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# Snow cover in the Ukrainian Carpathians

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Based on the results of regular monitoring during 1961–2020, the main features of snow cover in the Ukrainian Carpathians were determined. The observation data at the meteorological stations, mainly located at high altitude, show an increasing trend in snow cover depth in winter and in the first half of spring. At the same time, there is a decrease in snow cover duration at low altitudes and an increase at high altitudes. General trends for the mountain area are higher air temperature and lower wind speed. Simultaneously precipitation changes are small or absent. It has been shown that decrease of wind speed over the last decades should be taken into account to determine the actual changes in snow cover. As a result of this decrease, the snow cover depth in the mountains became more uniform than at the beginning of the observations: larger on mountain tops and smaller in ravines and mountain forests. This means that in general, the snow cover depth and snow water equivalent in the mountains are stable. This was confirmed by the fact that during spring flood the water runoff of local rivers remained without essential changes.

KEY WORDS: snow cover, air temperature, precipitation, wind speed, river runoff, the Ukrainian Carpathians

## Introduction

Climate change in the mountains, in particular of air temperature and snow cover is a popular issue of many scientific studies. Their results showed a trend towards temperature increase (Holko et al., 2020; Marin et al., 2014; Marty and Meister, 2012; Migala et al., 2016; Tomczyk et al., 2021; Vyshnevskyi and Donich, 2021). This increase has been accelerating in recent decades. In particular, the winter of 2019/2020 in Central Europe was much warmer than usual. This could not but affect the snow cover.

The increase of air temperature can give ground for considering a possible decreasing trend in snow cover depth. At the same time, the changes of snow cover depth and its duration are not quite obvious, partly due to essential variability of these parameters. Moreover, in some cases, research results are contradictory.

The study (Tomczyk et al., 2021) showed the decrease in the number of days with snow cover for the most of Poland, except for the mountain region, where there was an increase, but not statistically significant. A decrease in snow cover depth was determined at low, and an increase − at high altitudes. The authors (Tomczyk et al., 2021) consider that the duration of snow cover strongly depends on the temperature, and the snow cover depth depends on the amount of precipitation in the form of snowfall.

Some other results were obtained for the neighboring area in the Tatra Mountains (Holko et al., 2020). At the station, located at an altitude of 1778 m a.s.l, there is a slight declining tendency of snow cover and at the station with an altitude of 1991 m a.s.l. no changes are noticeable. Simultaneously the duration of snow cover at both stations remained unchanged. A decreasing tendency for the snow cover and the water in it during 1951–2017 was obtained in a study (Fontrodona et al., 2018) on the main part of Europe. At the same time for the coldest areas in Europe, an increase in mean and maximum snow depths is observed. The study (Bulygina, et al., 2009) carried out as to territory of Russia showed the decrease of snow cover on its larger part except Central Siberia and the coast of the Sea of Okhotsk, where it increased. Negative temporal trends in snow cover depth were found in Norway for low altitude stations and positive trends were indicated for the stations over 850 m a.s.l. (Skaugen et al., 2012). Studies (Marty and Meister, 2012) in the Swiss Alps found no changes in snow depth in mid-winter. However, there is a decreasing trend in snow cover depth during the snowmelt period in the spring and summer months.

The dependence of snow cover parameters on important factors has been studied in (Malgorzata, 2002). It was determined that in mountain conditions they have a worse correlation than in lowland ones.

Some studies of snow cover are grounded on remote sensing data. The article (Notarnicola, 2020) contains the statement about significant negative trends in snow area and snow cover depth in the European Alps and the Carpathian Mountains during 2000–2018. The same results were shown in the study (Dong and Menzel, 2019) carried out for the central European region covered by low mountains.

The precipitation, in particular, in the cold period, generally did not change essentially (Repel et al., 2021; Rožnovský et al., 2020; Kubiak-Wojcicka, 2020).

Many studies show the decrease tendency of wind speed (Birsan et al., 2020; Marin et al., 2014; Spinoni et al., 2015; Vyshnevskyi and Donich, 2021). It is important that the decrease of maximum monthly wind speed exceeds the decrease of mean monthly wind speed. This decrease is more pronounced during the months with the highest wind speed (Birsan et al, 2020).

The study (Grünewald et al., 2014) shows the possibility of wind to redistribute the snow from exposed to sheltered locations. The erosion of snow by the wind is the largest at high altitudes, as wind speed increases with elevation.

Despite some climate changes, in particular snow cover, the river runoff during spring flooding is rather stable. In some European regions there is a trend towards earlier spring floods, in some – to later ones (Blöschl et al., 2017). The studies (Halmová and Pekárová, 2020; Holko et al., 2020; Gorbachova et al., 2018; Bačová Mitková and Halmová, 2020; Mostowik et al., 2019) show that the changes of maximum discharges and runoff volume during spring flood in the Carpathians Mountains are small or absent. As can be seen, there is a problem with finding factors that affect both snow cover and river runoff during spring flood. In our opinion, the uncertainty regarding changes in snow cover depth and river runoff is due to ignoring of some factors, including the changes of wind speed during the last decades. So, the main goal of this study is to specify the real changes in snow depth in the Ukrainian Carpathians as an important factor influencing river runoff.

## The study area

The studied area of the Ukrainian Carpathians is the central part of the Carpathian Mountains. The total length of these mountains is about 240 km, the width is 50 km, the largest altitude is 2061 m a.s.l. (Hoverla Mountain). The characteristic feature of these mountains is the presence of ridges, which go almost parallel to each other. The highest ridge, where Hoverla Mountain is located, has the name of Chornohora or Chornohirskyi Ridge. The second by altitude is Svidovets Ridge with the highest altitude of 1883 m a.s.l., located a little bit northwest from Chornohirskyi Ridge. The volumetric image of the Ukrainian Carpathians, created on the basis of Shuttle Radar Topography Mission (SRTM) digital elevation model, is shown in Fig. 1.

## Methodology and data

In the Ukrainian Carpathians there are about a dozen meteorological stations at different altitudes. Only two of them are located at a rather high altitude. The first station Plai is located on the southwestern macroslope of the mountains; its altitude is 1331.5 m a.s.l. The second station Pozhezhevska with the altitude of 1451 m a.s.l. is located on the northeastern macroslope on the distance 2.6 km from Hoverla Mountain. The other stations are located at low-mountain terrain; their altitudes range from 432 to 762.5 m a.s.l. Typically, these stations are located in river valleys on the outskirts of local towns and villages (Table 1).

In addition to measuring the parameters of the snow cover parameters (dates of its formation, depth and dates of its disappearance), these meteorological stations measure many other parameters: air temperature,

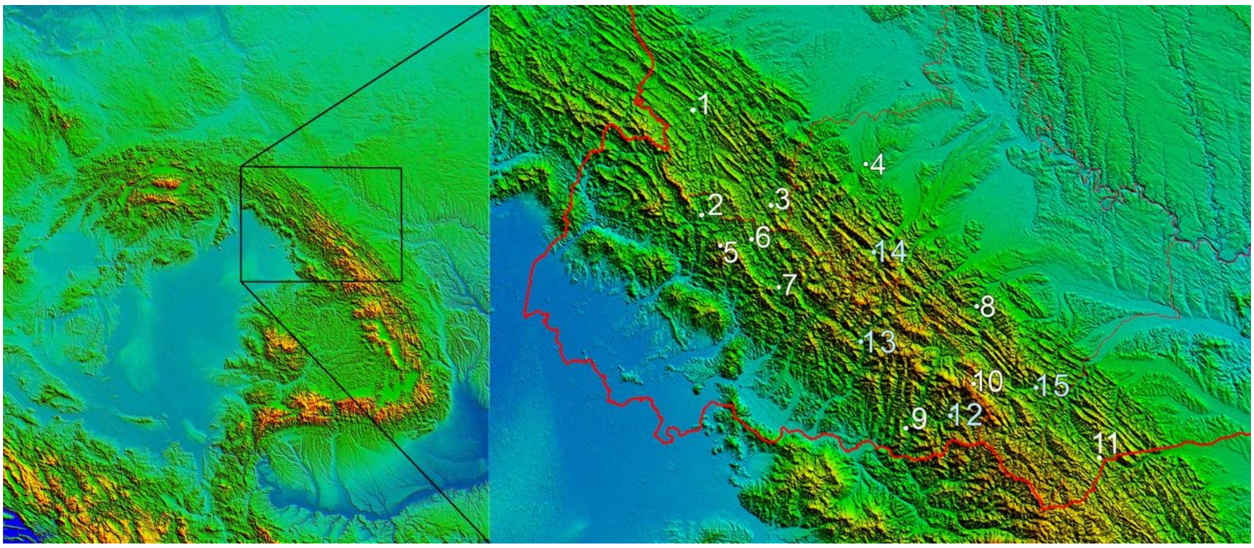


*Fig. 1. Volumetric image of the Carpathian Mountains with location of the meteorological stations in its Ukrainian part (1 – Turka, 2 – Nyzhni Vorota, 3 – Slavske, 4 – Dolyna, 5 – Plai, 6 – Nyzhnii Studenyi, 7 – Mezhihiria, 8 – Yaremche, 9 – Rakhiv, 10 – Pozhezhevska, 11 – Seliatyn) and studied hydrological stations (12 – Bila Tysa – Luhi, 13 – Teresva – Ust-Chorna, 14 – Limnitsa – Osmoloda, 15 – Chornyi Cheremosh – Verkhovyna).*

precipitation, wind speed, etc. Relevant meteorological parameters were processed for the period 1961–2020. In many cases the data for the periods of 1961–1990 and 1991–2020 were analyzed separately.
Certain attention was also paid to the river runoff – mainly to the inner year distribution. Changes in river runoff and possible factors that may cause them were analyzed. The remote sensing data (mainly of Landsat satellites) were also used in the study.

## Results

### *Snow cover depth*

The largest snow depth in the Ukrainian Carpathians is observed at the meteorological stations Plai and Pozhezhevska, located at the largest altitude. During 1991–2020 the mean snow depth at the meteorological station Plai in the third decade of February, when it is the largest, is 47 cm. In turn, the mean snow depth at the meteorological station Pozhezhevska in the third decade of March, when it is the largest, reaches 43 cm. The mean snow depth among the largest measured values at these meteorological stations is 74 and 79 cm respectively.
During 1991–2020 the largest snow depth was registered at the end of the cold and snowy winter of 1998/1999. That winter the mean snow depth among the largest measured ones at 11 meteorological stations was 106 cm. The lowest value was observed in winter 2015/2016, when it was 20 cm.
The available data show that snow cover depth during the period of 1961–2020 slightly changed. At stations located in low-mountain terrain a small snow depth decrease is observed in December and January. Simultaneously, is observed a small increase during the period from February till the middle of April. The changes at the highest stations are much more obvious. There is a significant increase in snow cover depth, especially in winter and in the first half of spring (Fig. 2).
As can be seen in Fig. 2, the largest snow cover depth in the last three decades is observed somewhat later than before. The obtained result gives possibility to make the conclusion that snow cover depth in the Ukrainian Carpathians has an increasing trend. This result coincides with results published in the articles (Tomczyk et al., 2021; Skaugen et al., 2012), but it is different from other ones obtained in other regions – mainly at lowland conditions. Therefore, this issue is considered in more detail in the discussion. The relationship between snow cover depth and snow cover duration at the neighboring stations is generally weak. It is stronger for the snow cover duration and it is weak (almost absent) when concerning the snow cover depth.

**Table 1. The parameters of meteorological stations in the Ukrainian Carpathians**

| № | Name | Altitude [m a.s.l.] | Latitude | Longitude |
|---|---|---|---|---|
| 1 | Turka | 592.4 | N49°09'01" | E23°01'47" |
| 2 | Nyzhni Vorota | 488.7 | N48°46'30" | E23°05'52" |
| 3 | Slavske | 593.6 | N48°50'31" | E23°26'57" |
| 4 | Dolyna | 467.6 | N48°58'37" | E23°59'52" |
| 5 | Plai | 1331.5 | N48°40'03" | E23°11'53" |
| 6 | Nyzhnii Studenyi | 611.4 | N48°42'04" | E23°21'57" |
| 7 | Mezhihiria | 455.4 | N48°31'37" | E23°30'17" |
| 8 | Yaremche | 531.3 | N48°27'10" | E24°33'12" |
| 9 | Rakhiv | 432.1 | N48°02'52" | E24°11'54" |
| 10 | Pozhezhevska | 1451 | N48°09'14" | E24°32'04" |
| 11 | Seliatyn | 762.5 | N47°52'36" | E25°12'59" |

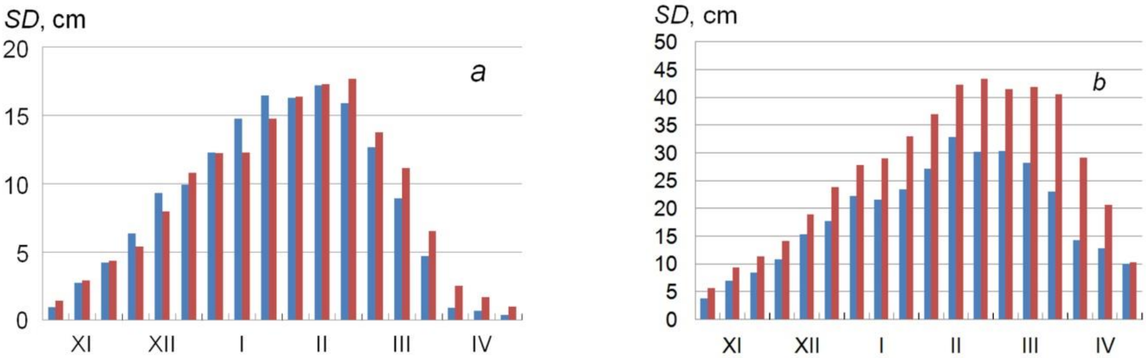


*Fig. 2. The mean snow depth in the Ukrainian Carpathians: a) – at 9 meteorological stations in low-mountain terrain, b) – at highest Plai and Pozhezhevska stations; left columns – during 1961–1990, right columns – during 1991–2020.*

***Snow cover duration***

Data on snow cover, as well as data on the formation, duration and disappearance of snow cover depend on the altitude. This dependence is much stronger than the dependence on latitude. The longest snow cover duration (SCD) is observed at the highest meteorological stations Plai and Pozhezhevska, where during 1991–2020 it was 157 and 158 days, respectively. In the previous period of 1961–1990 this duration at both stations was the same – 153 days. Thus, we see a small increase. The increasing trend in the snow cover depth and duration at Pozhezhevska station in 1961–2010 was also identified in the study (Błażejczyk and Skrynyk, 2019).

The snow cover duration at the meteorological stations in low-mountain terrain is much smaller. Thus, at Mezhihiria station (southwestern macroslope of the mountains) in 1961–1990 it was 99 days, in 1991–2020 it was 92 days. In turn, at Yaremche station (notheastern macroslope of the mountains) in 1961–1990 it was 98 days and in 1991–2020 it was 91 days. Over the last 30 years, a decrease in the duration of snow cover has been observed at all low-lying meteorological stations (Fig. 3).

The snow cover duration correlates with the cold period duration, which at low altitude commonly lasts from December till February and at high altitude − from the second part of November till the end of March. Very long period with snow was observed in cold period of 1995–1996, which was caused by the cold November in 1995. That winter the snow cover duration at Pozhezhevska station reached 185 days. On the other hand, the shortest periods were observed in cold periods 2000–2001 and 2019–2020. During winter of 2019–2020 the mean air temperature at the meteorological stations, located at low altitude, was higher than 0°C. As a result, the snow cover duration was about twice shorter than usual.

The snow cover in the mountains was studied with the use of satellite images of Landsat satelites, which have spatial resolution 30 m. The available satellite images prove the essential impact of altitude on snow cover formation and melting. Generally, the formation of snow cover starts on the Chornohorskyi Ridge, which is the highest. Almost simultaneously, it is formed on the Svydavets Ridge, which is located nearby – a little bit to the northwest. The longest duration of snow cover is observed on these ridges as well (Fig. 4).

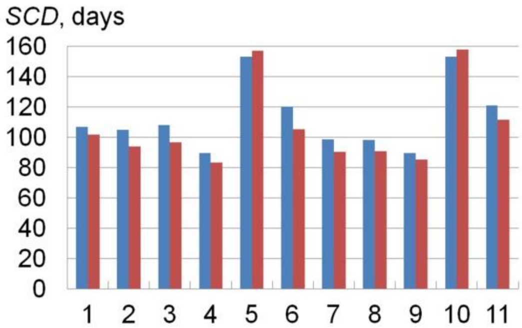


*Fig. 3. The snow cover duration at meteorological stations in the Ukrainian Carpathians: 1 – Turka, 2 – Nyzhni Vorota, 3 – Slavske, 4 – Dolyna, 5 – Plai, 6 – Nyzhnii Studenyi, 7 – Mezhihiria, 8 – Yaremche, 9 – Rakhiv, 10 – Pozhezhevska, 11 – Seliatyn; left columns – during 1961–1990, right columns – during 1991–2020.*

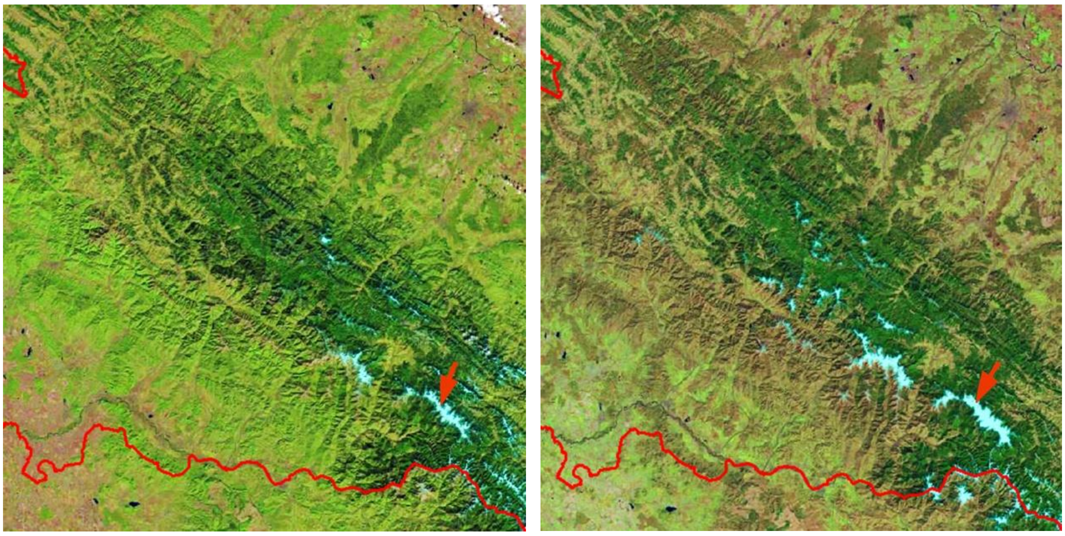

*Fig. 4. The snow cover in the Ukrainian Carpathians: on the left – on 05.10.2013, on the right – on 30.03.2014 (the Chornohirskyi Ridge is shown by arrow).*

In cold spring, snow cover in the mountains can be observed until May or even until the first half of June. In particular, the existence of snow can be seen in a satellite image obtained on June 11, 1985. At this time, the remnants of snow are observed not on the mountain tops, but on their northern and northeastern slopes. This fact is confirmed by actual observations and satellite images. A study (Vyshneskyi and Shevchuk, 2017), conducted using the thermal channel B10 of the Landsat 8 satellite, showed that the lowest surface temperature in the day time is observed on the northern and northeastern slopes of the mountains.

***Air temperature***

Among factors which influence snow cover depth is air temperature. As in many regions in the world, in the Ukrainian Carpathians a vivid increasing trend in air temperatures is observed. That refers the stations located both at low and high altitude (Fig. 5).
As can be seen on Fig. 5, the increase in mean air temperature during the period of 1961−2020 is about 2°C. The increase at the meteorological stations, located at the low altitude, is some larger than those ones located at the high attitude.
The mean annual air temperature at all 11 meteorological stations in 1961–1990 was 5.6°C, and in 1991–2020 it was 6.6°C.
Considering the question of snow cover depth, it is important to analyze the air temperature in the cold period. These data show that the increase of air temperature at low altitude is larger, than at high altitude. At the same time, at high altitudes, the increase in air temperature in summer is more noticeable (Fig. 6).
The similar results as to the seasonal features were described in many other papers (Rangwala and Miller, 2012; Spinoni et al, 2015). The study (Rangwala and Miller, 2012) showed that in the Swiss Alps the rate of temperature rise in the summer period is the largest and in the autumn period is the lowest.
The increase in temperature in January (the coldest month of the year) at the stations, located at a rather small altitude, in most cases has the range of 0.5–0.6°C per decade. In turn, at the highest stations Plai and Pozhezhevska the increase is much smaller – 0.15–0.2°C per decade.

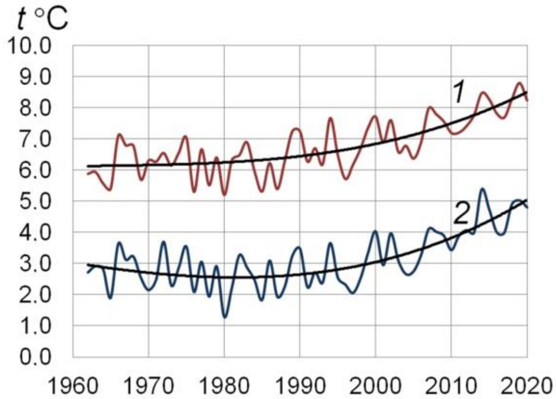


*Fig. 5. The increase in mean annual air temperature in the Ukrainian Carpathians during 1961–2020: 1 – at 9 meteorological stations, located at the low attitude, 2 – at two ones, located at the high attitude.*

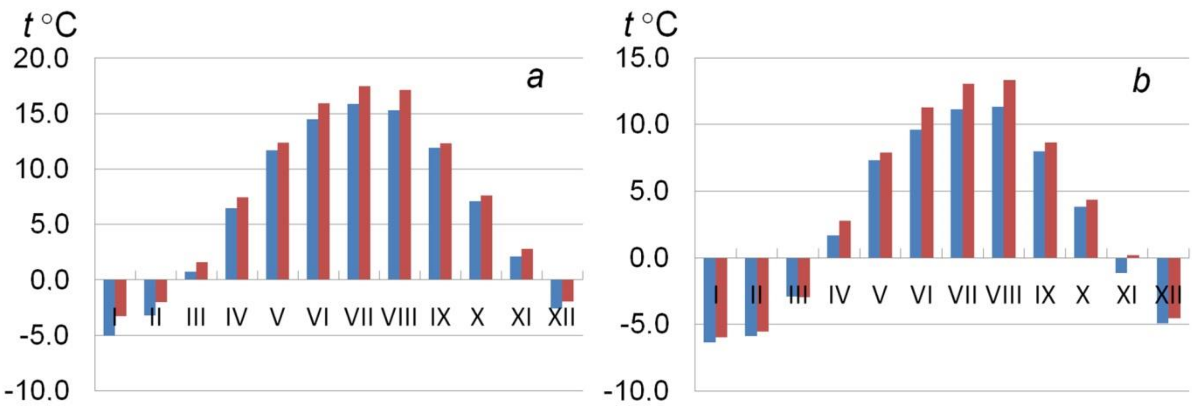


*Fig. 6. The increase in mean monthly air temperature in the Ukrainian Carpathians: a) – at 9 meteorological stations, located in low-mountain terrain, b) – at highest Plai and Pozhezhevska stations. Left columns – during 1961–1990, right columns – during 1991–2020.*

The increase in air temperature has some impact on the plants, in particular on the forest. On the large altitude it is observed the increase of forest area. In particular it can be seen in satellite images of the surrounding of the Pozhezhevska station (Fig. 7).

***Precipitation***

Another factor which has influence on the snow depth is precipitation. This parameter in the Ukrainian Carpathians is uneven in space and in time. It depends on the altitude and location of the meteorological stations as to the mountains ridges. The largest amount of annual precipitation is observed at the meteorological stations Plai and Pozhezhevska, which are at the largest altitudes. During 1961–1990, the mean amount of precipitation at these stations was 1641 and 1436 mm, in 1991–2020, respectively, 1451 and 1536 mm. At the same time, the lowest precipitation is observed at the meteorological stations Dolyna and Seliatyn, where it is about 1.5 times smaller. Generally, the changes in the amount of precipitation during 1961–2020 are not large (Fig. 8).
The comparison of data for the periods of 1961–1990 and 1991–2020 shows the small increasing trend in the amount of precipitation in February and March that can be the reason of snow cover increase in this period. At the same time, these changes are not statistically significant.
The tendency of winter precipitation increase is also observed in the Bieszczady Mountains, located to the northwest of the Ukrainian Carpathians (Mostowik et al., 2019).

***Wind speed (WS)***

The important factor which can influence the snow cover depth is the wind speed. Nevertheless, this influence is generally ignored. However, its value in the mountains is much larger (about twice or even more) than at the lowland. At the Pozhezhevska meteorological station the mean annual wind speed in 1991–2020 was 5.5 m $s^{-1}$ or about twice larger than at lowland. Almost the same is the wind speed at Plai station – 5.3 m $s^{-1}$. It is important that during the observation period started in 1961, wind speed essentially decreased. This decrease is observed throughout the year, but in the second half of the year it is the largest (Fig. 9). The decrease of wind speed is observed at low located stations as well, but the changes are smaller, than at the high located stations.
The similar results as to the decrease in wind speed were

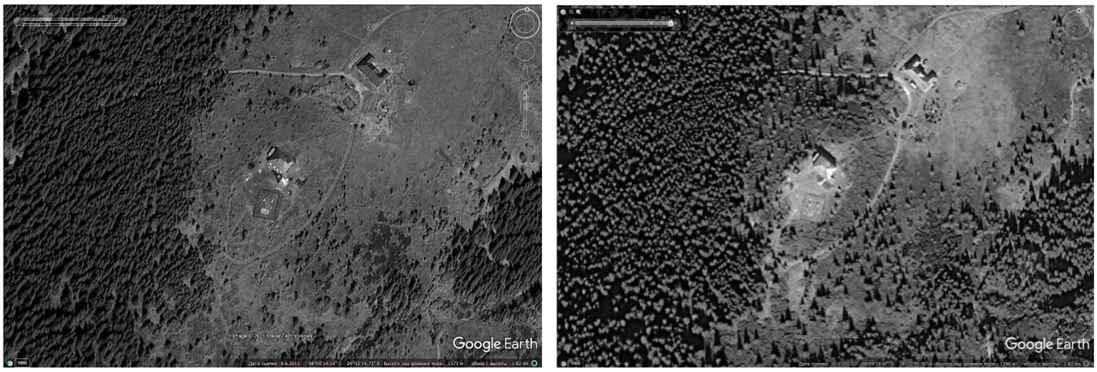


*Fig. 7. The changes of forest spread nearby Pozhezhevska station (in the centre): on the left – on 06.08.2011, on the right – on 01.10.2017.*

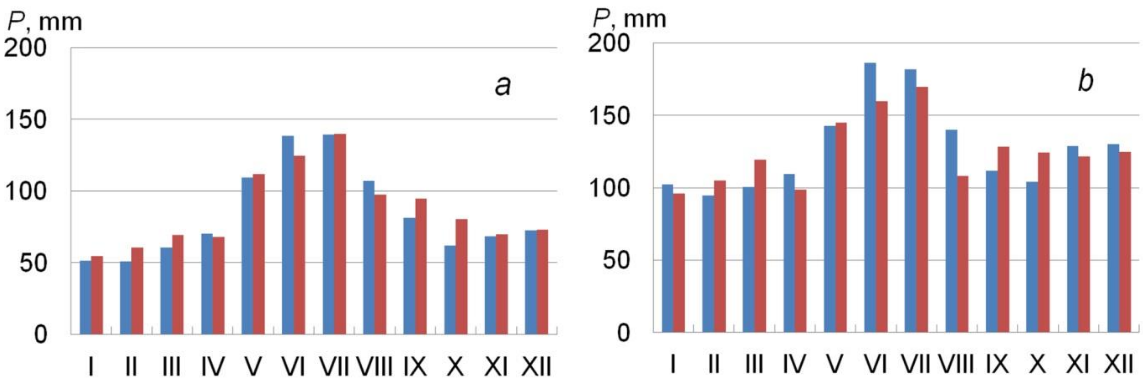


*Fig. 8. The mean monthly amount of precipitation in the Ukrainian Carpathians: a) – at 9 meteorological stations, located in low-mountain terrain, b) – at highest Plai and Pozhezhevska stations. Left columns – during 1961–1990, right columns – during 1991–2020.*

obtained in many other regions of the world including the Carpathian Mountains (Birsan et al., 2020; Marin et al., 2014; Spinoni et al., 2015).

***The river runoff***

The analyses of river runoff can help to evaluate the obtained results as to the changes of snow cover depth in the Carpathian Mountains. It would be logical to assume that the increase of snow cover depth must cause the increase of river runoff during the spring flood.
In order to evaluate the impact of snow cover changes on the river runoff the data of 4 local rivers with rather high river basins were processed. Two river basins (Bila Tysa – Luhi and Teresva – Ust-Chorna) are located on the southwestern macroslope and two ones (Limnitsa – Osmoloda and Chornyi Cheremosh – Verkhovyna) are located on the northeastern macroslope. The mean altitude of these river basins has range 1100–1200 m a.s.l. The available data of these rivers show that water runoff during spring flood practically did not change. At the same time, there is small increase in period January–March. The changes of runoff volume during the period from March till May in a whole are very small (Fig. 10).

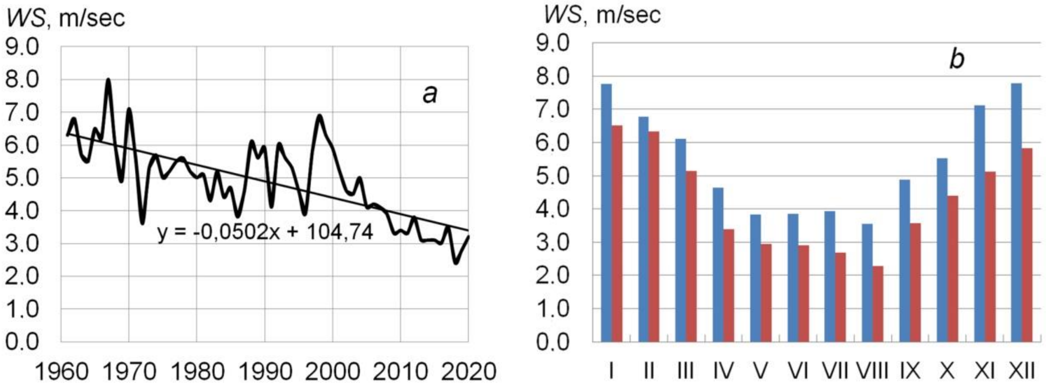


*Fig. 9. The changes of wind speed at the Pozhezhevska station: a) – mean annual values, b) – by months (left columns – 1961–1990, right columns – 1991–2020).*

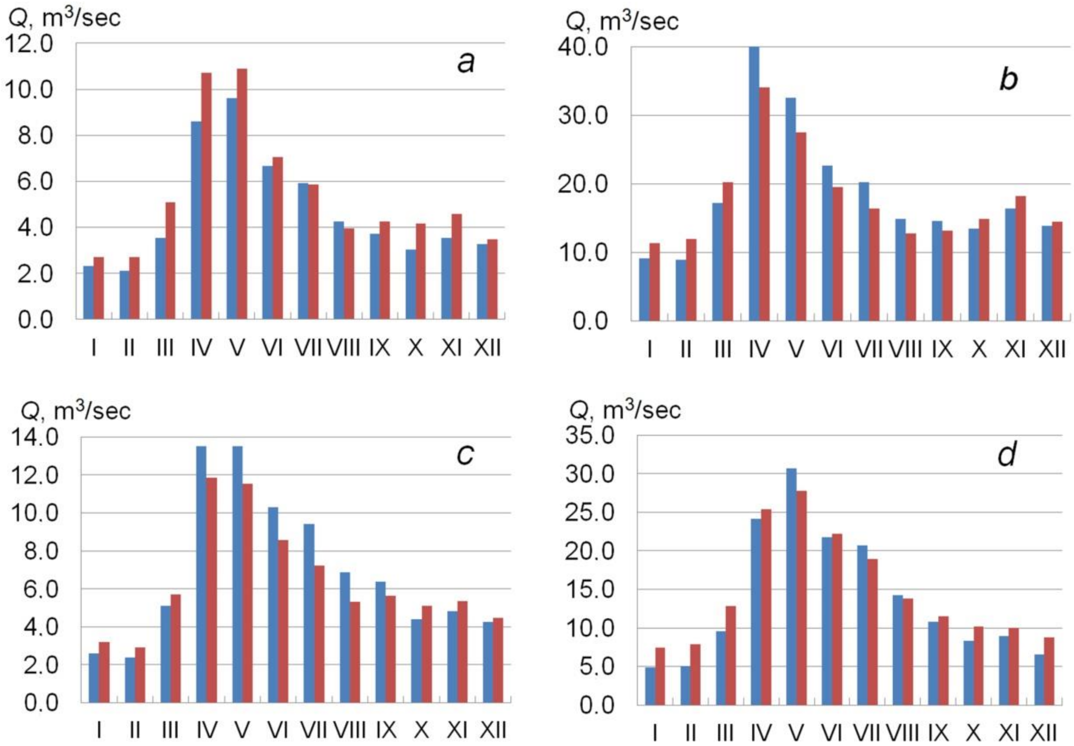


*Fig. 10. Intra-annual distribution of water discharge on the Ukrainian Carpathians rivers: a) – Bila Tysa – Luhi, b) – Teresva – Ust-Chorna, c) – Limnitsa – Osmoloda, d) – Chornyi Cheremosh – Verkhovyna (left columns – 1961–1990, right columns – 1991–2020).*

These data show that generally, the volume of water in the snow cover did not change. It is possible to assume that the earlier melting of snow cover is observed due to the impact of air temperature increase partly during winter thaws. It is the reason of river runoff increase in this period.

**Discussion**

The available data show that the changes of snow cover on the different altitudes are different. In fact the different is not only altitude, but surroundings. The meteorological stations Plai and Pozhezhevska are located at the tops of mountains, the others − mainly inside the river valleys, where the wind speed is much smaller.

It is well known (Grünewald et al., 2014), that under the influence of wind the snow cover depth is greater in ravines and river valleys, as well as in forests and bushes. The difference in snow depth increases with the increase of wind speed. When the wind speed is small, the snow cover depth becomes uniform.

Special observations near the both highest meteorological stations show the possibility of snow cover depth up to 2 or even 3 m. At the same time, the snow depth at the meteorological sites is essentially smaller.

It means that decrease of wind speed can change the distribution of snow cover in the mountains, making it more uniform: larger on the tops of mountains and smaller in ravines, river valleys, forests and bushes.

To check this idea we analyzed the impact of precipitation and wind speed on snow cover depth – more correctly, its change (ΔSD) during winter months. The impact of precipitation on the change of snow cover depth is direct, and the impact of wind speed is opposite. On a whole, these dependences are not strong, but their comparison for the periods of 1961–1990 and 1991–2020 shows some differences. The correlation between precipitation and the change of snow cover depth during the last three decades became closer than in the previous period (Fig. 11).

On the other hand, the impact of wind speed on the change of snow cover depth in 1961–1990 was larger than in 1991–2020.

The regressive analyses shows the same result as to the influence of precipitation and wind speed on the change of snow cover depth: the correlation between snow cover depth and precipitation is positive, between snow cover depth and wind speed is negative.

The effect of wind speed on snow cover also is seen in the example of the relationships between the snow cover depth and the duration of snow cover at neighboring stations. Over the last three decades, the correlation has become closer than during the first three decades. First of all it concerns the stations, located in low-mountain terrain.

It can be added that strong wind can blow off the existing snow cover with the speed that exceeds the speed of melting process. This can be seen in the example of the conditions observed at the Pozhezhevska station in March 2006. After a heavy snowfall on March 4–7, 2006, the snow cover depth here reached 121 cm. On March 9, 2006, a strong wind with an average daily speed of 8 m/sec caused the snow cover decrease from 121 cm to 101 cm. Next day strong wind reduced the snow cover from 101 cm to 75 cm and then to 69 cm. We add that during this period the air temperature was much lower than 0°C (Fig. 12).

This case shows the great impact of wind speed on the snow cover depth in the mountains. Obviously, in the highest mountains, this impact is even greater. Thus, the essential decrease of wind speed during the last 60 years is a very important factor influencing snow cover redistribution in the mountains. In our opinion, some decrease of wind speed in the mountains can be the result of altitude increase of forest spread. As can be seen in Fig. 7 this altitude is really increasing.

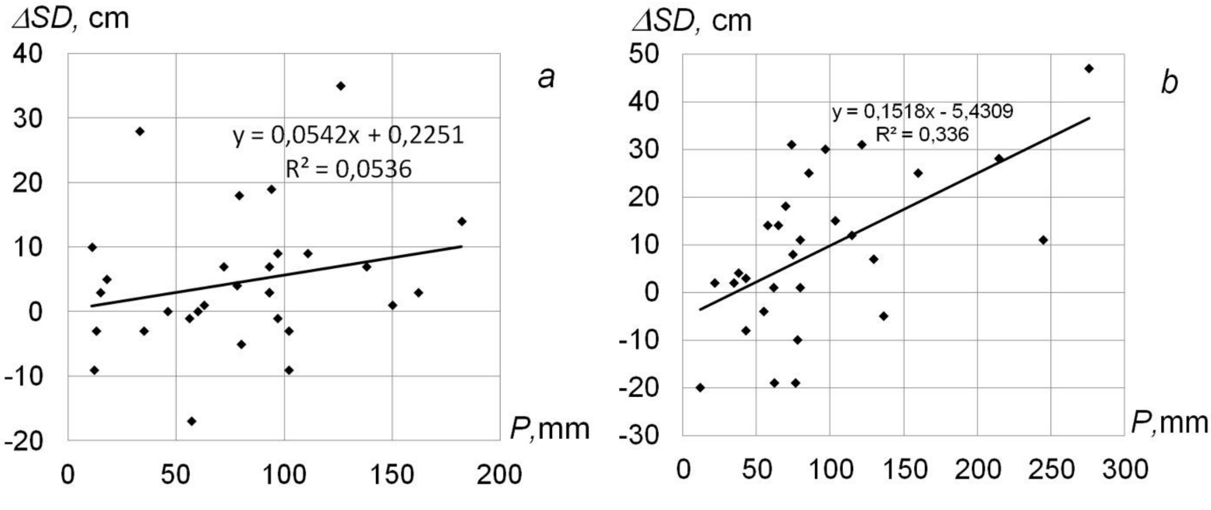


*Fig. 11. The correlation between precipitation and the changes of snow cover depth at Pozhezhevska station in January: a) – 1961–1990, b) – 1991–2020.*

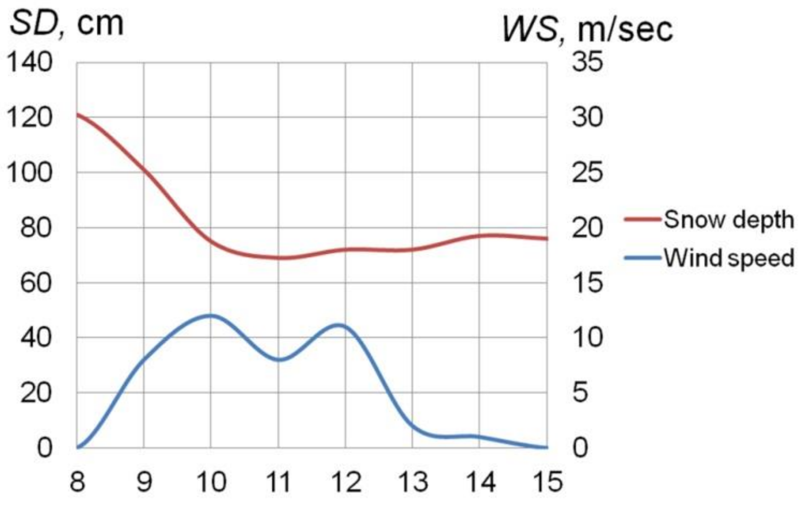


*Fig. 12. The changes of snow cover depth and wind speed at Pozhezhevska station on March 8–15, 2006.*

**Conclusions**

Monitoring at the meteorological stations in the Ukrainian Carpathians, especially at high altitudes, show an increasing trend in snow cover depth. Simultaneously it is observed the increase of air temperature and the decrease of wind speed. However, when assessing changes in the snow cover depth, it is necessary to take into account the effect of wind. Strong wind causes the significant redistribution of snow across the territory and this is the reason of snow cover decrease on the mountain tops and its increase in ravines, river valleys and forests. The observed decrease in wind speed in recent decades is accompanied by the alignment of the snow cover depth in the mountains. The absence of noticeable changes in snow cover in the mountains is confirmed by data on river runoff. The river runoff during the spring flood practically has not changed.

These results will be more visible in case of treatment of data observed not only at meteorological stations but in mountain ravines, river valleys and forests.

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