9	1.8	N/A	0.98	496	608

The accuracy measures of models by months are summarized in Tab. 26. Though the maximum proportion of correct is 74% (D7x44), by a selection of the best model for each month, the overall accuracy could be improved. The performance ranges from 66% in May to 93 % in November. Model G7x51JAN was calculated on sample of January-February data. Other monthly models are not included for the reason that their performance was not better than that of seasonal ones. Similarly, if only single station was used for the selection of input variables, the best general model reached maximum proportion of correct only about 66% (Lomnický štít).

Tab. 26: Proportion of correct and incorrect avalanche danger levels. Accuracy of the forecasts for individual months.

Model	PC*	PNCD	Nov	Dec	Jan	Feb	Mar	Apr	May
G7x19	72%	0%	55%	81%	81%	75%	81%	54%	66%
G6x12	72%	1%	57%	80%	78%	75%	70%	69%	56%
D7x44	74%	0%	81%	82%	78%	76%	68%	64%	60%
M7x54	69%	0%	70%	82%	70%	67%	73%	51%	47%
W7x39	68%	0%	74%	81%	69%	66%	70%	51%	60%
W7x17	71%	0%	93%	82%	72%	69%	67%	58%	53%
G7x51JF	60%	6%	48%	71%	67%	84%	59%	34%	0%
S12	59%	N/A	65%	48%	65%	61%	58%	59%	N/A

Model S12, which was published in author's diploma thesis [104] as the most successful for dry avalanches, is mentioned for comparison.

The Tab. 27 summarizes the most important variables for various regression models. Numerous are mainly the following elements: new snow height (V28), relative humidity (V14, V12), total snow depth (V29), precipitation amount (V31), air temperatures (V1-V5), snow water equivalent (V30), positive air temperature (V19) and wind speed (V9). From the elaborate variables defined in section 2.2.1: Salway's famous variable V48, V59 (the cube root of Salway's variable V46 seems to be better), V25 (west component of wind vector), V18 (squared temperature amplitude), V32 (the product of snow depth and rainfall, firstly used by Salway), V42 (the product of NS and logarithm of wind speed), and another Salway's variables: V47, V49, and V50.
The variables preceding the forecasted day at maximum 5 days were selected by stepwise regression, even though variables for 7 days backward were available.

Tab. 27: Top ten variables sorted by importance. ŽJ=Ždiar-Javorina, LŠ=Lomnický štít, ŠP=Štrbské Pleso, PB=Podbanské, CH=Chopok, SK=Skalnaté pleso, TL=Tatranská Lomnica.

G7x19	G6x12	D7x44	M7x54	W7x39	W7x17	G7x51JF
ŽJx4V14	ŽJx4V14	ŽJx4V14	ŠPx1V4	LŠx1V50	ŽJx4V14	TLx2V30
LŠx3V29	ŠPx2V29	ŽJxV28	LŠx3V28	ŽJxV28	LŠx3V29	ŠPxV19
LŠx3V28	LŠx1V59	TLx2V30	ŽJxV28	LŠx3V29	LŠx3V28	ŠPx2V28
ŠPx2V28	SKx2V28	CHx3V1	ŠPxV19	ŠPxV19	PBx1V31	PBx1V31
PBx5V3	LŠx3V28	LŠx3V28	ŽJx4V14	ŠPx1V18	PBx5V48	TLx3V32
CHx3V1	CHx3V1	PBx5V48	ŠPx2V30	PBx5V48	CHx3V1	CHx4V12
PBx1V31	ŠPx1V28	PBx1V31	ŠPx1V18	ŽJx4V14	ŽJxV28	ŠPx1V49
ŠPx2V29	SKx4V59	PBx3V28	ŠPx2V29	LŠx1V47	LŠxV25	LŠx5V42
ŠPx1V28	CHx2V9	LŠxV25	ŠPx3V4	LŠx3V28	SKx1V28	PBx2V3
ŠPxV29	ŽJxV28	LŠx1V59	ŠPx1V28	PBx1V31	ŠPx2V28	ŽJx4V14

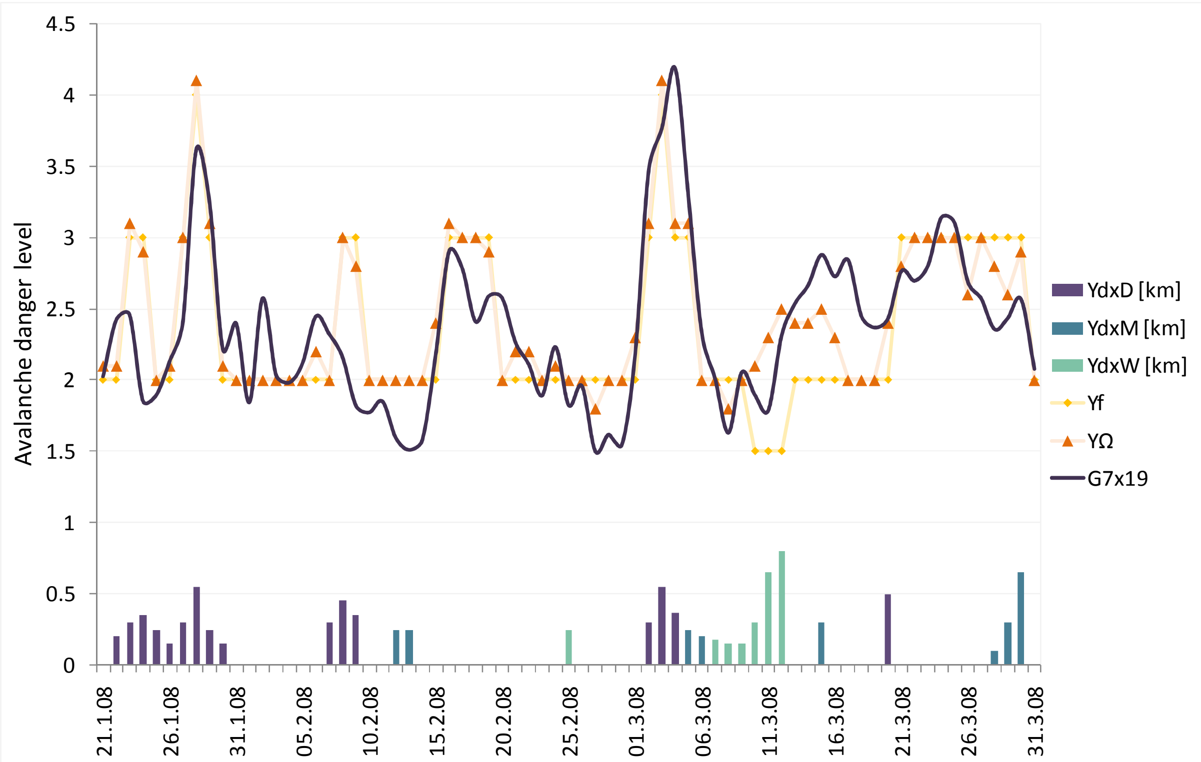


Fig. 24: Avalanche danger levels forecasted by the G7x19 model. Bars represent track lengths (Ydx) of the largest avalanche (Dry, Mixed, Wet) in kilometres. Yf is forecast issued by the APC, Y_{Ω} is verified forecast.

An example of forecasted avalanche danger levels by the G7x19 model shows quite successful performance (see Fig. 24). The time period is intentionally chosen so that all types of avalanches can be found there. The accuracy of both human and statistical forecasting of wet avalanches is smaller (note 2nd decade of March 2008 on the graph).

5.3.4 Nearest neighbour method

Variables from the G7x19 model were used for the NNB method. Suitable logarithmic transformations, such as ln(x+c) or ln(c-x), were applied on variables with skewness coefficient > 2 or <-2, respectively. Moreover, as suggested by Cordy [19], the variables were standardized by subtracting the overall mean and dividing the result by the standard deviation. Simple distance metric was used at the first stage: $\Delta d = \sum_j \Delta x_j^{\ 2}$. Then weights were applied, based on correlations with avalanche danger levels: $\Delta d = \sum_j c_j \Delta x_j^{\ 2}$.

Tab. 28 summarizes the fitness statistics of the most successful configurations of the NNB models, including the foreign ones for comparison. N is number of optimum nearest neighbours; k is threshold used for discrimination between avalanche and non-avalanche day, e.g. k=4 means that the day is classified as avalanche day if at least 4 of all N neighbours are associated with avalanche activity.

Tab. 28: Fitness statistics for various models.

Model	k/N	PC	UAA	TSS	BIAS	Test rows	Avalanche rows %
AFS, Kootenay Pass, (Cordy et al.), [19]	6/30	0.75	0.76	0.54	2.12	1336	13%
Cornice, Scotland, (Purves et al.), [79]	3/10	0.80	0.76	0.52	1.12	202	25%
NNB7x19Unweighted	9/26	0.67	0.63	0.27	2.44	1025	15%
NNB7x19Weighted	8/25	0.64	0.63	0.27	2.67	1025	15%

The weights based on correlations did not improved the model, because none of the four fitness statistics was closer to 1, which is a perfect score.
On average, the model NNB7x19U (using 26 neighbours) shows 10 neighbours with avalanches for avalanche day, and 7 “avalanche neighbours” for non-avalanche day.
In 47% of the days the avalanche danger levels calculated as an average of all selected neighbours (26) were in agreement with the verified hazard levels. This is in comparison with regression models poor result, because the PC* was about 74% there.

5.3.5 Discussion

The HT Mts. with area of about 250 km^2 can be considered as one compact region, either geomorphologic or climatological. According to McClung and Schaerer [59], the regional models correspond to areas of 100 km^2 and heavily relies on meteorological data. In Slovakian part of the range, the most of main valleys are south-oriented, and the only exception is the north-east part, where also the climate is little different when compared with the rest of the mountain range. However, this region may be represented by Ždiar-Javorina station only and also the number as well as reliability of avalanche records at present is not sufficient to create the new sub-region for forecasting. Therefore all models were designed only for the HT Mts. as one region. More additional data such as stability observations and snow profiles should be used to forecast in lower (local) scales. The regionalization remains the challenge for the future, on condition that more snowpack data will be available for the particular sub-region, represented by at least one station.

The hit rates published in Tab. 25 indicate that the ***regression models*** face problems with underforecasting of the danger level 3. Avalanche forecaster should bear this drawback in mind. From another point of view, forecasters have a tendency to retain the danger level and are rather careful when the avalanche activity is decreasing. The onset of avalanche activity is often rapid and, to say the truth, sometimes even surprising, while the expected ending should be proved by observations. This waiting for some additional information consumes some time and delays the forecaster's decision to cancel/degrade the avalanche danger. This is general feature in forecasting of rare dangerous events.
Introducing long-term variables could improve the models. For example, we can define a Boolean variable *hoar* η=1 IF temperature gradient exceeds 10°C/m for more than 3 consecutive days. Similarly, we can define a variable *ice crust*. However, the best way is to obtain the weak layers information from snow profiles and implement a stability index.
Another improvement is expected in future, when data from specialized AWS will be included.
For operational use of the models, a complex data mining system that collects all the necessary data into unified environment (e.g. a database) is necessary at the APC. The SLPDB database is designed rather as historical and climatological, containing quality checked data. Since some models rely on values of daily SWE, a module for calculation of daily SWE from weekly measurements is needed as well.

Insufficient detection of avalanches is a weak spot of the ***NNB method***. Othmar Buser [15] mentions periods with worse visibility, which hinders the monitoring of avalanche activity. Therefore, occurrence of fog/haze is useful information to select with nearest neighbours.
Another distortion might be caused by days when only little snow remains in release zones as a result of recent avalanche activity. On these days, the avalanches would occur if they had not fallen (spontaneously or with a little help of explosives) on previous days. However, this problem becomes more expressed on small scales (few avalanche slopes). Sometimes it is useful for the avalanche forecaster to retrieve also few days before the neighbour days.
The overall performance of the NNB7x19U model is hardly comparable with foreign models. Further improvements could be firstly achieved by better transformations of basic input variables. Using genetic algorithms could be an objective solution to further problem with appropriate weights. The model should be installed in user-friendly environment that will make testing of different weighting schemes easier. Also the selection of variables should be performed more carefully, because different variables are important throughout the winter. The variables from the best regression models can be used for particular months.
In spite of all mentioned problems, there is an advantage that model provides user with days from the past, similar in terms of weather to current situation. Although the NNB model gives inadequate avalanche characteristics, the forecaster may unveil other important variables or other than meteorological factors that are decisive for the particular case.
Several technical problems appear in operational use, such as incomplete or delayed reception of daily observations. However, the method is expected to improve later on, as more experiences with its use will identify its weak points.

6. Conclusion

Overview of the research

The dynamics of snow conditions influence many human activities such as tourism, agriculture, hydrology, traffic, architecture, etc. Therefore the changes in climate in mountainous areas have been the concern of domestic and foreign authors from different disciplines.

The most significant domestic studies on snow climate are mentioned in chronological order in Chapter 1, which reflects **1st** objective of the thesis. As a result of the plethora of relevant data from foreign sources, only the most recent ones are mentioned. Special emphasis was put on the state-of-the-art homogenization techniques that are still being improved. The homogenization is part and parcel of any climate change study, especially when a limited number of stations are available.

The research on snow avalanches in Slovakia began in late 1950s, and even during the years of isolation due to political ideology some fruitful results were achieved, such as avalanche cadastre. The scope of the APC from its beginning was that it would primarily be put into practice and operation rather than being purely a scientific research project. As a result, scientific literature is available mainly from foreign alpine countries, and this was the essential source of inspiration for the methods and techniques selected for avalanche forecasting. However, the development of the APC in recent decades has paved the way for further applied research and cooperation with other institutes and universities.

Quality control

Quality control process was probably the most time-consuming task of this study. Only about half of all 40 stations located above 700 mASL were selected for homogenization (refer to Appendix A and Tab. 12). The homogenization was preceded by some quality control procedures. Time series with missing and erroneous data were completed or corrected, but those with more than 12 months data missing were not used for the creation of the reference series or for climatological analysis. Inhomogeneities in monthly and yearly temperature, precipitation, and new and total snow depth series (detected by several tests using AnClim software) were verified by metadata. The final approval of detected inhomogeneities was conducted by the author after consideration of their significance and metadata. Subsequently, adjustments were applied on daily data using ProClim software [101] (q-q method).

Despite notable progress, several problems are connected with homogenization, and nowadays there is still no generally approved methodology for homogenization, especially for adjusting of daily data. The best way is to ignore stations with inhomogeneities because even if they are adjusted, they are not as reliable as the stations where no inhomogeneities were detected. Another important factor was the creation of reference series: in case of snow depth, there are only few time series available in the period of 1921-1961. The lack of suitable neighbours is typical also for the highest stations, where snow falls quite often, whilst only rain occurs at lower elevation stations.

The result of the QC process was a good-quality dataset of daily meteorological elements and another daily dataset with parameters describing avalanche activity. By achieving this result, **2nd** and **3rd** objectives were fulfilled.

Climate trends

Climate trend analysis was the **4th** objective, once after the set of homogeneous series had been created. The results can be found in Section 5.2. It is possible to use current variability of climatological elements to estimate the future climate. Stations without inhomogeneities are preferred, but due to the insufficient number, the adjusted time series are used, while the unadjusted has served for comparison and assessment of reliability.

The *air temperature* is definitely rising at all stations, no matter which period is taken in the trend analysis. Furthermore, the warming has becoming more intense and significant at all stations (except for Ždiar-Javorina) since 1981. Focusing on seasonal changes, there is on average a weak, insignificant cooling (up to -0.06°C/10yr in September) or no trend in autumn months, while the most significant warming is most clearly pronounced in January (0.5°C/10yr), May (0.4°C/10yr) and July (0.35°C/10yr). With a warmer atmosphere we can expect greater variability as well as an increased frequency of extreme events.

Precipitation totals at most of stations tend to increase significantly from 1951/61. Reductions were only detected at the adjusted Tatranská Lomnica (significant) and Šumiac stations. Precipitation regime tends to change most dynamically in summer months. The highest rise is present in July and March (4 mm/10yr on average), while the drop in June and November is on average -3 and -1 mm/10yr.

With the exceptions of the Chopok and Telgárt stations, which have shown a significant decrease and the Lomnický štít and Skalnaté pleso stations which have shown a significant increase, the remaining stations have recorded insignificantly increasing trends in yearly *snowfall totals*. Trends by months revealed slight rise in March and November (3 cm/10yr on average), at the expense of December (-1 cm/10yr). There is no straightforward dependence on altitude.

Overall reduction of average *snow depth* was identified (up to -1.35 cm/10yr at Skalnaté pleso), except for Lomnický štít (significant increase of 10.55 cm/10yr) and Ždiar-Javorina. The highest station is situated above a "crossover level", above which negative snow trends turn to positive. Ždiar-Javorina is in relatively colder climate at the north-east part of mountain range, unlike Skalnaté pleso station located on a southern slope. These stations have opposing trends and are outliers in the snow-depth-trend background. Different trends are probably caused by diverse sensitivity to changing synoptic patterns.

Snow regime throughout the year has also changed. The delayed beginning, later annual maximum, earlier and more intensive melting at the end of winter characterises the new snow regime at the majority of stations below 2000 mASL. However, some stations covered with snow for the most of April tend to prolong the end of winter up to 2 days/10yr, but only with smaller snow depths.

Insignificant diminution in the *number of days with snow* cover of 10 cm or more is observed primarily in the Low Tatra Mts. One quite interesting contrast was unveiled, focusing on 50 cm threshold in trends between neighbouring Lomnický štít (+10.4 days/10yr, significant) and Skalnaté pleso (-7.6 days/10yr). On average, the reduction is well-expressed in January, while the increase takes place mainly in April.

Developers of ski resorts are interested in *100-day-rule* parameter, which is used for the assessment of profitability. Based on absolute minima, the critical altitude with snow depth duration at least of 100 days is about 1300 mASL. A further noticeable fact is that the minimum snow depth during 100 days reaches 20 cm or more only at elevations above 1000 mASL, on average. Seemingly, there is no significant change at lower elevation stations and this characteristic decreases mainly at elevations between 1200 and 2100 mASL (refer to Fig. 20).

A substantial decrease in *solid precipitation* is evident at altitudes between 1000-1500 mASL, mainly because of the increase in mixed forms. The solid fraction is decreasing slightly also at

stations below 1000 mASL due to slight increase in both mixed and liquid ratios. There is a critical break-point altitude, above which the trends changes; i.e. the fraction of solid precipitation tends to stagnate or even increase during winter. This level is estimated approximately in 1900 mASL on northern and in 2300 mASL on southern slopes.
Overall increase of *snow water equivalent* was observed in period 1981/82-2005/06. The greatest increase is observed in March, while only minor decrease in May. Due to diminishing solid fraction of precipitation and increase in SWE we can conclude that snow water content as well as snowpack density tends to rise. This partially accounts for the prevailing increase of new snow heights along with the decrease of total snow cover depth. The increase in mixed forms of precipitation plays in favour of denser snowpack, too. The increase of snow density has an impact on avalanche formation, and leads to the conclusion that in the future the wet avalanches will occur more frequently and earlier. This is what has been predicted for the Aspen ski area [54].

The results are consistent with recent studies:
A significant decrease of snow cover days has been observed in the lowlands. The general decrease of snow cover is well-marked in recent decades, except for the mountainous areas of Northern Slovakia, where the trends are indifferent or even increasing. [65]
The results correlate with a study from Poland [26], where an increasing trend of snow cover in the period 1948/49-1997/98 was observed in areas with abundant snow cover, i.e. in north-eastern Poland (snow cover depth) and in the mountains (snow cover duration). The year-to-year variability of snow cover has been increasing, particularly during the second half of the 20th century.
Bulgaria [76]: Over the 1931–2000 period snow cover exhibited evidence of decadal-scale variability but no evidence of any long-term trends linked to climate warming. Over the more recent 1971–2000 period, stations in the 1000–1500 elevation bands have exhibited more coherent temporal variability in maximum snow accumulation and a trend toward a later start to the snow cover season.
Laternser [53] processed Swiss snow and avalanche data, and published unique long-term trends (1931-1999) in his thesis. Increases were prevalent in snow characteristics until 1980s, followed by significant decreases till 1999. Other regional studies lead by Beniston [10] revealed moderate increase in snow characteristics above 1700-2000 mASL, since mild winters are accompanied with more abundant precipitation, falling as snow at higher altitudes. On the contrary, lower altitudes are exposed to more frequent liquid rainfalls. Scherrer [85] wrote: “In the late 20th century, significant decreases in snow days have been observed for low-altitude stations. Simple statistical modelling shows that these trends can be mainly attributed to increases in temperature. The seasonal mean precipitation influence on trends is small.”

Avalanche forecasting
Results in Section 5.3 fulfil the final objective of this work (Objective **5**). Subsection 5.3.1 describes some relations between serious avalanche events and synoptic situations. Forecasting methods used in the thesis can be applied to other mountain ranges in Slovakia. Anyway, the quality of the technique was preferred to the quantity.
The HT Mts. with area of about 250 km^2 can be considered as one compact region, either geomorphologic or climatological. However, this region could be divided into 2-3 sub-regions (north, south, optionally northeast), reflecting the statement published by McClung and Schaerer [59] that the regional models correspond to areas of 100 km^2. However, the number as well as reliability of avalanche records, available at the present is not sufficient to create the new sub-regions for forecasting. Therefore all models were designed only for the HT Mts.

as one region. More additional data such as stability observations and snow profiles should be used to forecast in lower (local) scales. The regionalization remains the challenge for the future, on condition that more snowpack data will be available for the particular sub-region, represented by at least one station.
Though all possible data sources were used, various improvements could be made in the future. It is crucially important to carry out the measurements of special APC stations more professionally and regularly. These time series were not processed due to their short length. Another challenge is the new special automatic measurements performed on hourly basis that have recently been introduced, in particular the data that is obtained from these specially designed devices, such as snow surface temperature sensor, ultrasound snow depth sensor, web-camera, etc...
The best regression model achieved an overall accuracy of 74%, that is an improvement by 15% when compared to the first regression model published in the author's diploma thesis [104]. This noticeable improvement in regression models was achieved by the following facts:

- More variables from more stations were available for the stepwise selection,
- Longer periods were available for the calculation of coefficients,
- Added divisions of the dataset lead to a variety of monthly models

Moreover, some original modifications were made during the application of the technique. It is worth mentioning some variables suggested by the author that proved to be successful: the cube root of Salway's variable V46 seems to be better than the sole V46, west/north components of wind speed vector is a solution to handle wind direction, squared temperature amplitude, the product of new snow and logarithm of wind speed, relative settlement is sometimes better than absolute (the first time used by Salway), and finally variable V34, which is a measure of contrast between old and new snow density.
The idea of a separate model for dry and wet avalanches was extended for mixed avalanches. This division of data proved to be useful, because a variety of models were created. Each model has some advantages and drawbacks, but by wise selection of the best model for each month, the overall accuracy would range between 66% in May to 93 % in November. On the down side, all models have problem with underforecasting of the avalanche danger level 3.
Variables from the most successful model designed for the prediction of all types of avalanches served as key variables for the NNB model. The weights based on correlations did not improve the model. On average, the model NNB7x19U (using 26 neighbours) shows 10 neighbours with avalanches for avalanche day, and 7 "avalanche neighbours" for non-avalanche day. In 47% of the days the avalanche danger levels calculated as an average of all selected neighbours (26) were in agreement with the verified hazard levels. The performance of NXD-VG model used in Switzerland, which is based on the NNB method and estimates avalanche hazard levels, varies between 49-61% for different winters, and in 96% the difference is within one hazard level [33]. The NNB models used for calculation of avalanche danger achieved, in comparison with regression models, poor results because the PC* was about 74% there. It is hard to compare the regression models with other studies, because most of them predict avalanche and non-avalanche days. Foreign NNB models are quite successful in this area, because the unweighted average accuracy is about 76%, in comparison with 63% for the best NNB model developed in this work.
Computer-assisted models help the avalanche forecaster to gain confidence and reduce the risk of failure caused by the human factor.

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[2*] http://www.avalanche.ca – The Avalanche Glossary
[3*] http://www.geog.ubc.ca – publications
[4*] http://www.perseus.tufts.edu – Perseus Digital Library
[5*] http://www.wetterzentrale.de – NCEP reanalysis (500 mbar)

Data sources:

- APC: Avalanche records in paper form, since 1991 in electronic form
  Meteorological data from MRS weather stations
- SHMI: metadata + data from climatological database KMIS
- MicroStep-MIS: data from AWS in Jasná

Appendix

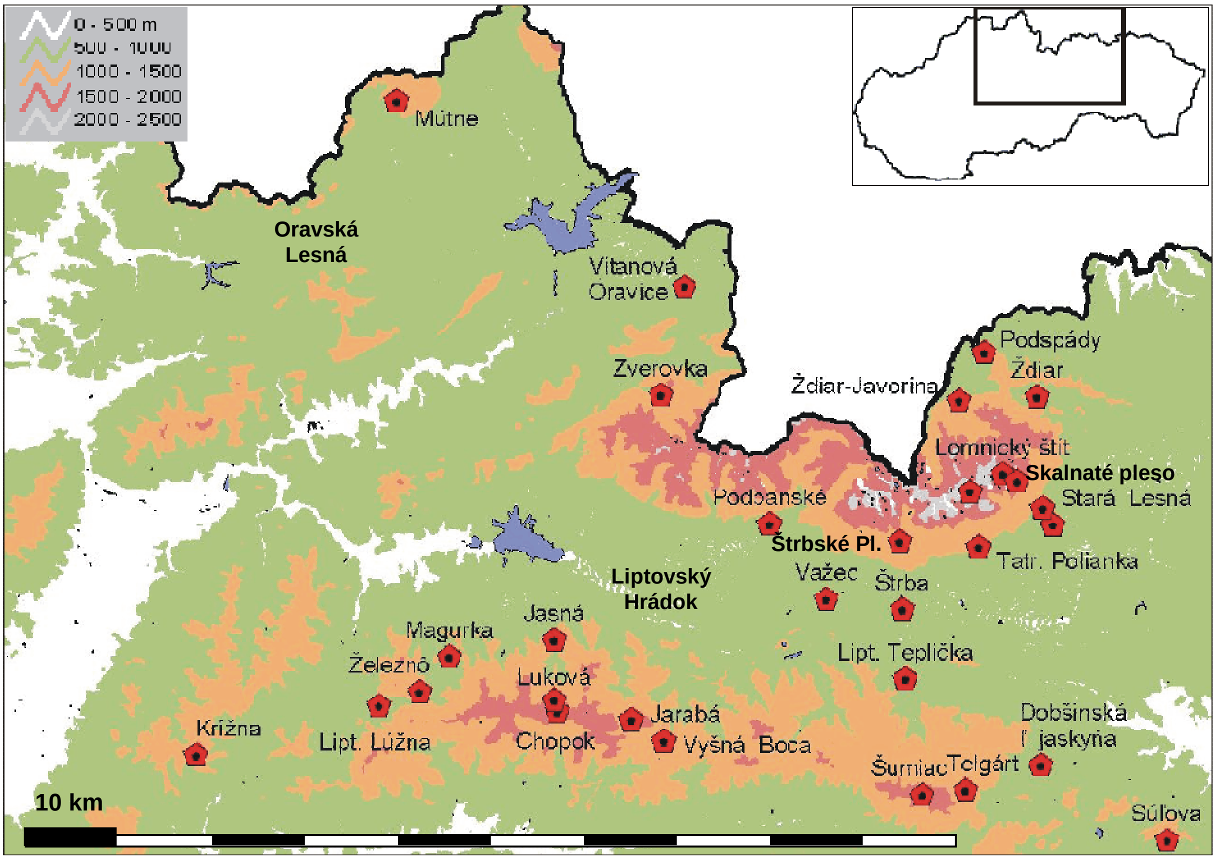
A. The list of meteorological stations

Tab. 29: The list of all meteorological stations used in the thesis.

ID	Abbr.	Station name	Latitude	Longitude	Altitude [m]
12100	LŠ	Lomnický štít	49°11' 43" N	20°12' 54" E	2635
21080	CH	Chopok	48°56' 38" N	19°35' 32" E	2008
12120	SK	Skalnaté pleso	49°11' 22" N	20°14' 04" E	1783
21100	LU	Luková pod Chopkom	48°57' 00" N	19°35' 00" E	1661
34200	KR	Krížna	48°52' 38" N	19°04' 45" E	1570
20080	ŠP	Štrbské Pleso	49°07' 18" N	20°03' 38" E	1354
21120	DJ	Demänovská Dolina - Jasná	48°58' 00" N	19°35' 00" E	1196
21240	PL	Partizánska Ľupča - Magurka	48°56' 35" N	19°26' 04" E	1045
11020	ZJ	Ždiar-Javorina	49°16' 19" N	20°08' 05" E	1030
23120	ZU	Zuberec - Zverovka	49°14' 58" N	19°42' 44" E	1027
54120	LR	Lom nad Rimavicou	48°38' 39" N	19°39' 03" E	1018
21260	PŽ	Partizánska Ľupča - Železnô	48°57' 00" N	19°24' 00" E	1000
34170	DO	Donovaly	48°52' 46" N	19°13' 35" E	992
12050	TP	Tatranská Polianka	49°07' 19" N	20°11' 15" E	975
20220	PB	Podbanské	49°08' 24" N	19°54' 38" E	972
20160	VB	Vyšná Boca	48°55' 51" N	19°45' 25" E	930
11040	PS	Podspády	49°15' 55" N	20°10' 37" E	910
13060	ŽD	Ždiar	49°16' 21" N	20°15' 30" E	905
33020	TG	Telgárt	48°50' 55" N	20°11' 21" E	901
20020	LT	Liptovská Teplička	48°57' 05" N	20°05' 30" E	900
52080	SV	Súľova	48°48' 45" N	20°28' 54" E	900
34020	JA	Jarabá	48°53' 43" N	19°42' 09" E	892
12190	KD	Kežmarok-Dvorce	49°04' 36" N	20°32' 49" E	888
33040	SU	Šumiac	48°50' 32" N	20°07' 36" E	887
57020	DL	Dobšinská ľadová jaskyňa	48°52' 38" N	20°17' 38" E	875
60020	DU	Dubnik	48°55' 22" N	21°27' 46" E	875
23060	VO	Vitanová - Oravice	49°16' 59" N	19°45' 29" E	853
22080	MU	Mútne	49°28' 00" N	19°18' 00" E	835
12020	ŠB	Štrba	49°03' 28" N	20°04' 20" E	829
12140	TL	Tatranská Lomnica	49°09' 52" N	20°17' 17" E	827
20100	VA	Važec	49°03' 21" N	19°59' 09" E	814

ID	Abbr.	Station name	Latitude	Longitude	Altitude [m]
21380	LL	Liptovská Lužná	48°56' 00" N	19°21' 00" E	810
12090	SL	Stará Lesná	49°09' 10" N	20°17' 28" E	808
21180	HU	Huty	49°13' 00" N	19°34' 00" E	795
22160	OP	Oravská Polhora - Hlina	49°33' 00" N	19°22' 00" E	794
22240	SH	Suchá Hora	49°22' 00" N	19°47' 00" E	789
56040	VE	Vernár	48°55' 04" N	20°16' 07" E	783
22020	OL	Oravská Lesná	49°22' 06" N	19°10' 59" E	780
21040	ŽI	Žiar	49°07' 03" N	19°39' 47" E	747
20260	LH	Liptovský Hrádok	49°02' 21" N	19°43' 31" E	640

B. Map of selected meteorological stations



C. International avalanche danger scale

Tab. 30: International avalanche danger scale / Degree of hazard.

Danger level	Snowpack stability	Avalanche triggering probability
1. Low	The snowpack is generally well bonded or loose and stressless.	Triggering is generally possible only with high additional loads on a few locations in steep extreme terrain. Only a few sluffs and small natural avalanches are possible.
2 Moderate	The snowpack is moderately well bonded on some steep slopes, otherwise it is generally well bonded.	Triggering is possible in particular with high additional loads, particularly on the steep slopes indicated in the bulletin. Large natural avalanches are not likely.
3 Considerable (high)	The snowpack is moderately to weakly bonded on many steep slopes.	Triggering is possible, sometimes even with low additional loads, particularly on the steep slopes that are indicated in the bulletin. In certain conditions, some medium but also few large sized natural avalanches are possible.
4 High (very high)	The snowpack is weakly bonded on most steep slopes.	Triggering is probable even with low additional loads on numerous steep slopes. In some conditions, frequent medium or several large sized natural avalanches are likely.
5 Very high (extreme)	The snowpack is generally weakly bonded and largely unstable.	Numerous large natural avalanches are likely, even on moderately steep terrain.

Source: www.avalanches.org, April 2010.

New terms suggested for danger levels in brackets are about to use since the 2010/2011 winter, if they are approved by the EAWS.

moderately steep terrain: slopes shallower than 30°
steep slope: slope stepper than 30°
steep extreme terrain: particularly unfavourable in terms of the incline (mostly steeper than 40 degrees), terrain profile, proximity to ridge, smoothness of underlying ground surface

additional loads:
high (e.g. group of skiers without spaces, pistemachine, avalanche blasting)
low (e.g. individual skier, snowshoer)

D. Glossary (English-Slovak)

English	Slovak
air blast	tlaková vlna (pred lavínou)
air humidity	vlhkosť vzduchu
air temperature	teplota vzduchu
altitude	nadmorská výška
angular crystals	hranaté kryštáliky
avalanche danger avalanche hazard	lavínové nebezpečenstvo
avalanche risk	lavínové riziko
avalanche path avalanche track	lavínová dráha
blowing snow	zvírený sneh
classification trees	klasifikačné stromy
cloud cover sky condition cloudiness	oblačnosť
cluster analysis	zhluková (klastrová) analýza
compression test tap test	poklepový test
confined gully avalanche channelled	žľabová lavína
cornice	previs, prevej
critical angle angle of repose static friction angle	kritický uhol statického trenia (závisí od vlastností snehu a charakteru povrchu svahu)
deflecting dyke	ochranná hrádza
dendritic crystals	rozvetvené, vláknité kryštáliky
density of new snow	hustota nového snehu
depth hoar	dutinová inovať
drifting snow	naviaty (odnesený) sneh
dry-snow avalanche	lavína zo suchého snehu
faceted crystals	zbrúsené, zaoblené kryštáliky
flow(ing) avalanche	tečúca lavína
full depth avalanche	základová lavína
glide crack	sklzová trhlina
graupel	krúpa, krúpka, zrnitý sneh
gully	úžina, roklina
heavy snowfall event	výrazne silné sneženie
hot spots	kritické body (na lavínovom svahu)
large scale flow patterns	rozsiahle systémy atmosférickej cirkulácie
logistic regression	logistická regresia
loose-snow avalanche	lavína s bodovým odtrhom

English	Slovak
mean snowfall	priemerná výška nového snehu
morphology	morfológia (členitosť)
new snow height (depth)	výška nového snehu
powder avalanche airborne avalanche	prachová lavína
precipitation	atmosférické zrážky
precipitation intensity precipitation rate	intenzita zrážok
precipitation form	forma zrážok
precipitation type	druh zrážok
ram hardness	záťažová tvrdosť
rime icing	námraza
rimed crystals	zmrznuté kryštáliky námrazy
rocky outcrops	skalné výčnelky
runout zone zone of deposition	pásmo nánosu
Rutschblock test	zosuvný blok (blokový test sklzu)
sastrugi	zástruhy (vlnky zmrznutého snehu)
screened box meteorological shelter	meteorologická búdka (so žalúziami)
settling of snow cover	sadanie snehovej pokrývky
shovel shear test	test sklzu lopatkou
sintering	zatavenie vytváranie väzieb medzi snehovými kryštálmi difúziou vodnej pary
slab avalanche	dosková lavína
slab layer	snehová doska
slope angle	sklon svahu
slope length	dĺžka svahu
slope orientation slope aspect	expozícia svahu
slope width	šírka pásma odtrhu
sluff slough slush flows	splaz, malá lavínka
snow cover extent	rozloha (rozsah) snehovej pokrývky
snow depth (height)	výška snehovej pokrývky
snow surface condition	povrch snehu
snow surface temperature	teplota povrchu snehu
snowfall intensity snowfall rate	intenzita sneženia
snowshoe	snežnice
global solar radiation	globálne žiarenie
starting zone zone of origin	pásmo odtrhu

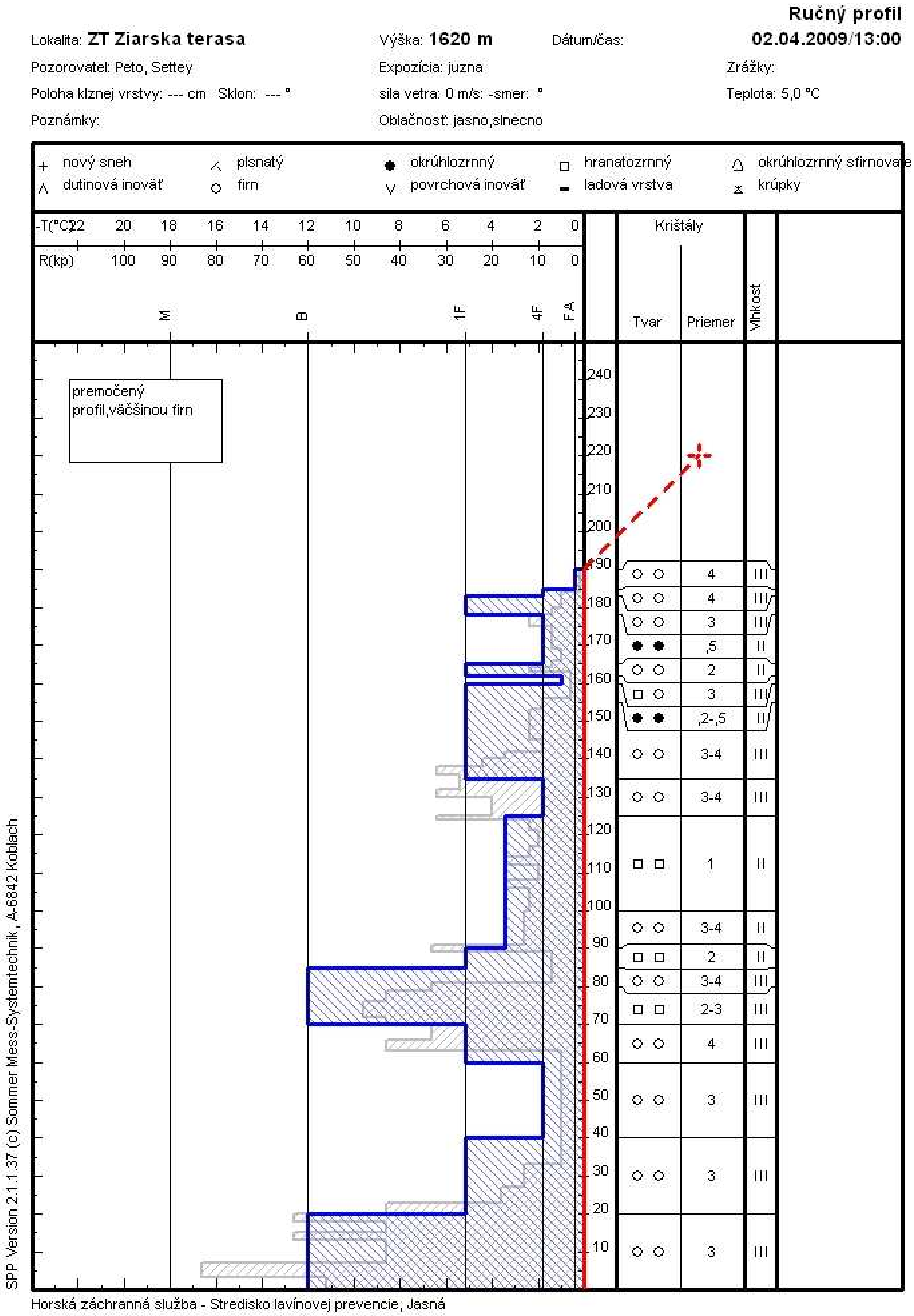
English	Slovak
step-wise regression	postupná (kroková) regresia
stiffness	tuhosť, tvrdosť
striation	ryha, pruhovanie (napr. na kryštáli)
Stuffblock test	test spustením závažia
stump	peň, výčnelok, pahýľ
sunshine duration	trvanie slnečného svitu
surface hoar	povrchová inovať
surface-layer avalanche	povrchová lavína
terminus track length	dosah, dráha, dĺžka lavíny
terrain roughness terrain condition	drsnosť povrchu
tilt board test	test naklonením doštičky
unconfined avalanche	plošná lavína (podľa tvaru dráhy v transportnom pásme)
vegetation	vegetácia (les, lúka, skalný povrch, voľné kamene a skaly)
water equivalent of snow cover snow water equivalent	vodná hodnota snehovej pokrývky
water lubrication	mazanie (medzi snehovými vrstvami) spôsobené stekajúcou vodou
wet-snow avalanche	lavína z mokrého snehu
whumpf	„humf“; zvuk šíriaci sa pozdĺž zlomu pri kolapse snehových dosiek zaťažením
wind direction	smer vetra
wind gust	náraz vetra
wind loading	zavievanie snehu vetrom
wind speed, velocity	rýchlosť vetra
wind vane	veterná lopatka (ružica)
zone of transition track zone	prechodové pásmo, pásmo (dráha) prechodu

E. Weather in February 1983 (example from historical data)

Warm wave at the end of January was changed with heavy cooling on the 2nd Feb. In the following days, relatively windy and cold weather prevailed at higher altitudes. The situation was rather stable, except for the 5th Feb, when snow drifted locally. Considerable avalanche danger was issued on **9th Feb, as a result of intense snowfall that started on the day before and lasted until 13th Feb. However, no large avalanches were recorded**. Surprisingly, during cold and windy period from **17th to 18th, several large avalanches were released (Malý Závrat to the south, from the Lomnický hrebeň ridge into the Malá Studená dolina, Stredohrot over the Halajov žľab)**.
Next period of avalanche danger occurred **from 21st, when numerous avalanches were falling from steep gullies in the afternoon.** The danger was issued until the next morning, and afterward no avalanche was triggered. Local danger lasted until 24th and on 25th it was cancelled in the morning. Much to our surprise, **some avalanches released in places**, especially in mid altitudes **(e. g. z Cmitera do Lievikovej kotliny), as a consequence of warming around noon**. This was the definitive end, and no danger was issued then (it would have been late). On the following day the danger was diminishing because the wet snow had been frozen, and despite the next two sunny days the snowpack remained stable.
Probing was performed in the Veľká Studená dolina and in the Mengusovská dolina regularly, but at Skalnaté pleso it was done only once, because of frequent closure of cableway, windy conditions and closed pathways. Generally, we can conclude that the local avalanche danger remains in certain sites even during periods when it was not issued. This is on account of changeable weather and unevenly distributed snow cover. Also the results from penetration probes made on weekly basis are considerably different.

F. Snow profile

Example of snow profile observed 8 days after the release of climax avalanche in Žiarska dolina, which is the largest avalanche ever observed in Slovakia. The snow in deposit could be evenly filled in a 6 m high basin of surface equal to 47 football fields. www.laviny.sk



G. AWS Webcam

Pictures taken from web-cameras installed on AWS are useful source for the detection and precise dating of avalanches on sample slopes. The pictures are sent in real time to the centre currently on hourly basis. Moreover, the pictures can be found on www.laviny.sk.

Fig. 25: Hrubá kopa, 2008-03-30 12UTC.

Fig. 26: Hrubá kopa, 2008-03-30 14UTC.