

## SYNOPTIC CONDITIONS RELATED TO HEAVY SNOWFALLS IN TATRA MOUNTAINS

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**Abstract:** Synoptic patterns responsible for extreme snowfalls (exceeding 30 cm daily) in the Tatra Mountains were determined. Daily data of snow cover depth in six stations, regarding years 1991-2010, were used. The number of days with snowfalls did not reveal any particular trend in the last 20 years in the Tatra Mountains, apart from the highest elevation, where the seasonal number of days with snowfalls decreased significantly. Synoptic conditions of the abundant snowfalls were characterized using reanalysis data of daily sea level pressure, 500 hPa geopotential heights and grid-based temperature at isobaric level 850 hPa, derived from National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) dataset. Four types of synoptic patterns favorable for heavy snowfalls in the Tatra Mountains were distinguished. Abundant snowfalls require sufficient supply of moisture at low temperature conditions. Cyclonal systems bringing snowfalls located over the central and eastern Europe, may form centers in the north and bring humid air masses from the the Baltic Sea region or in the south. In the latter case, distant humid and warm air masses from Mediterranean region transform on the long way and they meet the colder air coming by the lower stream usually from the closer distance from northern or eastern direction. The described processes signify warm fronts structure, with the active warm and humid air of distant southern origin climbing upwards on the cooler and more stable polar air masses from the north or east. At the same time, blocking anticyclones spread over the Atlantic, suppressing western airflow, dominant in the moderate zone. The results obtained in the study could be useful for forecasting abundant snowfalls in the Tatra Mountains and for predicting the increasing risk of avalanches. Furthermore, they enable to evaluate and explain changes in the snowfall activity in the highest Carpathian range.

**Key words:** Tatra Mountains, snowfall, circulation patterns, temperature, back trajectories

### 1. INTRODUCTION

Snow is an important climatic variable in cold and mountain regions. As a function of two weather variables: temperature and precipitation it is considered to be a sensitive parameter of climate variability and change (Falarz, 2004, Beniston et al., 2011; Lopez-Moreno & Goyette, 2011). At the same time, winter snow cover is important for the environment as it controls numerous environmental and ecological processes (Jonas et al., 2008). Furthermore, it enables to develop economic activities related to winter tourism in mountains (Uhlmann et al., 2009).

Studying appearance of snow, more attention should be paid to abundant snowfalls, which have a negative economic impact on community, causing

traffic hazards, communication problems and even paralyzing the community life. Heavy snowfalls may also trigger environmental damage as a consequence of heavy loads of accumulated snow (Lopez-Moreno & Goyette, 2011).

Extremely heavy snowfall events are a natural hazard in mountains. Like other extreme events, they are by definition rare but still do occur and usually have severe consequences. Abundant snow supply, combined with strong winds and unstable snowpack, contribute to the formation of avalanches. Sometimes snowfalls cause them directly and instantly (Blanchet et al., 2009; Schneebeli & Laternser, 2004). Apart from the environmental damage, avalanches often cause fatalities and economic loss due to property damage, snow removal and human rescue.

Because of an enormous impact of extreme events on environment as well as on economic and social human activities, there has been a growing interest in climatic extremes. Many ways of defining such events has been elaborated (Naveau et al., 2005). Despite many ways of defining and interpreting extreme snowfalls (Blanchet et al., 2009), the value of 30 cm of fresh snow is widely used for mountainous regions as a threshold from which the beginning of snow avalanches is expected (Esteban et al., 2005).

Several previous studies have examined the relationships between atmospheric conditions and snowfalls. Cazacios (1994) studied the statistics of snow storm phenomena in the north part of the Eastern Carpathians and elaborated a case study of severe snowstorms in November 1993. Birkeland & Mock (1996) defined circulation patterns causing abundant snowfalls at Bridger Bowl (Montana, USA). Plaut et al., (2001) studied the links of winter precipitation in the Alps with the large-scale circulation. Esteban et al., (2005) determined several different circulation patterns related to heavy snowfalls in the Pyrenees.

The aim of this study is to find the synoptic patterns responsible for extreme snowfalls in the Tatra Mountains. Closer analysis of atmospheric conditions bringing snowfalls may be useful to predict them and consequently to mitigate avalanche hazards.

## 2. DATA AND METHODS

The analysis concerns the Tatra Mountains, which is the highest range in the Carpathian Mountains. Six stations located along the main range were taken into consideration (Fig. 1). Daily data of snow cover depth in each of the six stations, regarding 20 years 1991-2010, were used. Data from four Polish stations were obtained from the Institute of Meteorology and Water Management and data from two Slovakian stations were kindly supported

by Slovak Hydrometeorological Institute.

Snow depth observations at the meteorological stations are taken once a day at 6:00 UTC (Universal Time Coordinated) with the 1 cm precision. A day when the snow has the depth of  $\geq 1$  cm is considered as the day with snow cover.

For the main purpose of the study, the days during which the depth of snow cover increased by  $\geq 30$  cm in at least one of the six stations used, were selected. Changes in the snow cover depth were calculated by subtracting the snow cover depth of a given day from the snow cover depth of the following day. The amount of 30 cm of fresh snow falling in 24 hours is considered as a threshold from which the avalanche risk increases significantly in most of mountain ranges, including the Tatra Mountains (Esteban et al., 2005).

Relating the occurrence of abundant snowfalls in the Tatra Mountains to synoptic conditions, the 'environment to circulation' approach was applied. In this method, the circulation classification is carried along specific environment-based criteria set for a particular environmental phenomenon, i.e. daily increase in snow cover depth by  $\geq 30$  cm in this case (Yarnal, 1993; Yarnal et al., 2001; Dayan et al., 2012). In order to recognize pressure patterns and circulation conditions, which are favorable for extreme snowfalls, the daily sea level pressure (SLP), 500 hPa geopotential heights (Z500) and grid-based temperature values at isobaric level 850 hPa (T850) data were used. These data were selected from the National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al., 1996).

Firstly, composite maps of SLP and 500 hPa geopotential heights means and anomalies were constructed for the days with the increase in snow cover depth by  $\geq 30$  cm. Anomalies were computed as differences between composite values and multiannual means of the winter season.

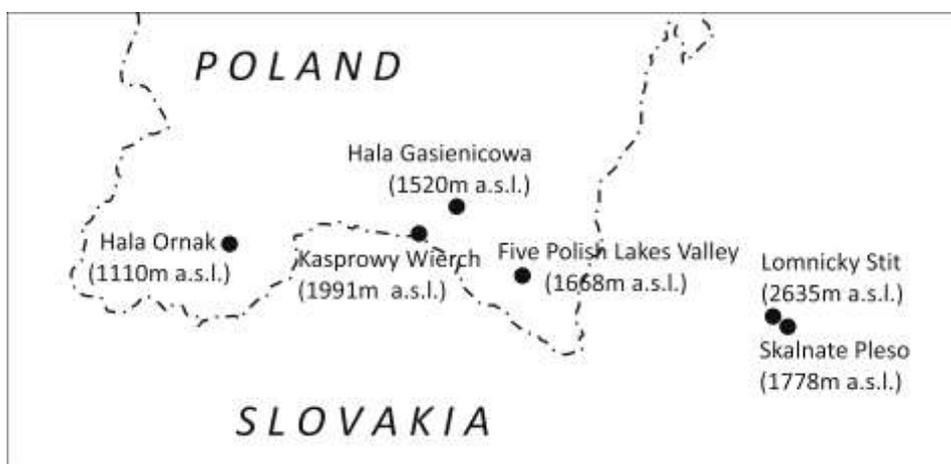


Figure 1. Location and altitude of stations taken to the analysis.

The synoptic area encompasses the region 35-70°N latitude by 35°W-40°E longitude with 2.5° resolution. Additionally, anomalies of T850 were constructed for the area 40-65°N latitude by 0-35°E longitude.

Furthermore, different circulation types were distinguished among the days with heavy snowfalls. First of all, the factor analysis technique, namely the Principal Component Analysis (PCA), was applied to the standardized daily SLP data in order to derive the dominant patterns of the SLP field variability and to reduce the data dimensionality. PCA is often used for interrelated data, such as the SLP field. Next, the Ward's minimum variance method was used to cluster the new components (Ward, 1963).

Both the composite analysis and clustering techniques together with PCA have been used previously to identify the atmospheric circulation patterns associated with heavy snowfalls in the mountains (Birkeland & Mock, 1996, Esteban et al., 2005). The Ward's method chosen in this study is the most frequently used hierarchical clustering technique for climatic classification and for identifying the atmospheric circulation patterns associated with occurrence of specific weather phenomena (e.g. Kalkstein et al., 1987, Esteban et al., 2005, Bednorz 2011).

Finally, back trajectories of air masses for the chosen days with the most effective snowfalls, representing each of the distinguished types, were constructed, using the NOAA HYSPLIT model (Rolph, 2012; Draxler & Rolph, 2012). The model analyzed air masses movement for three altitudes above sea level: 1000 meters (corresponding to the central part of the mixing layer), 2500 meters (corresponding to the mean altitude of isobaric surface 850 hPa) and 5000-5500 meters (corresponding to the altitude of isobaric surface 500 hPa). The analysis of air trajectory at the three altitudes provided significant input to the information obtained from the composite pressure maps and made it possible to identify probable source area of air masses causing abundant snowfalls in the Tatra Mountains. This method is often used to detect the source area of pollution deposit (Avila & Alarcon, 1999; Salvador et al., 2010).

### 3. RESULTS

Snow cover may appear for more than half a year in most analyzed stations. The mean annual number of days with snow cover ranges from 158.7 at the lowest altitude (Hala Gasienicowa) to about 260 days at the highest peak (Lomnický Stit) (Table 1). Low values of the standard deviation computed

for the annual number of snow days suggest small year-to-year variability of snowiness in the Tatra Mountains. The variability coefficient, computed as a ratio of standard deviation to a mean value does not exceed 10%. Nevertheless, the amount of snow expressed as the depth of snow cover is more changeable year-to-year. Mean seasonal depth of snow cover range from about 33 cm (Skalnate Pleso) to 131 cm (Lomnický Stit) and multiannual variability coefficient exceeds 20% or even 30% in some stations. In general, snowiness increases with the altitude. All snow cover statistics achieve the highest values for Lomnický Stit, which belongs to the highest Tatra and Carpathian peaks and also for Kasprowy Wierch which is situated in the Western Tatra Mountains, favorably to prevailing western winds, bringing precipitation. Unlike conditions occur in Skalnate Pleso, which is placed in the rain shadow of Lomnický Stit and therefore obtains less snow than other stations at lower altitudes.

The accumulation of winter permanent snow cover usually starts in October or in the beginning of November. Snow usually persists until the end of April in the lower locations and until the beginning of June in higher stations. During a single winter season there are on the average from 46 (Ornak) to 104 (Lomnický Stit) days with snowfalls, resulting in snow accumulation (Fig. 2).

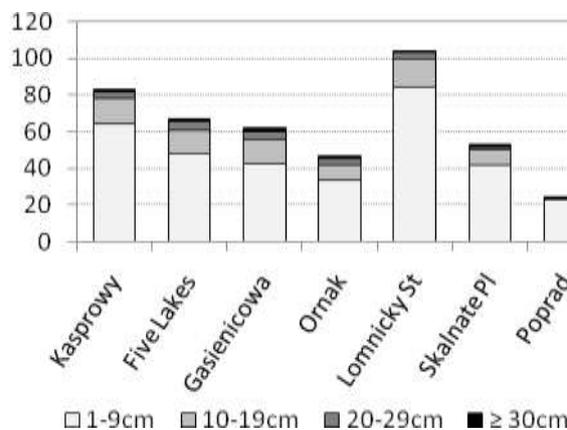


Figure 2. Mean annual number of days with the daily increase of snow cover by a given value, for years 1991-2010.

Most of snowfalls result in the daily increase in snow cover depth by 1-9 cm (several dozen each year in every station). Much less cases of snowfalls bring higher snow accumulation, and there are on the average only one or two cases annually of accumulation exceeding 30 cm. Obviously, there are years, when the days with such abundant snowfalls are recorded in one station a few times in a season, and on the other hand, there are winters, when such abundant snowfalls do not appear at all.

Table 1. The basic statistics of snow cover in analyzed stations, computed for seasons 1991/1992-2009-2010.

Station	Number of days with snow cover		Depth of snow cover		Mean max depth	Abs. max depth
	Mean	Sd. dev.	Mean	Sd. dev.		
Kasprowy Wierch	220.4	15.3	97.2	28.0	221.4	355 (Apr 1995)
Five Polish Lakes	214.5	16.7	99.1	26.2	208.9	320 (Apr 1995)
Hala Gasienicowa	185.9	17.6	71.2	21.4	164.3	267 (Mar 2000)
Hala Ornak	158.7	17.0	51.1	19.0	125.3	210 (Mar 2009)
Lomnicky Stit	260.4	17.9	131.3	31.0	295.6	408 (Mar 2009)
Skalnate Pleso	179.9	13.3	32.8	11.7	90.9	170 (Mar 2009)

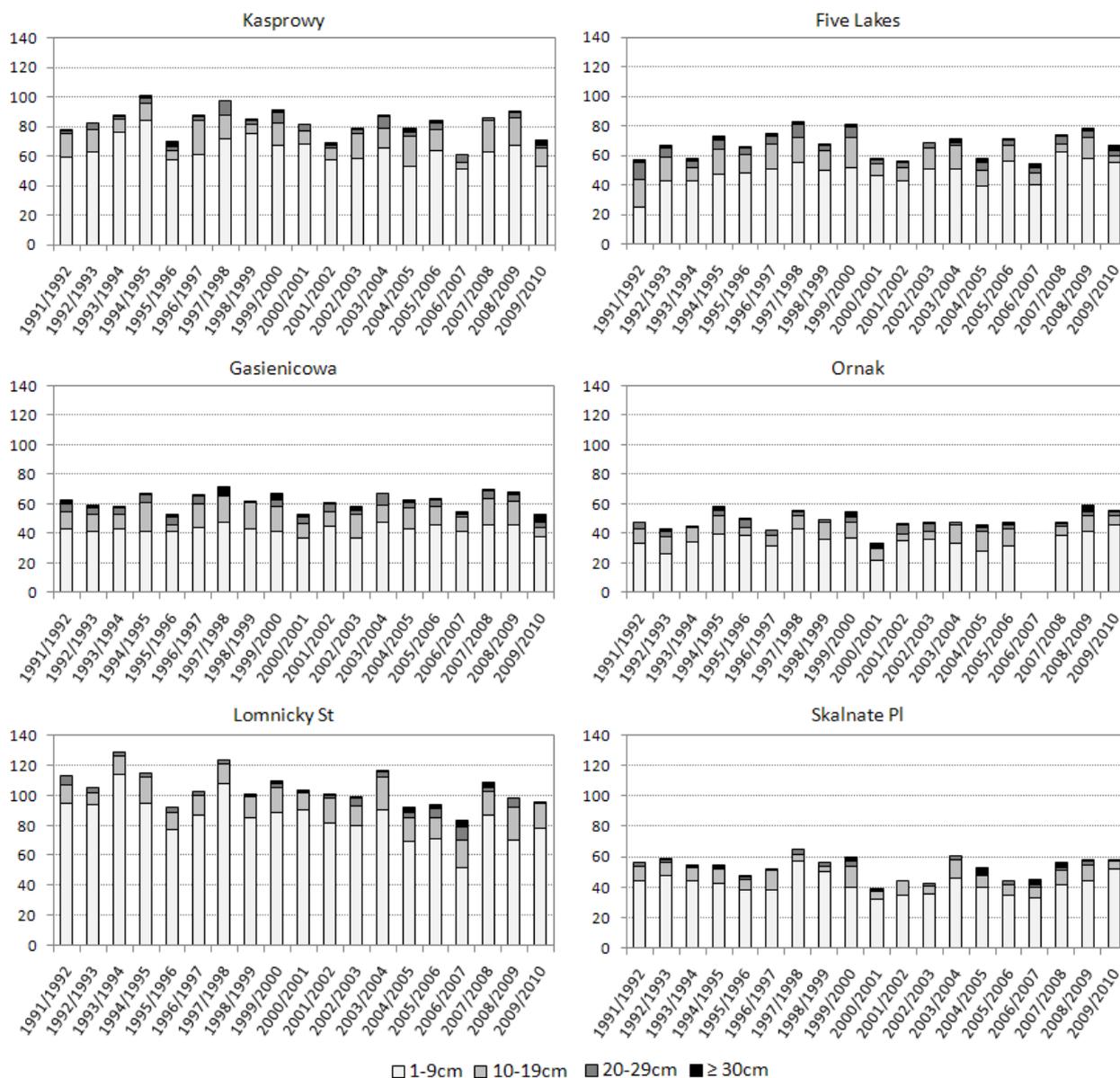


Figure 3. Number of days with snowfalls, causing the daily increase in snow cover depth by a given value.

The year-to-year variability of number of days with a daily increase in snow cover depth by a given value is shown in figure 3. Despite decreasing snow cover depth trend found in the Tatra Mountains (Falarz, 2004), the number of days with snowfalls

did not reveal any particular trend in the last 20 years in most of stations. Only Lomnicky Stit characterizes with a statistically significant trend of changes in the seasonal number of days with snowfalls (-10 days per 10 years).

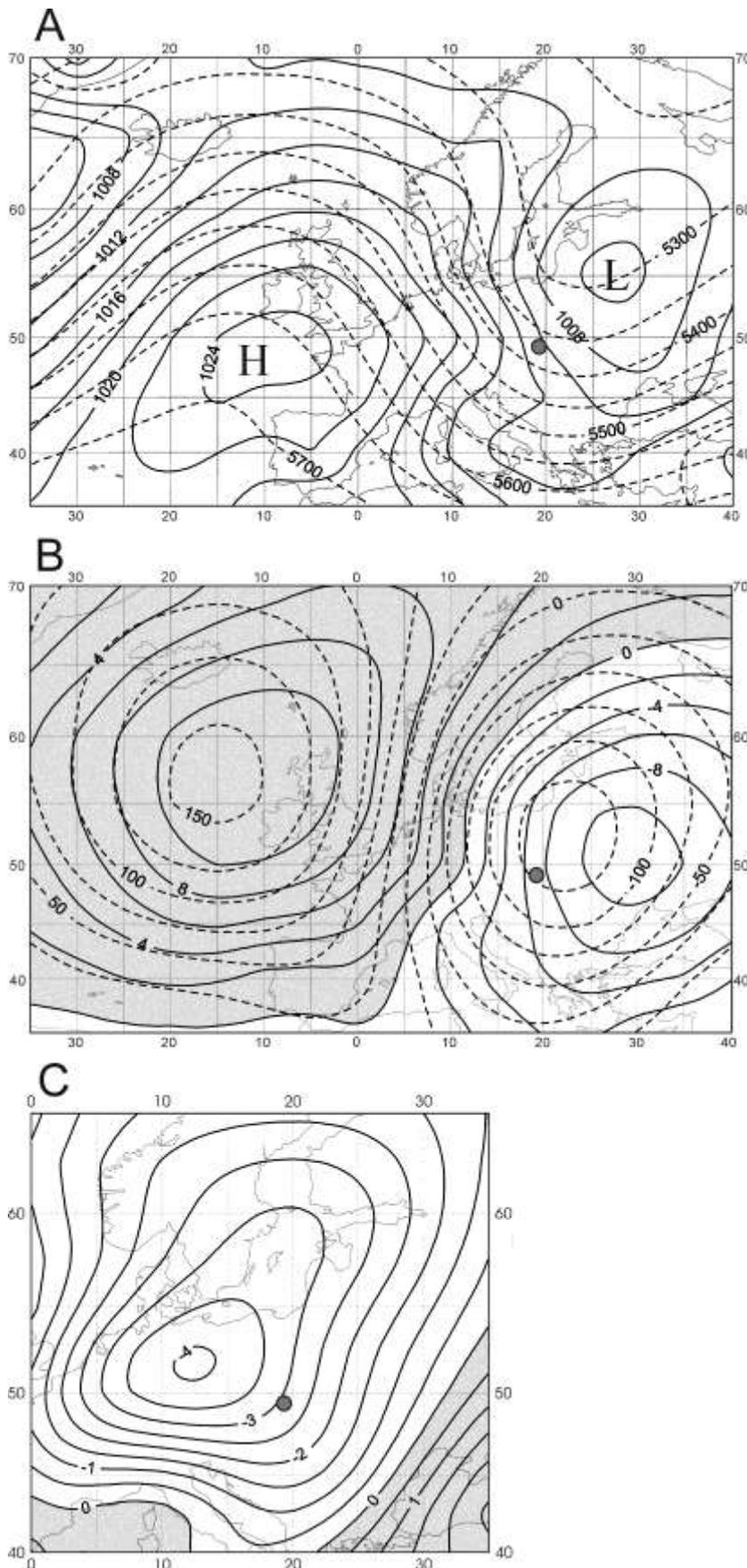


Figure 4. Composite map (A) and anomaly map (B) of SLP (solid lines) and Z500 (broken lines), C – anomaly map of T850 for the days with heavy snowfalls in Tatra Mountains (location marked with a dot).

To recognize the synoptic conditions causing abundant snowfalls in the Tatra Mountains and, accordingly, increasing the risk of avalanches, composite maps and anomaly maps of pressure and thermal conditions over the Euroatlantic sector of Northern Hemisphere were constructed.

Firstly, the days during which snow cover depth increased by  $\geq 30$  cm in at least one of the six stations used, were selected. In the 20-years period there were 110 days fulfilling this condition. A contour map of SLP representing the selected days shows a low pressure system spreading over central and Eastern Europe with its centre located east to the Baltic Sea (Fig. 4A). It is an area of negative SLP anomalies (Fig. 4B).

At the same time, higher-than-normal SLP is observed over Atlantic Ocean and Western Europe. Contours of Z500 bend to the north over the Atlantic and to the south in central Europe, suggesting northerly and northwesterly flow in the middle troposphere over central Europe (Fig. 4B).

A composite anomaly map shows the SLP and Z500 hPa height differences between the selected weather situations (days with snowfalls resulting in snow cover depth increases of  $\geq 30$  cm) and climatic normals for the cold part of the year (Nov-Apr). The interpretation of the contoured composite anomalies is similar to the traditional weather anomaly maps, with clockwise (anticyclonic) flow around the positive centers and counterclockwise (cyclonic) flow around the negative centers (Birkeland & Mock, 1996). Centers of negative anomalies both SLP and Z500 occur right east to the Tatra range and centers of positive anomalies are located west to the British Islands. Consequently, circulation in the days with abundant snowfalls in the Tatra Mountains is characterized by a

strong northerly flow component over central Europe, in contrast to the average western circulation in moderate climate zone (Fig. 4B).

The northern flow brings a cold air to the central Europe and causes negative anomalies of temperature in the lower troposphere, exceeding  $-3^{\circ}\text{C}$  over the vast area west and southwest to the Tatra range (Fig. 4C).

Obviously, the circulation patterns observed during the selected 110 days could not be identical; therefore the attempt was made to cluster them into groups. The PCA together with the clustering technique applied to the SLP data allowed to distinguish four most relevant clusters i.e. types of synoptic situations causing abundant snowfalls in the Tatra Mountains. Again, composite maps of SLP were constructed for each type (Fig. 5).

All types represent congruent patterns of SLP field, with the high pressure in the west and low pressure in the east of the study area. Western anticyclones usually have centers over the British Islands and spread over the entire North Atlantic. In most cases (apart from the type 3) the the Icelandic Low is shifted back from its regular winter location. The distinguished types differ mainly by the location of eastern cyclones.

In the type 1 cyclonic centre spreads meridionally from Scandinavia to Mediterranean, having a centre east to the Baltic Sea. Such pressure system causes strong northerly flow at sea level over central Europe which brings cold air and. Negative anomalies of T850 spread over the Scandinavian Peninsula and central Europe reaching  $-3.5^{\circ}\text{C}$  over Germany.

Northern flow at sea level may be accompanied with counterclockwise direction of airflow at higher levels. The demonstration of such situation is shown at back trajectories at figure 6 drawn for snowstorms on Oct 14-15 2009 (belonging to type 1), which caused increase in snow cover by more than 30 cm in five of six analyzed stations. In the middle troposphere, the air comes from cyclones located over east Mediterranean (green trajectory), providing warm and humid air. Meeting of the northern air, coming at in the low troposphere, and the air of Mediterranean origin in higher levels, results in abundant snowfalls in the Tatra range.

Similar conditions are represented by the type 2 (Fig. 5). However, this time eastern cyclone is deeper (up to 1014 hPa) and its centre locates over the Italian Peninsula. In the lower troposphere air comes from northern and northeastern direction.

It is a very cold air (maybe from continental origin), which is proved by strong negative anomalies of T850 spreading over entire Europe, exceeding  $-5^{\circ}\text{C}$  over Poland and Germany. Again, in the middle troposphere

the air comes from cyclone located over east Mediterranean (green trajectory in figure 6, type 2), which is a reservoir of humidity, necessary for forming snowfalls. The back trajectory representing type 2 was constructed for Feb 05-06 2003, when the snowfalls exceeded the threshold of 30 cm in four of six stations.

The type 3 (Fig. 5) differs from the others by the deep (SLP below 996 hPa in the centre) Icelandic Low. It is located in the regular winter position i.e. southwest to Iceland. In this connection the Atlantic anticyclone reaches only southwestern edges of Europe. The pressure pattern over Atlantic together with the east European cyclone induces northwestern flow of the air masses in the lower troposphere (comp. Fig. 6, type 3). They bring colder-than-normal air over central Europe; anomalies of T850 exceed  $-3^{\circ}\text{C}$  over Poland and Germany. At the same time the upper troposphere air comes from the Mediterranean, providing resources of humidity, prerequisite for snowfalls.

The type 4 is distinguished by a high pressure gradient over central Europe (Fig. 5). It is evoked by a big pressure difference between the strong Azorean High ( $> 1026$  hPa in the centre) and a deep cyclonal system ( $< 998$  hPa in the centre) spreading northeast to Poland. Negative anomalies of temperature cover the entire northern and central Europe, exceeding  $4.5^{\circ}\text{C}$  over the Baltic Sea, which becomes this time a source of humidity, as the northern flow is observed in the entire tropospheric profile (Fig. 6, type 4).

#### 4. DISCUSSION

Most studies on snow cover in European mountainous regions suggest that in recent climate changes towards warmer and wetter conditions, snow cover will tend to decrease, particularly at lower altitudes (Uhlmann et al., 2009; Laternser & Schneebeli, 2003; Beniston et al., 2011; Lopez-Moreno & Goyette, 2011). In the Tatra Mountains increasing trend of snow cover duration was observed in the 20<sup>th</sup> century, together with decreasing trend of snow cover depth (Falarz, 2004). However, the last years of the 20<sup>th</sup> century characterized with significant decrease in nival conditions in the Tatras (Żmudzka, 2011). In this study the deteriorating snow conditions were confirmed only in the highest elevation, where the seasonal number of days with snowfalls decreased significantly.

Snow occurrence is determined by the air temperature, precipitation and, indirectly, by atmospheric circulation. Therefore, studying the reasons of long- or short- term changes in snow occurrence, synoptic conditions of snowfalls and snow persistence should be considered.

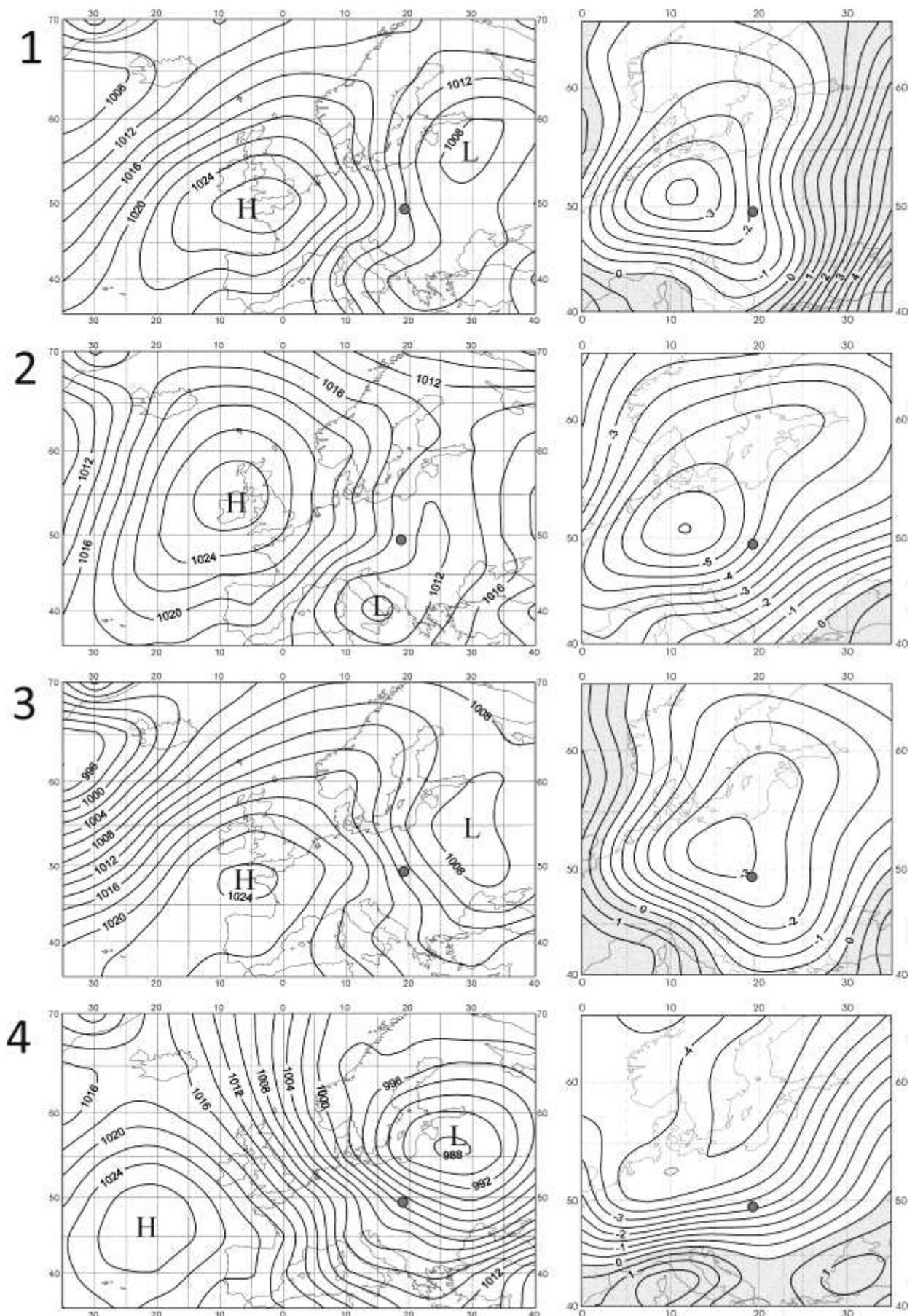


Figure 5. Four circulation types distinguished among the days with the increase in snow cover depth of  $\geq 30$  cm. Left column – SLP, right column – anomalies of T850 (positive values are shaded).

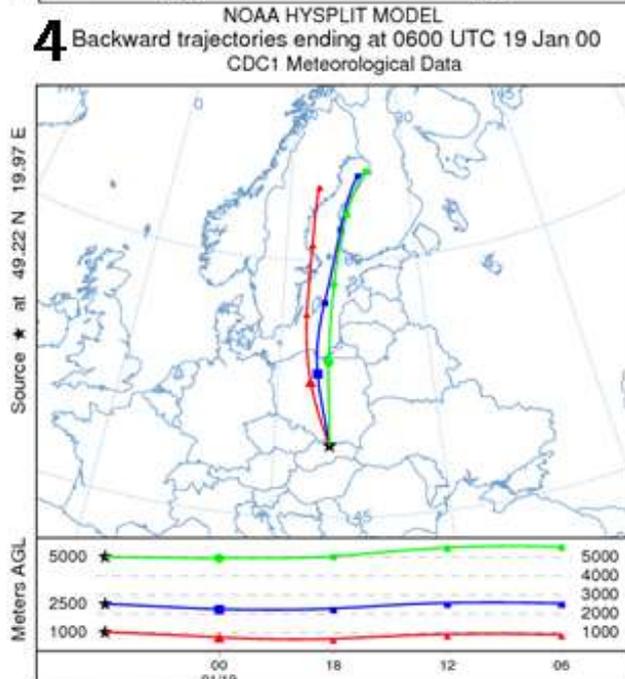
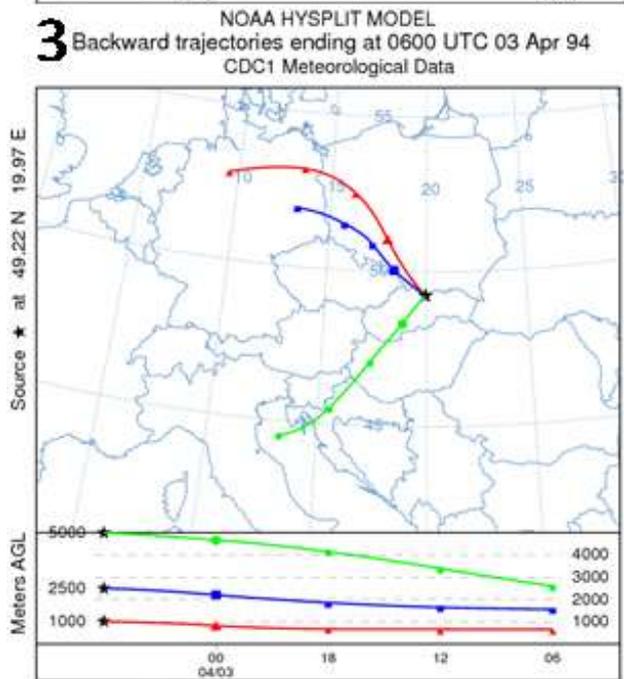
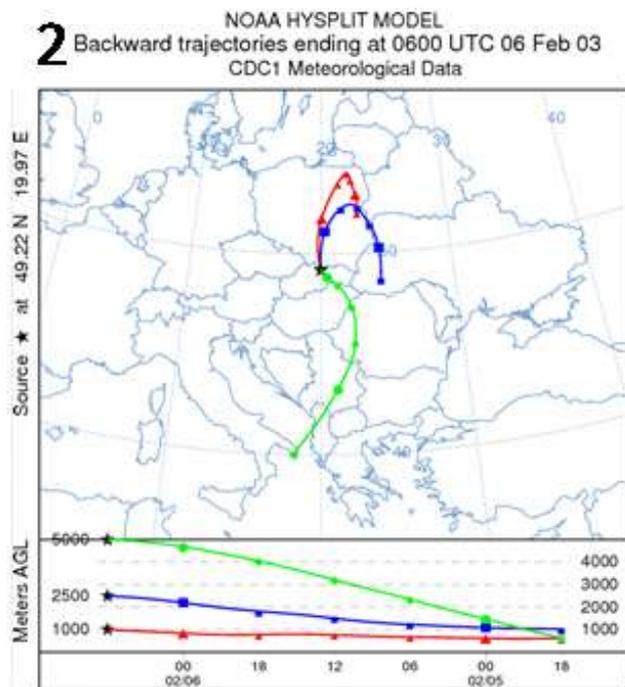
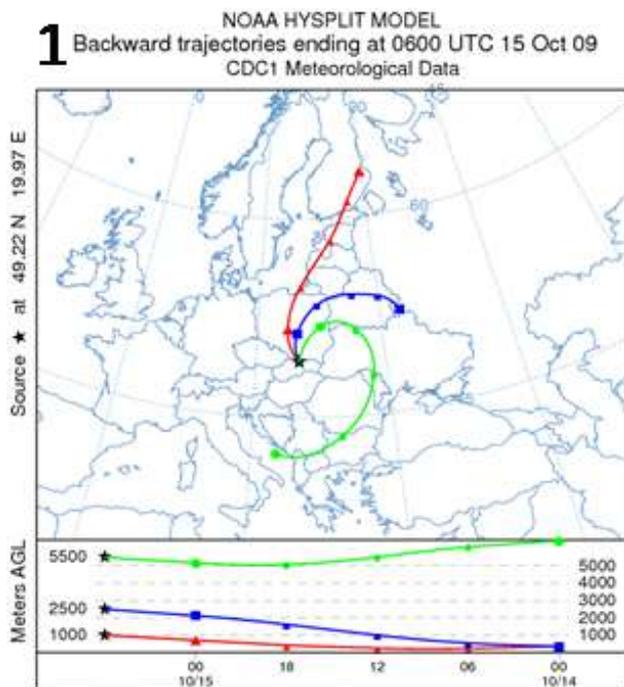


Figure 6. The 24-hours back trajectories for chosen days with heavy snowfalls in Tatra Mountains, representing the distinguished types (1-4).

Abundant snowfalls require sufficient supply of moisture at low temperature conditions. For the Tatra Mountains there are two reservoirs of moisture: Mediterranean or Baltic Sea region. Cyclonal systems bringing snowfalls located over the central and eastern Europe, may form centers in the north and bring humid air masses from the Baltic Sea region. Cyclonic centers may also form in the south. In this case, distant humid and warm air masses from Mediterranean region transform on the long way and they meet the colder air coming by the

lower stream usually from the closer distance from northern or eastern direction. Meeting of these two different elements results in heavy snowfalls in the Tatra Mountains. The described processes signify warm fronts structure, with the active warm and humid air of distant southern origin climbing upwards on the cooler and more stable polar air masses from the north or east. At the same time, blocking anticyclones spread over the Atlantic, suppressing the western airflow, dominant in the moderate zone. Similar circulation patterns related to

intense snowfalls in Austria were postulated by Spreitzhofer (1999a, 1999b, 2000). One pattern, with a low over the Baltic Sea and the high over Iberian Peninsula induced northwesterly flow and the other, with a low-pressure system over the western Mediterranean remains above-mentioned conditions. In turn, Esteban et al., (2005), defining atmospheric circulation conditions related to heavy snowfalls in Pyrenees, recognized blocking anticyclone over Atlantic in most defined pressure patterns.

## 5. CONCLUSIONS

The number of days with snowfalls did not reveal any particular trend in the last 20 years in the Tatra Mountains, apart from the highest elevation, where the seasonal number of days with snowfalls decreased significantly.

Occurrence of snowfalls in Tatra Mountains is strongly determined by circulation conditions, namely low pressure systems appearing in Eastern Europe and high pressure in the west. Consequently, circulation in the days with abundant snowfalls is characterized by a strong northerly flow component over central Europe, in contrast to the average western circulation in moderate climate zone. The northern flow brings a cold air to the central Europe and causes negative anomalies of temperature in the lower troposphere, over the vast area west and southwest to the Tatra range. The location of eastern cyclones, causing abundant snowfalls may be different and they may form centers in the north and bring humid air masses from the Baltic Sea region or in the south, bringing humid and warm air masses from the Mediterranean region. At the same time, blocking anticyclones spread over the Atlantic, suppressing the western airflow, dominant in the moderate zone.

Circulation patterns favourable for abundant snowfalls in Tatra Mountains, which were established, described and depicted in the maps in this study, could be useful for forecasting abundant snowfalls and predicting the increasing risk of avalanches in the Tatra Mountains. Furthermore, they enable to evaluate and explain changes in the snowfall activity in the highest Carpathian range.

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