Comparison of soil frost depth and its duration determined by soil frost tube and soil temperature interpolation

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Abstract: Soil frost and the depth of freezing are important for the plant development and for the building industry as well. The depth of soil frost is estimated directly by soil frost tube and indirectly from diagrams of soil temperature according to the isotherm of $0\,°C$ (zero-isotherm). The soil temperature measurement is often used for evaluation of freezing depth, because the frost tubes measurement is rarely performed. Measurement by frost tube is done once a day at 7 a.m. and soil temperature in 5, 10, 20, 50 and 100 cm is measured in three observation terms at 7 a.m., 2 p.m. and 9 p.m. Data from agroclimatological station Pohořelice (1971–2000) were used for the evaluation. Three specific real cold periods (1978–1979, 1984–1985 and 1990–1991) and mean frost depth and absolute maximal frost depth for the whole period were evaluated. Course of frost, terms of beginning and the end of frost period and the term of maximum freezing assessed by both methods are almost identical in all real evaluated periods. The results show that the soil frost depth measured by soil frost tube is often higher than that estimated from soil temperature diagrams. It might be caused by graphical processing, as soil temperatures are measured only at five given depths and the depth of zero isotherm is determined by their interpolation. The most significant differences between both methods were observed when evaluating average values for the entire period 1971–2000.

Key words: soil freezing, frost tube, soil temperature, zero-isotherm

1. Introduction

Almost thirty percent of the earth's surface periodically freeze and about twenty percent are in a state of permafrost *(Sharratt et al., 1997)*. Thaw

depth measurements of permafrost on the Calypsostranda plain showed wide variation in the active layer thickness over relatively small distances. This fact should be taken into account when producing general schemes and models of permafrost active layer development, which are needed for scientific as well as applied purposes *(Repelewska-Pekalowa and Pekala, 2003)*.

Autumn tillage leaves the soil unprotected. Melting snow on the frozen soil increases the risk of water erosion particularly in the areas of cereal production *(Lundekvam et al., 2003)*. Freezing and thawing may increase intensity of soil erosion by up to 24–90% compared with soil which is not affected by freezing and thawing *(Edwards and Burney, 1987)*. A combination of melting snow, frozen surface and saturated soil layer leads to rill erosion *(Øygarden, 2003)*. The creation of rill erosion in the northwest United States as a result of freezing and thawing of soil is described by *Mc-Cool and Williams (2005)*. However snow cover retains rainfall, insulates and prevents soil freezing *(Male and Gray, 1981; Steppuhn, 1981)*. The influence of minimum temperatures on freezing depth is affected by the snow cover depth. Continuous snow cover with a minimum depth of 10 cm significantly reduces soil freezing *Hrbek and Krhounek (1957)*.

Soil frost and the depth of freezing are important for plant development, for agriculture and forestry and also for a building industry. Frost heaving sometimes induces severe damage to constructions *(Phukan, 1985)* and plants in the agricultural field *(Sharratt and McCool, 2005)*. *Auclair et al. (2010)* developed a model based on the sum of z-scores of soil frost (December–February) and drought in summer (May–September) that accurately predicts timing and severity of dieback on sugar maple (*Acer saccharum* Marsh.), *Betula* spp., *Fraxinus* spp., and red spruce (*Picea rubens* Sarg.).

Accurate automatic devices are not developed yet due to difficult soil freezing measurement *(Slabá, 1972; Fišák, 1994)*. *Hayhoe and Balchin (1986)* examined the degree of freezing and thawing at intermediate depth intervals.

Soil freezing evaluation is often based on soil temperature course. *Boušková (1961)* evaluated the freezing according to an average soil temperature of 0 °C. *Lednický (1979)* and others proceeded similarly. *Climate of CSSR – Tables (1961)* contains monthly average soil temperatures for 17 stations, maximum and minimum soil temperatures from 11 stations in the Czech

Republic (measured at depths of 10, 20, 50 and 100 cm for the period 1924 to 1953) and similar data for depths of 15, 30, 60 and 100 cm in Slovakia. *Climate of CSSR – Collective Study (1969)* presents monthly average soil temperature and duration of season with temperatures lower than $0\,^\circ\text{C}$ for the chosen Czech Hydrometeorological Institute stations. *Rožnovský (1990)* analyzed the soil temperature for the period of 1956–1986 for Pohořelice station. *Coufal et al. (1993)* dealt with soil temperatures in cold season. The map outputs for the period 1961 to 1990 are processed for 35 stations and freezing evaluation is based on absolute minimum of soil temperatures (which are negative up to 50 cm). Soil temperature regimes are discussed in detail by *Bedrna (1989),* and *Bedrna and Gašparovic (1986).*

The paper compares two methods widely used for soil freezing determination and documents their differences and similarities. The results point out possible variability of obtained data.

2. Material and methods

Measurement of soil freezing depth by soil frost tube was confronted with daily average soil temperature at depths of 5, 10, 20, 50 and 100 cm. Data from agroclimatological station Pohořelice for the period 1971–2000 were evaluated. The results were graphically expressed.

The station is located in the floodplain of the Jihlava river at the altitude of 180 m a.s.l. The average annual temperature is $9.0\,^\circ\text{C}$ and annual rainfall 480 mm. Pedological characteristics of Pohořelice stations are presented in Table 1 and 2. Soil type is stratified fluvisol. The upper part

Table 1. Soil profile characteristics

Depth (cm) Index of genetical horizon	Soil type	Structure	Other features
0 - 10 Ad	clay	humic granular	strong rooting
10 - 40 IM	sandy clay	low humic granular	
40 - 60 IIM	sandy clay	polyedric	Fe and Mn pellets
60 - 100 D	sand	incoherent	roots up to 60 cm

Table 2. Basic physical soil parameters

Depth (cm)	Particles < 0,01 / Porosity	Water holding capacity	Wilting point	Retention water capacity (mm)
	% vol.			
10	31.28/49.69	36.74	13.38	23.36
20	31.28/49.69	36.74	13.38	23.36
30	26.80/47.31	39.93	12.04	27.89
40	26.80/47.31	39.93	12.04	27.89
50	29.48/41.92	32.01	12.84	19.17
60	29.48/41.92	32.01	12.84	19.17
70	6.16/38.42	15.74	5.84	9.90
80	6.16/38.42	15.74	5.84	9.90
90	6.16/38.42	15.74	5.84	9.90
100	6.16/38.42	15.74	5.84	9.90

of the profile (10 cm) is influenced by divot (granular structure). Content of particles smaller than 0.01 mm is 31% (loam soil). The upper part is followed by about 50 cm thick layer (10 cm to 60 cm) which is affected by water (Fe, Mn pellets). Content of clay particles decreases with depth – from 30% (horizon M I and M II) to 6% (D horizon). The wilting point is thus reduced there. Porosity also decreases with depth (i.e. available water-holding capacity decreases).

Depth of soil freezing determined by frost tube:

Soil frost tube consists of a rubber hose with a scale of 5 cm which is filled with foam rubber strip and distilled water. The hose is placed into the protective tube permanently embedded in the soil. Depth of freezing is verified by touch with centimeter accuracy. Frost tube is placed under grass stand. Measurement is performed once a day at 7 a.m.

Depth of soil freezing determined by soil temperature:

Two types of thermometers are used for soil temperature measurement at Pohořelice station. Curved thermometers with the range of $-30\,°C$ to $+45\,°C$ are used for measurement at shallow depths (5, 10 and 20 cm).

Deep mercury thermometers with the range of $-25\,°C$ to $+35\,°C$ are used for measurements at the depth of 50 and 100 cm. Soil temperature is measured in observation terms 7 a.m., 2 p.m. and 9 p.m.

For the soil temperatures interpolation the program SURFER 8 was used (Kriging method of interpolation).

Evaluated periods:

Three specific real cold periods with different course of soil freezing and snow cover were chosen for the evaluation: 1978–1979, 1984–1985 and 1990–1991.

Mean depth of freezing was assessed as an average freezing depth for each day from November 1 till April 30 for the entire evaluated period 1971–2000. Maximal depth of freezing was assessed as absolute maximum freezing depth for every day from November 1 till April 30 for the entire evaluated period 1971–2000. Maximal freezing depth determines non freezing depth.

Graphical representation:

Figures 1, 3, 5, 7 and 9 are based on soil frost tube measurement. They contain depth of soil freezing, depth of snow cover and course of air ground temperature minimum. Air ground temperature minimum is measured below the snow cover at the soil surface.

Figures 2, 4, 6, 8 and 10 are based on interpolation of soil temperature measurement (from 5 to 100 cm under soil surface).

3. Results and discussion

Figures 1 and 2 present the results of soil freezing measurement for the cold period of 1978–1979.

Measurement by soil frost tube shows two or three freezing periods respectively. The first period lasted from December 3 till 29. In the middle of the period the soil defrosted almost up to the surface but the ground layer was permanently frozen. The second main frozen period lasted from January 1 till March 2. Maximum depth of freezing (to the depth of 56 cm) was observed on January 26.

Interpolation of soil temperatures shows a similar course of soil freezing. The beginning of both periods and the end of the first one were estimated

in the same terms as by frost tube. There is no visible sub-melting period in the middle of first freezing period in Fig. 2.

The end of the main freezing period was assessed about three days later than by frost tube. Maximum depth of freezing and its term correspond to the frost tube method.

Figures 3 and 4 present results of soil freezing measurement for the cold period of 1984–1985.

Measurement by soil frost tube shows some short-time and shallow (not deeper than 5 cm) freezing periods in November and at the beginning of December. Permanent soil freezing occurred from December 23 till March 17. Maximum depth of soil freezing (50 cm) was measured on February 17. A gradual melting from ground level started on March 4.

Interpolation of soil temperatures shows very similar course of soil freezing. The beginning and the end of freezing period is almost the same as in the first example. Also the melting from ground level (5 cm under surface in this case) corresponds with previously assessed term quite punctually. The main difference was observed when estimating the maximum soil freezing depth. While the frost tube method determined the value as 50 cm, the soil interpolation determined it just as 44 cm. The term of maximum freezing (February 27) was assessed by both methods.

Figures 5 and 6 present the results of soil freezing measurement for the cold period 1990–1991.

Measurement by soil frost tube shows some short-time and shallow (not deeper than 5 cm) freezing periods in December and at the beginning of January. Permanent soil freezing lasted from November 14 till March 14. Maximum depth of soil freezing, 48 cm, was measured on February 24. A gradual melting from ground level started on March 1.

Interpolation of soil temperatures shows very similar course of soil freezing. The beginning and the end of freezing period are almost the same as when using frost tube method (just the end of freezing was assessed 2 days earlier). Also the melting from ground level (5 cm under surface in this case) is visible in Fig. 6. Maximum depth of freezing estimated by soil interpolation methods is about 10 cm lower then by frost tube method. The term of maximum freezing (February 24) was assessed by both methods.

Figures 7 and 8 present the results of average soil freezing depth for the entire evaluated period 1971–2000.
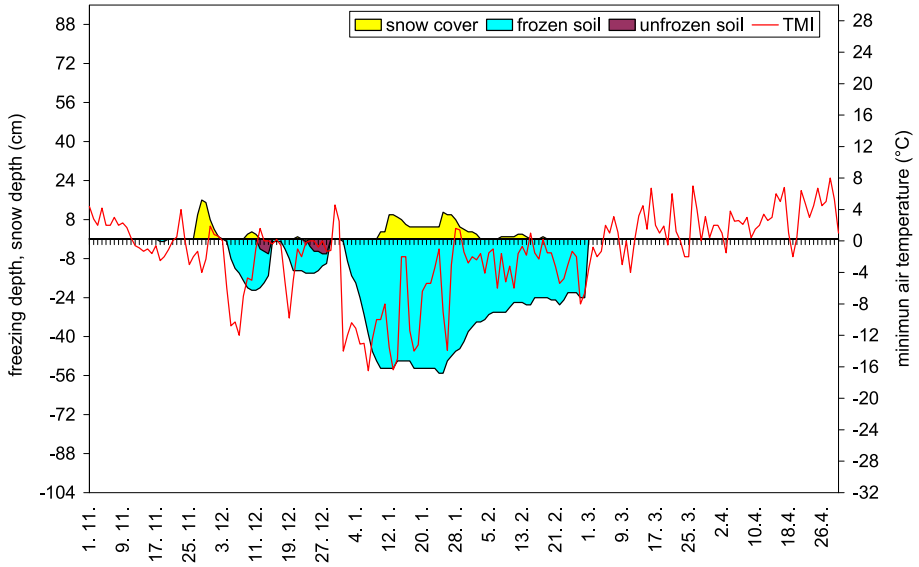
Fig. 1. Depth of soil freezing, depth of snow cover and the course of air ground temperature minimum, cold season 1978–1979.
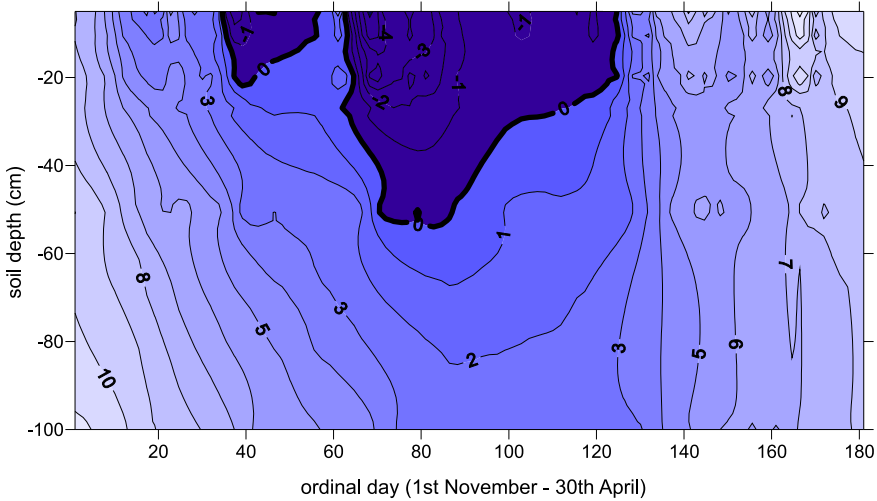

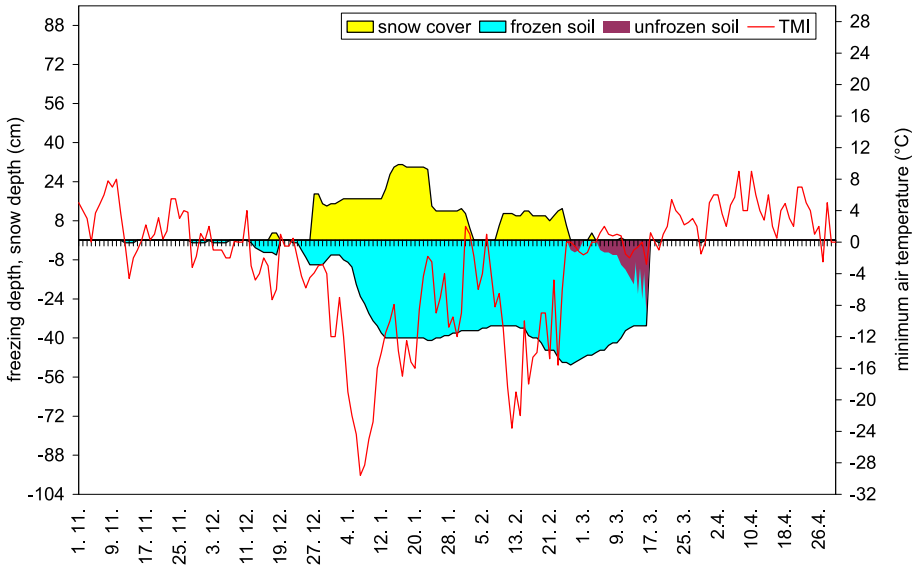Fig. 2. Interpolation of soil temperature measurement, cold season 1978–1979.

Fig. 3. Dept of soil freezing, depth of snow cover and course of air ground temperature minimum, cold season 1984–1985.
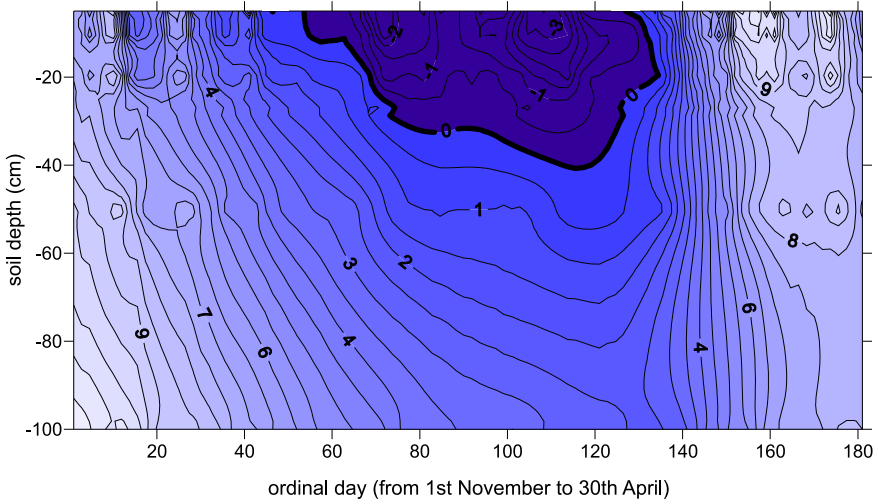

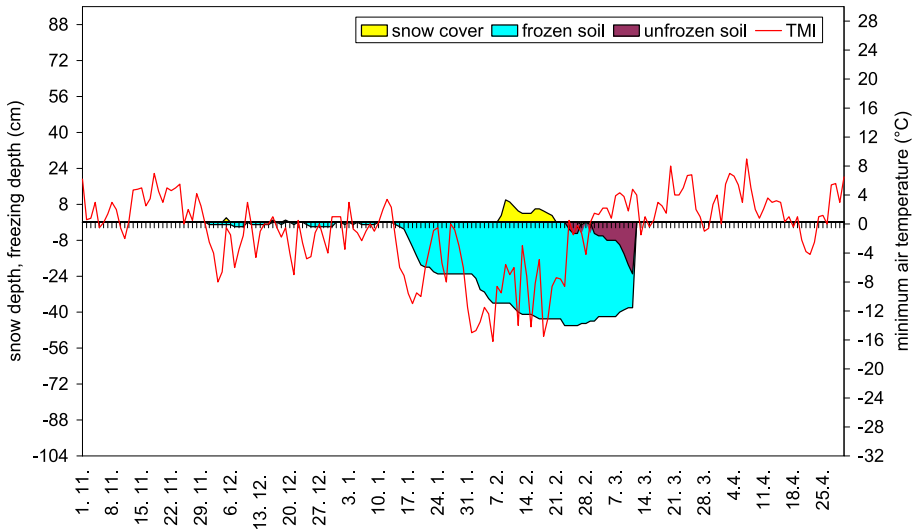Fig. 4. Interpolation of soil temperature measurement, cold season 1984–1985.

262

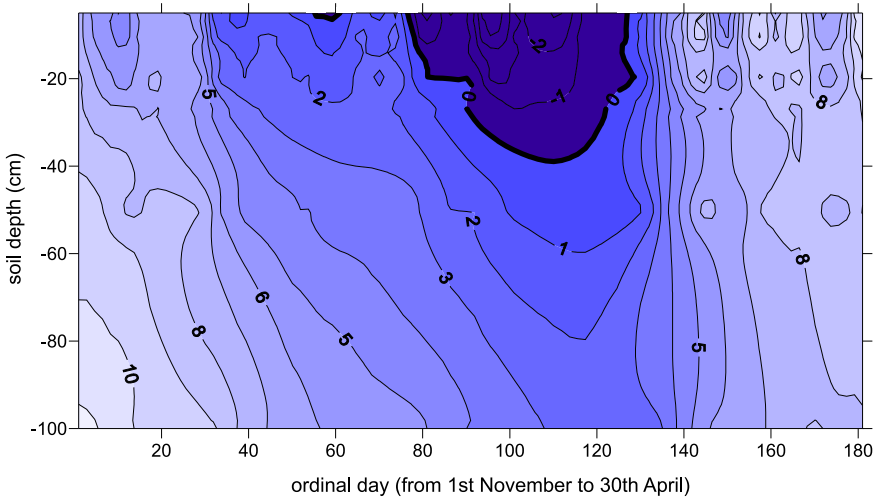Fig. 5. Dept of soil freezing, depth of snow cover and course of air ground temperature minimum, cold season 1990–1991.

Fig. 6. Interpolation of soil temperature measurement, cold season 1990–1991.
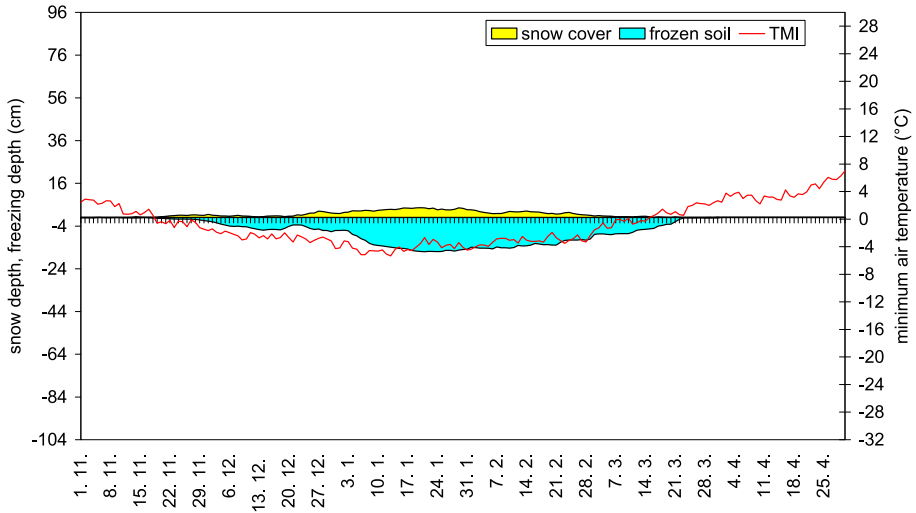
263

Fig. 7. Depth of soil freezing, depth of snow cover and course of air ground temperature minimum, average values for the period of 1971–2000.
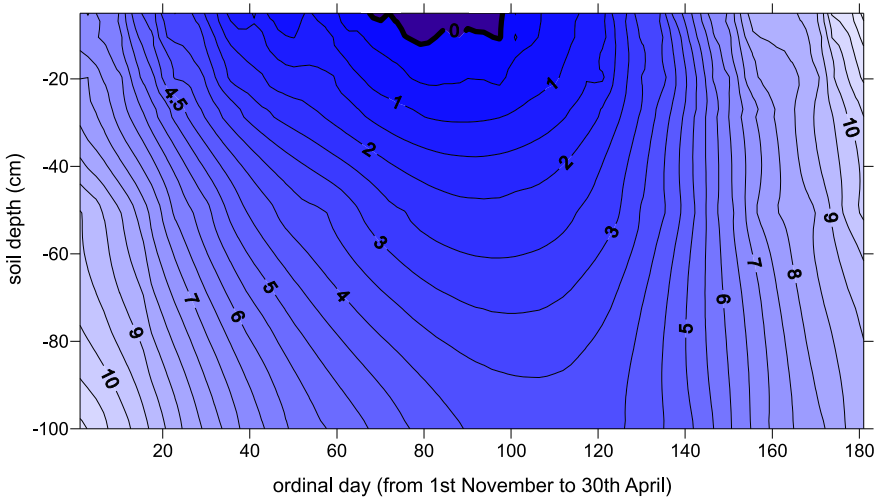

Fig. 8. Interpolation of soil temperature measurement, average values for the period of 1971–2000.
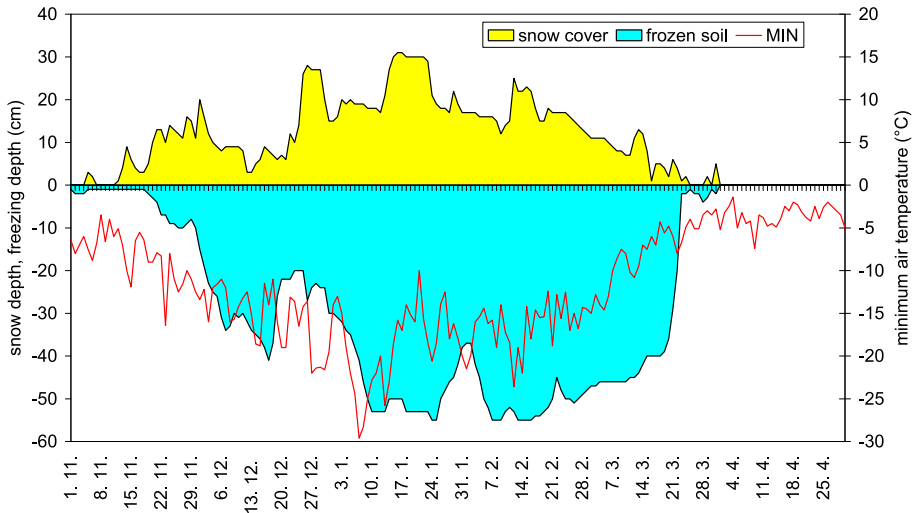
264

Fig. 9. Maximum depth of soil freezing, maximum depth of snow cover and course of minimum value of air ground temperature minimum for the period of 1971–2000.
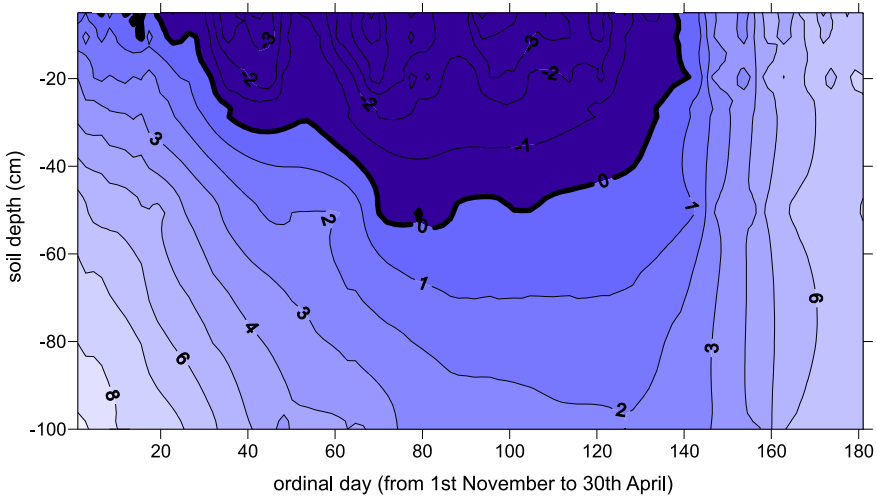

Fig. 10. Course of absolute minimum soil temperature for the period of 1971 to 2000.

265

Comparison of mean values obtained by both methods showed the most significant differences in freezing period lasting. Freezing period estimated by frost tube started on November 22. The depth of freezing did not reach to 5 cm until December 12. Freezing at 5 cm assessed by the soil temperature interpolation started on January 7 (i.e. 24 day latter). The maximum freezing depths determined by both methods correspond to each other quite well (16 cm by frost tube and 14 cm by soil temperature interpolation).

Figures 9 and 10 present the results of absolute maximum soil freezing depth for the entire evaluated period 1971–2000.

The absolute maxima of soil freezing obtained by both methods correspond to each other very well. Freezing period at 5 cm lasted from November 20 till March 24 in both cases. Also maximum depths of freezing determined by both methods are almost the same (i.e. 54 or 52 cm, respectively). The course of freezing determined by both methods is similar.

4. Conclusion

The depth of soil freezing is assessed directly by soil frost tube and indirectly from diagrams of soil temperature course according to 0 °C isotherm. The isotherm was graphically expressed by SURFER software. This program provides only graphical outputs and data set of interpolated isotherms cannot be subsequently obtained. Thus the regression analyses between data series of 0 °C isotherm and soil freezing depth cannot be included into the evaluation.

For comparison of the above mentioned two methods a data of Czech Hydrometeorological Institute agroclimatological station Pohořelice for the period of 1971–2000 were used. The soil type at Pohořelice station is fluvisol stratified (FLi) at floodplain deposits. Three real cold periods (1978–1979, 1984–1985 and 1990–1991) with different course of soil freezing and snow cover depth were chosen for the evaluation. Mean depth of freezing and absolute maximal depth of freezing were also evaluated.

The beginning and the end of freezing period assessed by both methods correspond to each other very well (with maximum several days accuracy). Both methods indicate more freezing periods caused by soil melting and freezing changing during the winter.

The soil freezing depth determined according to the soil temperatures is often lower than that determined by the frost tube. This difference might be caused by the graphic processing, as soil temperatures are measured only at given depths (5, 10, 20, 50 a 100 cm) and depth of zero isotherm is determined just by interpolation of these depths. Absolute daily maximum of freezing for long term period (non freezing depth determination) showed a punctual accordance of both methods.

Soil temperature interpolation method is not suitable when soil freezes just in shallow depths. The first depth of standard soil temperature measurement is 5 cm. Graphical output of the interpolation does not provide extrapolated values to the surface (i.e. 0 cm depth). Also a partial melting in shallow surface layer cannot by expressed by this method.

Frost tube measurement requires manual data collection in daily step while soil temperatures can be measured automatically. Soil temperature interpolation method allows soil freezing estimation without difficulty and time consuming manual measurement.

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