Dynamics of soil freezing

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A b s t r a c t : The knowledge of the soil environment is significant from the climatological, technical and biological point of view. For plants, soil is an environment from which they get nutriments and water, soil supports them and creates conditions for wintering. In our climatic conditions, a typical manifestation of the climate is the decreasing of the soil temperatures during the winter season under the freezing point, i.e. the occurrence of the freezing of the soil. This phenomenon has not been studied very widely, and there are many more data to be found about the temperatures of soil. Freezing is often determined, according to the soil temperature of 0° C, but this procedure is not the best. The scarcity of data on the freezing of soil is given also by the fact, that its measurement is difficult. Out of the agroclimatological stations of the Czech Hydrometeorological Institute, the freezing of soil is being measured by the cryopedometer. The evaluation of measurement for the period of 1961 to 2004 at the Pohořelice station, where the soil is formed by chernozems, has brought the following results. On average the freezing of soil occurs from November 23 to March 28, i.e. 127 days. The freezing reached the maximum depth from January 26 to 30, 1964, when the soil was frozen to a depth of 74 cm. On the other hand, there are years, when the depth of freezing does not exceed 2 cm. The freezing of the soil is very variable both during individual years and during the cold period. A significant phenomenon is the alternation of the states of freezing and melting of the soil, mainly in March. The occurrence of the average height of the snow cover is in the period from November 22 to March 15. Its occurrence is also very changeable, extraordinarily it may occur out of the whole cold period only several days or just one day. The influence of the snow cover on the depth of soil freezing for height of snow to about 10 cm is overridden by the influence of the advection of cold air.

Key words: freezing of soil, snow cover, cryopedometer, soil temperature, agroclimatological stations

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1. Introduction

In our natural conditions, a typical manifestation of the climate in the winter period is the decreasing of soil temperatures below freezing point (freezing of soils), which is defined by the *Meteorological Dictionary (1993)* as the freezing of soil solution when its temperature is lower than its freezing point. The depth of freezing of the soil depends apart from the intensity of the frosts and their duration also on the type and state of the soil and on its snow cover, vegetation cover etc. With respect to the difficulty of measuring soil freezing, accurate measuring apparatuses have so far not been developed; the frost-meter that is being used is a mere aid rather than an accurate apparatus (*Slabá, 1972; Krhounek, 1955*), and therefore this period is very often denoted as a period with soil temperatures below 0° C.

In the climatologic literature, more often than evaluation of the freezing of soil, we find analyses of soil temperatures, from which we derive the period and further freezing characteristics. In the *Climate of CSSR – Tables* (1961), we find average monthly temperatures at depths of 10, 20, 50 and 100 cm for the period of 1924-1953, or shorter for 17 stations, and maximum and minimum temperatures from 11 stations on the territories of the Czech Republic (CR) and the Slovak Republic (SR) with similar data for depths of 15, 30, 60 and 100 cm. In the *Climate of CSSR - Collective Study* (1969), in the chapter "Soil temperature", there are average monthly soil temperatures and periods with temperatures equal to or lower than 0° C quoted for the stations of Čáslav-Filipov, Havlíčkův Brod, Klatovy, Rožnov pod Radhoštěm, Hurbanovo and Starý Smokovec.

Many authors have studied soil temperatures in our conditions (*Možný, 1991; Němec, 2001; Němeček et al., 1990).* For Brno, soil temperatures were analysed by *Lednický (1979). Coufal et al.(1993)* deal with soil temperatures in the cold part of the year (October to March), where the statistical analysis of the time series was carried out for stations of Cheb, Doksany, Havlíčkův Brod, Olomouc and Pohořelice, and map processing was carried out for 35 stations predominantly for the monitoring period of 1961-1990. For the evaluation of soil freezing in this work, of use are mainly data on the absolute minima of soil temperatures, which are negative down to the depth of 50 cm. The coldest winter in the evaluated 30-year period was the winter of 1962/1963, with the most pronounced manifestations at the

station of Doksany, where the temperature of 0° C was measured at depths below 100 cm. The station of Pohořelice has only a table with soil temperatures for 5 cm, so that it is not possible to compare our results. The soil temperatures at the Pohořelice station for the period of 1956-1985 have been analysed by *Rožnovský (1990).*

Data on freezing of soil were published by *Bouškova (1961)*, who, however, derived soil freezing from soil temperatures, or from the course of the average temperature of soil of 0° C.

Hrbek and Krhounek (1957) studied the influence of the snow cover on soil freezing. They found, that higher snow cover causes the decrease of soil temperatures, and therefore also freezing. Freezing of soil for Slovak Republic can be found in *(Valuš, 1967). Bedrna (1989)* studied temperature soil regimes in detail.

The knowledge of the depth of soil freezing during the winter period is important mainly for agriculture and the construction industry. It is determined either by interpolation from a graph of the course of soil temperatures based on soil thermometers, or by direct measuring by cryopedometer. From the biological viewpoint, it is a part of the period of vegetation rest, however for wintering plants, mainly agricultural crops, it can have a negative impact. During high values of decreasing of the temperature, a damage or complete annihilation of plant organs occurs (freezing-out). This happens especially when temperatures below and above zero alternate, when the breaking of roots occurs *(Petr, 1991; Slavíková, 1986* and others). By *Kurpelová et al. (1975)* it is very important to know the wintering conditions of cultural plants not only for their further development, for the creation of bases for their next crop, but also from the point of view of the economy of growing a certain culture. The wintering of winter crops is influenced by two main factors. These are on one hand external factors, such as the influence of weather, and on the other hand internal factors, peculiar to plants, species and sorts, also known as biological factors. Out of the external weather factors, which can influence wintering the most, both in the positive and the negative sense, the following are most important: autumn, pre-spring and spring frosts, snow cover and precipitation overall, thaws and frosts, moisture under the snow cover, alternate freezing and thawing of soil, especially surface layers, wind, soil moisture in the autumn.

Among the internal biological factors that influence wintering of winter

crops are the balance and bulk of the stand, development stage of the plants before wintering, the degree of hardiness (frost-proofness) of plants, species, or sort. After quoting at least the basic external and internal factors which influence wintering, we shall further be more concerned only with external meteorological wintering conditions. It is necessary to realise, that these external factors, such as frosts, snow cover of different thickness, wetted soil surface, temperature fluctuation, ice crust, wind, winter and pre-spring drought etc. do not make themselves felt in isolation, but mostly act in a complex manner, in more combinations at the same time.

2. Material and methods

Data on soil freezing were gained from measurements at climatological station Pohořelice (elevation 184 m a.s.l., latitude 48° 59′ North, longitude 16° 41′ East), where soil freezing is measured by cryopedometer. The station is a part of a network of climatological stations of the Czech Hydrometeorological Institute. From available literature (*Climate of CSSR – Tables, 1961; Climatic Atlas of CR, 1958* and others) it is possible to say that our territory lies in the temperate zone, which is at the same time a region of transitional central-European climate. The climate of south Moravia is significantly influenced by circulation and geographical conditions. According to break-up to climatic regions, it is a warm region, dry sub-region, ward A2, which is characterized as warm, dry, with temperate winter, with shorter duration of sunshine. Within the framework of agroclimatic zoning, it is an agroclimatic warm macroregion, mostly warm region, mostly dry subregion, agroclimatic ward with relatively temperate winter. The processed period was 1961-2004. All procedures were made in agreement with methods quoted by *Nosek (1972)*.

Cryopedometer consists of a rubber hose, which is filled with foam gum and distilled water, and has a 5 cm graduation. This hose fits into a protective PVC-type material, which is permanently fixed in the soil. The depth of the hose which is under the soil surface is given by a mark on the hose that is flush with the soil. The cryopedometer is located on the station block of land in the soil under the grass in an unshaded place, best next to soil thermometers.

It is necessary from time to time to check the frost-meter's amount of distilled water in the measuring rubber hose, especially when doubting the proper functioning of the cryopedometer. In such case we remove the top valve and re-fill with distilled water. After re-filling, the valve is replaced and fixed back on the hose.

Measurement and recording of data on the freezing of the soil is made once a day, at 7 a.m., after reading the soil thermometers. The depth of freezing is found by touch. Unfrozen frost-meter is soft to touch. When it freezes, it is stiff at first, and it is possible by touch to ascertain the presence in the frost-meter of ice crystals. When freezing completely, the frost-meter becomes wholly rigid. The crystal-forming phase is considered to be a "freezing" phase. The depth of soil freezing is found by interpolation to a cm-accuracy, and is recorded in the appropriate column for the day of measurement in the daily recorder.

In the case of de-frosting of the soil surface, the depth of freezing is recorded by two numbers: e.g. 15/30. The first number represents the thawing of soil into a depth of 15 cm, and the second number represents the freezing of soil to 30 cm. If a new freezing of soil from the surface occurs, in other words if a new layer of ice or ice crystals forms, and this new layer is situated above the older ice layer and is separated from it by a layer of water, we record this by two fractions: e.g. 0/2; 5/10. The first number (the numerator) denotes the upper boundary of the frozen layer, and the second number (the denominator) denotes the lower boundary of the frozen layer. If a freezing of the soil in a thin surface layer (under 1 cm) occurs, which can be easily ascertained by eye, but cannot be satisfactorily measured by the frost-meter, we denote this soil surface freezing with the symbol "pp" for the appropriate day *(Slabá, 1972; Fišák, 1994)*.

3. Results and discussion

From a climatological point of view, according to statistical evaluation we may say, that in the Pohořelice region freezing of soil occurs from November 23 to March 28, i.e. 127 days. About this value and all others it must be said however, that this is a statistical mean, which does not express the very variable conditions of frozen soil occurrence. It is however a piece of

data, which allows us the comparison with other localities. As expressed in Fig. 1, at the beginning an average freezing into the depth of 1 cm occurs, which according to observation corresponds rather to the freezing of the soil surface.

This state lasts from November 23 to December 1. From this date, the depth of soil freezing increases and it reaches the highest average value, i.e. 19 cm, from January 20 to 28. We can consider this period, from the point of view of soil freezing, to be the height of winter. In the following days, the depth progressively lowers, so that from March 2 to 10 the frozen layer of soil is 10 cm thick. After 20th March, the depth of freezing quickly decreases, on March 21 it is 4 cm, on March 22 it is 3 cm, from March 23 to 26 the mean of freezing is 2 cm and on March 27 and 28 it is 1 cm. In literature review it was cited, that soil freezing is often put into connection with the height of snow cover. Its average height is also expressed in Fig. 1. In the long-term average we can see, that the occurrence of snow cover pre-dates the soil freezing by one day, i.e. the average height of 1 cm starts on November 22 and this height lasts till December 11, and on December 12 and 13 the average is under 1 cm. In the following days until December 21 the average height of snow is again only 1 cm, but apart from December 20, when the average is 2 cm. On average we may say, that the height of the snow cover from November 22 to December 21 is 1 cm. It is therefore obvious, that snow occurrence in this period is very changeable. From December 22, when the average height is 2 cm, the snow layer grows very little, with certain fluctuation. The highest average height of snow cover is 4 cm, namely in the continuous period from January 1 to 23, and then to February 1 it varies between 3 and 4 cm. From February 2 to 24 it fluctuates between 2 and 3 cm, from February 25 to March 7 it is 2 cm, and then follows on 1 cm, until March 15. The continuous occurrence of snow cover of any height is therefore in the period from November 22 to March 15.

From the course of average soil freezing and the average height of snow cover, no significant dependence stems. This knowledge is logical, for the given climatic conditions. To get to know the dynamics of soil freezing, we have focused on the analysis of the occurrence of extreme values within the framework of the evaluated time series, as quoted in the method.

The years evaluated were those with the occurrence of maximum and minimum freezing of soil, and those with the occurrence of maximum and

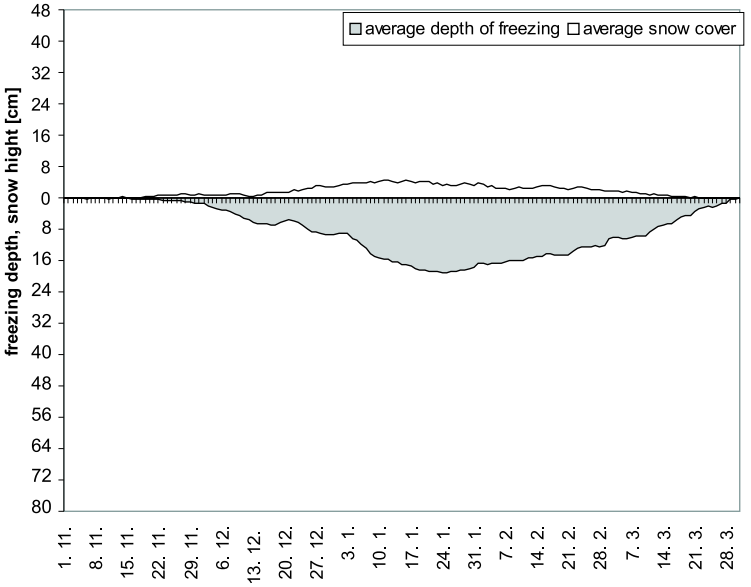

Fig. 1. Average depth of of freezing of soil and average height of snow cover at Pohořelice in the period from November 1 to March 31 during the years of 1961 to 2004.

minimum height of snow cover.

Out of all the years monitored, the winter when the soil froze the most in Pohořelice was the winter of 1963/64, see Fig. 2. The first day with frozen soil is December 8, 1963, the depth of freezing was 2 cm and during the following days it quickly increased. On the December 11, 1963, the frozen layer was 10 cm thick. On the December 13 it reached 12 cm, and on this day a total height of snow of 2 cm fell. On the following days the freezing continued, and on the December 17 it reached 20 cm already, whilst the snow cover increased by 1 cm every day, so that it was 6 cm. On the December 17 the snowing finished. The snow cover was decreasing very slowly, on the December 21 it was 4 cm and this remained until January 6. On the January 7 and 8 the snow cover decreased to the extent that there was no snow cover quoted for the January 9. The freezing of soil however still continued, and it reached a maximum on January 26 to 30, when the soil was frozen to a depth of 74 cm. This value is the maximum frozen soil depth for the whole period of monitoring, it is however not the longest period of frozen soil during cold weather. From January 31 the depth of freezing gradually decreased, when

on the March 28 the soil was still frozen to a depth of 38 cm. In Fig. 2 we can see a sudden change in the depth of freezing, because for March 29 to 31 the depth of 1 cm is quoted. This sudden jump is given by the fact, that the lowest frozen part of the soil was quoted, whereas from the March 21 the soil started thawing on the surface, on this day to 2 cm. On the March 28 the soil had thawed to 25 cm, so that the frozen layer was at the depth of 26 to 38 cm. Its thawing was then very quick, as can be seen from the occurrence of maximum freezing of soil. The height of snow of only a few cm, which moreover occurred after the beginning of soil freezing, did not significantly influence the freezing of the soil. The deciding factor was the overall cooling, i.e. low air temperatures. When comparing the results of *(Coufal et al., 1993)*, we can see that for the station of Doksany, the winters in the years 1962/63 and 1984/85 were designated as harsh winters. Even though in this work soil freezing is not evaluated, looking at temperature, from the quoted course of the thermoisopleth 0°, it is obvious, that the freezing of soil could reach below 70 cm in both winters. At the Pohořelice station the maximum depth of freezing during the winter of 1962/63 in the period of February 10 to 17 was 67 cm, during the winter of 1984/85 it was 51 cm on the February 26. As far as the length of continuous freezing is concerned, the period in the winter of 1962/63 had the longer period, from December 2 to March 26, whilst on December 18 and 19 only the soil surface was frozen. During the winter of 1984/85, the period of soil freezing was shorter, as compared to the winter of 1963/64. It started on December 22, 1984 and finished on March 16, 1985.

The basic influence of the air temperature, or more accurately the circulation and therefore advection of warm or cold air on our territory, is testified by the course of soil freezing in the cold period during 1982/83, when minimum values were recorded, see Fig. 3. In the true sense of the word, we can speak of soil freezing only during six days, namely February 22 to 27, 1983, when the depth of freezing is 2 cm. During other days, of which there were 32 during the whole period, the depth of freezing was only 1 cm, therefore only the soil surface. One interesting thing happened though, during March 1983 changeable freezing of the soil surface occurs, the last date being March 30. Such a late occurrence, i.e. March 30 or 31 was recorded only for six winters during the monitored period, whilst it was typical for winters of the first half of the nineties.

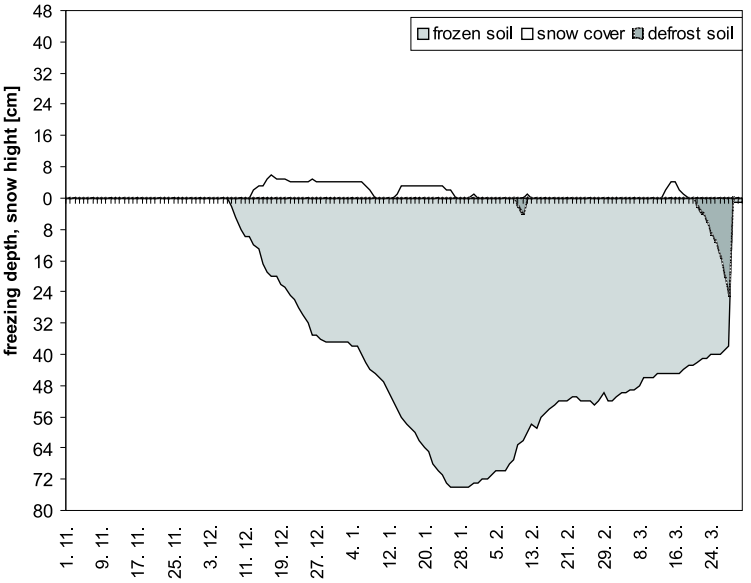

Fig. 2. Course of maximum freezing of the soil and height of snow cover at Pohořelice in the period from November 1, 1963 to March 31, 1964.

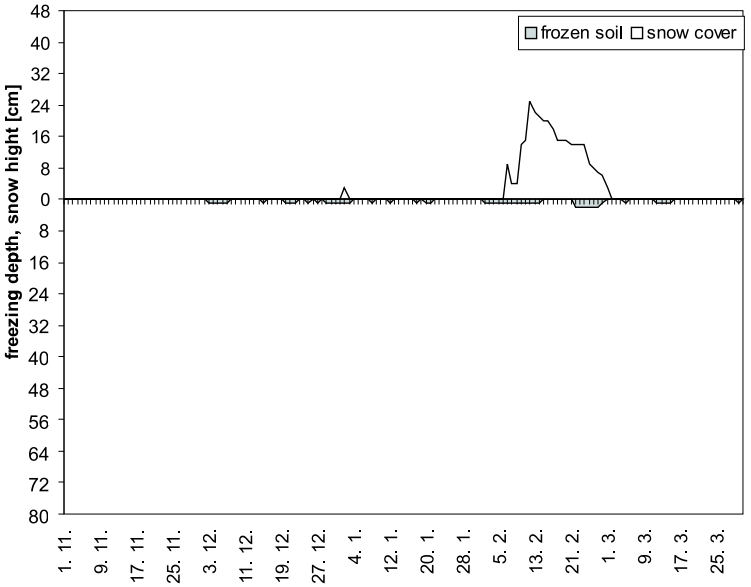

Fig. 3. Course of freezing of the soil and height of snow cover at Pohořelice in the period from November 1, 1982 to March 31, 1983.

As far as the height of the snow cover is concerned, during this period it snowed little. The first snow cover is recorded on the January 2, 1983, only on this day, and its height was 3 cm. Further occurrence was on the February 7, when the snow height reached 9 cm. The snow cover lasted till March 1 and it reached 25 cm on the February 12. With respect to the freezing of the soil of 1 cm, the evaluation of the influence of the snow cover is difficult. Surely it influenced the thawing of the soil surface between February 15 and February 21, 1983. But while this occurred, the soil froze again to a depth of 1 cm.

From the point of view of wintering of winter crops, the winter of 1983/84 was very interesting, and it is a typical example of a changeable freezing of the soil. Even though the freezing of the soil started on December 1, 1983, it was interrupted several times by a softening, when the soil completely thawed. The freezing of the soil ends, if we consider also freezing of the soil surface, on February 22, 1984. Here it is necessary to remind ourselves of the unfavorable result of changeable freezing.

For the evaluation of the influence of the snow cover, we shall utilise also the extreme occurrences of the snow cover. Fig. 4 depicts the course of the snow cover height for the evaluated period of 1969-1970. The snow cover occurred continuously from December 4, 1969 to February 8, 1970. In the period from February 9 to 14, the soil surface was bare except on February 11, when 1 cm of snow fell. Further period with snow cover started with solid snowing on February 15, when 23 cm of snow fell and this snow cover during intermittent snowing reached the greatest height, namely 25 cm on March 4 and 5, 1970. Since this peak, the snow cover height gradually diminished until to March 19, when it was 2 cm and the following day it had thawed. In this case we can confirm, that higher snow cover height influences the depth of soil freezing, because at snow heights between 20 and 10 cm the freezing of soil stopped and after 21 days the soil thawed completely. To be more accurate, when on February 15, 1970 we had a snow fall of 23 cm, the depth of freezing of soil was 14 cm. By February 28 the depth of freezing diminished to 10 cm, but on the March 7 it was only 2 cm and the following day the soil profile had thawed, while the snow height was 19 cm. An important finding is, that the thawing of the soil occurred not from the surface, but from the depth, therefore by the action of heat transfer to surface, and the snow cover so prevented the release of

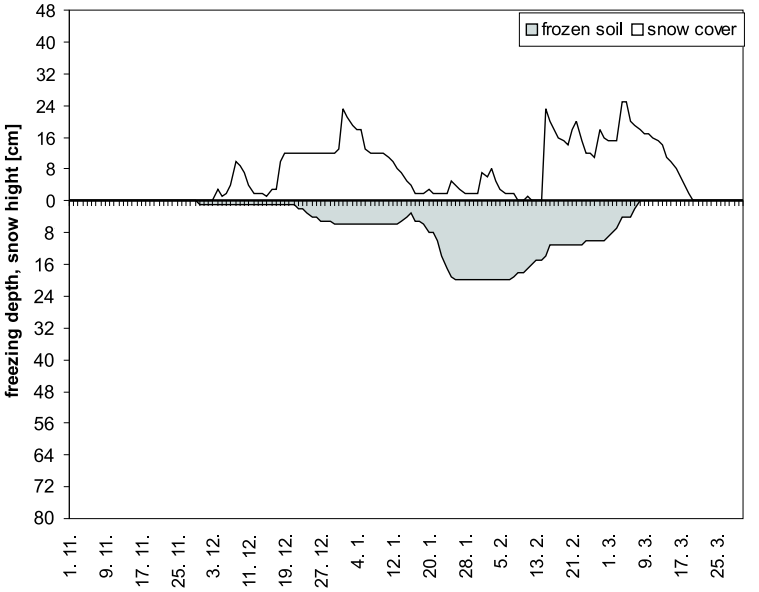

Fig. 4. Course of freezing of the soil and maximum snow cover heights at Pohořelice in the period from November 1, 1969 to March 31, 1970.

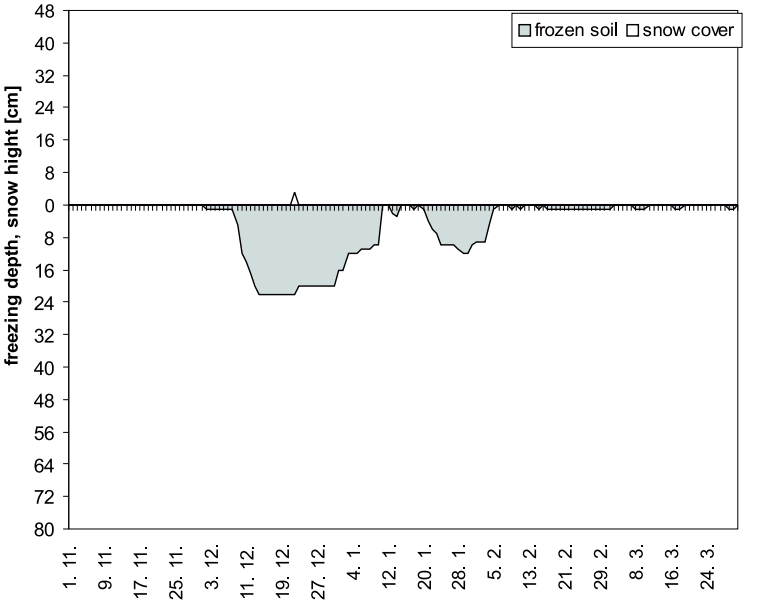

Fig. 5. Course of maximum freezing of the soil and minimum height of snow cover at Pohořelice in the period from November 1, 1991 to March 31, 1992.

heat from deeper layers.

The course of minimum freezing of soil in the cold part of the years 1982-1983 has already been commented upon, see Fig. 3. We remind of this period, because in it there did not occur a significant snow cover, but it was higher than in the period of 1991-1992, when in the whole period snow only occurred on December 23 and the height of the snow cover was 3 cm, see Fig. 5. The snow gradually melted during the same day. Under these conditions, we could expect high values of soil freezing, but the already mentioned influence of circulation, the weather course including the influence of air temperature had the effect, that the freezing did not even reach average values depth-wise or duration-wise. The freezing started on the December 2, when the surface of the soil froze to a depth of 1 cm and this state lasted till December 9, when thanks to cooling a depth of 5 cm was measured, on December 10 a depth of 12 cm was measured, and the maximum freezing to the depth of 22 cm was during December 14 to 22. The soil freezing gradually diminishes to January 10. From this date, the soil freezes and thaws in several daily intervals. A continuous freezing starts again on January 20, when the soil freezes to 1 cm, and lasts to February 5 with the maximum of freezing to 12 cm during January 29 and 30, 1992. Freezing to a depth of 1 cm then continually occurs during the days of February 17 to March 2. After this date during March, several days with freezing to 1 cm occurs. It is interesting, that just like for the period of 1982-1983, freezing to a depth occurs on March 29 and 30, 1992. We can therefore say, that also during this March, alternate freezing and thawing of the surface occurred.

4. Conclusion

From the analysis of measurement of freezing of soil at the Pohořelice station we get the following results. From the climotological point of view, the average freezing of soil occurs from November 23 to March 28 inclusive, i.e. 127 days. Of course this is a statistical average, which does not express the very changeable conditions of occurrence of frozen soil in the individual years. The average long-term depth of freezing of soil from the time of initial freezing reaches a maximum of 19 cm, during the days of January 20 to 28. We may regard this period from the point of view of soil freezing

as the height of winter. During the following days, the depth is gradually decreasing, so that during March 2 to 10 the frozen layer of soil is 10 cm thick. After 20th March, the depth of freezing rapidly diminishes.

The greatest depth of frozen soil during the monitored years was in the winter of 1963/64, when freezing started on the December 8, 1963, and reached the maximum of 74 cm during the days of January 26 to 30, 1964. The end of the freezing is given by a sudden jump. This is given by the fact, that from March 21 the soil started to thaw at the surface. On the March 28, 1964, the soil was thawed to 25 cm, so that the frozen layer was at a depth of 26 to 38 cm. Its thawing afterwards was very quick.

The course of freezing of the soil in the winter of 1982/83, when minimum depths of soil freezing have been recorded, testifies about the basic influence of air temperature, more accurately of circulation and therefore of advection of warm or cold air on our territory. In the course of March 1983, a significant phenomenon occurs, when changeable freezing of the surface occurs as late as March 30. This significant, but negative phenomenon for wintering of winter crops manifested itself strongly in the winter of 1983/84, when freezing of soil began on December 1, 1983, was interrupted several times by thawing, when the soil completely thawed, and soil freezing ended on February 22, 1984.

We can say about the occurrence of snow cover, that in the long-term average the snow cover in Pohořelice starts one day before the freezing of the soil, i.e. on November 22 and lasts till March 15. A maximum height, just 4 cm, is reached in the continuous period from January 1 to 23. It has turned out, that out of the course of average freezing of soil, and the average height of snow cover there does not follow any significant relationship, because the snow cover heights to 10 cm, divided to several occurrences during the cold period, do not significantly influence the soil freezing. On the contrary we can confirm, that the higher height of snow cover influences the depth of freezing, because for snow cover heights of 10 to 20 cm the soil freezing stopped and after 21 days complete thawing of the soil occurred, such as happened in February and March 1970. The newly fallen snow on February 15, 1970 reached 23 cm height and depth of soil freezing was 14 cm. By February 28 the depth of freezing diminished to 10 cm, but on the March 7 it was only 2 cm and the following day the soil profile had thawed, while the snow cover height was 19 cm. To the influence of higher snow cover it

is necessary to quote a finding, that the soil thawing takes place from the depth, therefore by the action of the transfer of heat to the surface, and the snow cover so prevents the release of heat from deeper layers through the surface. In the end it is necessary to emphasize, that the freezing of soil is the result of a complex action of a meteorological system, in short of weather and the soil environment, where a significant role is played, apart from physical properties of the soil, also by its exposition, plant cover etc. In this viewpoint, the results gained at climatological stations are basic or standard data, which will fluctuate according to environment.

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References

Bedrna Z., 1989: Soil regimes. Bratislava, Veda, 207 p. (in Slovak).

Bouškova V., 1961: Freezing of soil in Bohemia and Moravia. Meteorologické zprávy, **14**, 3, 70–71 (in Czech).

Climate of CSSR - Collective Study, 1969: Hydrometeorologický ústav, Praha, 357 p. (in Czech).

Climate of CSSR – Tables, 1961: Hydrometeorologický ústav, Praha, 379 p. (in Czech).

Climatic Atlas of the Czechoslovak Republic, 1958: Ústredná správa geodézie a kartografie, Bratislava, 106 p.

Coufal V., Kott I., Možný M., 1993: Soil temperatures in the cold part of the year in the period 1961-1990 on the territory of the Czech Republic. Národní klimatický program, Praha, 37 p., ISBN 80-05813_05-X. (in Czech).

Fišák J., 1994: Instructions for observers on meteorological stations. Metodický předpis ČHMÚ, **11**, CHMI, 3rd Re-worked edition, 115 p., ISBN 80-85813-12-2 (in Czech).

Hrbek J., Krhounek S., 1957: Freezing of soils during winter 1955-1956, Meteorologické zprávy, **10**, 1, 16–23 (in Czech).

Krhounek S., 1955: Freezing of soils and its measurement by soil frost-meter. Meteorologické zprávy, **8**, 5, 127–133 (in Czech).

Kurpelová M., Coufal L., Čulík J., 1975: Agroclimatic conditions of ČSSR. Hydrometeorlogický ústav, Bratislava 270 p. (in Slovak).

Lednický V., 1979: Depth of freezing of soil in Brno. Meteorologické zprávy, **32**, 1, 12–15 (in Czech).

Meteorological Dictionary. 1993: ČHMÚ, Praha, 594 p. (in Czech).

Možný M., 1991: Temperature regime of soils in the hop-growing region. Meteorologické zprávy, **44**, 4, 115–118 (in Czech).

Němec J., 2001: Valuation of agricultural land of the Czech Republic. Výzkumný ústav zemědělské ekonomiky Praha, 260 p., ISBN 80-85898-90-X (in Czech).

Němeček J., Smolíková L., Kutílek M., 1990: Pedology and paleopedology. Prague, Academia, 297 p. (in Czech).

Nosek M., 1972: Methods in climatology Academia, Praha, 434 p. (in Czech).

Petr J., 1991: Weather and Yield. Amsterdam, Elsevier, 288 p.

Rožnovský J., 1990: Characteristics of the course of soil temperatures. Acta univ. agric., fac. agron., (Brno), XXXVIII, **3-4**, 97–104.

Slabá N., 1972: Instructions for observers of meteorological stations of the CSSR. Handbook of regulations. Hydrometeorological Institute, **7**, 224 p. (in Czech).

Slavíková J., 1986: Plant Ecology. Univerzita Karlova, Praha, 247 p. (in Czech).

Valuš G., 1967: Freezing of soil in Slovakia. Meteorologické zprávy, **20**, 6, 151–153 (in Slovak).