Realization of the parametric snow cover model SMFE for snow characteristics calculation according to standard net meteorological observations

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1 Introduction

Nowadays careful description of thermo-hydro interaction between land surface and atmosphere becomes topical in numerical weather prediction problems. It is connected with higher reality of atmospheric models, higher requirements to the accuracy and space-time resolution of described weather processes. It should be noted that land-surface characteristics are model variables, so further success of their forecasting depends on their initial values accuracy. The technology of making initial fields of these characteristics is based on operational meteorological observations processing. In case when this or that model variable is not the measured value, some functional dependencies are used.

In atmospheric models snow cover is described in terms of snow water equivalent (SWE) as a part of hydrological cycle. Its evolution can be described as a result of generated precipitation in model, percolation and melt water runoff. A special importance has the exact determination of snow water resources during melting of snow for more accurate estimation and forecasting of boundaries of its bedding, which define the whole structure of heat balance for snow-covered and snow-free areas. The difficulty is that SWE is not a part of standard meteorological observations, its measurements are held on some specialized stations in the form of time series with discreteness of several days. Such a situation doesnt satisfy demands of systems of initial fields construction for weather forecast models. Besides snow cover is a complex heterogeneous porous medium, consisting of all the phase components with constantly changing properties, which depend on external (atmospheric) and internal (for example, compaction due to gravity) factors. During the research of forecasts of snow cover characteristics, calculated by COSMO-RU, it was ascertained that using of simple dependences based on monotonous "aging functions" for initial GME-fields generation([3], [4]) can led to distortion in snow water equivalent values in two times and more ([6], [7]).

Integration of parameterizations implemented in atmospheric models, including multi-layer snow models (for example, [16]) needs to specify a whole number of regularly not measured external parameters, in the first place - heat and radiation fluxes. These variables can be taken only from atmospheric model, what inevitably leads to accumulation of discrepancies and departure from reality during long snow periods modeling.

This research is dedicated to the realization and discussion of the results got from rather economical approach of the snow "lively cycle" parameterization (model SMFE - Snow Model based on Finite-Element approach). The input parameters for SMFE are only regular standard meteorological station observations. The model can be used in future as an element of the initial fields construction system for atmospheric models (as an example - mesoscale model COSMO-RU) and also as an instrument for snow characteristics calculation at stations, where meteorological observations are held - for such applied tasks as, for example, holding the competitions on winter sports, hydrological forecasts, agricultural works planning.

2 Goals and Objectives

The goal of the present research was to realize the algorithm of snow cover characteristics calculation using only standard surface meteorological observations (snow depth, 2 meters temperature, dew point, 10 meters wind speed in SYNOP-code). It is very important for weather forecast tasks that realistic initial fields should be input in the model during the fixed periods of calculation start. So the algorithm should contain the main mechanisms in snow cover changing and be realized during short periods of time. The algorithm should be rather universal, i.e. it should provide realistic results for different climatic zones, including mountainous regions.

In the framework of PP CORSO for tasks realization connected with meteorological support of approaching winter Olympic Games in Sochi information about snow characteristics and their forecast for stations is needed. This problem can be solved, as nowadays automatic meteorological stations sending information about meteorological parameters with the high discreteness in time are set on sport facilities. An additional part of the research was to estimate the applicability of "classical" dependencies known from literature (for example, integral formulas for evaporation calculation).

3 Materials and Methods

The basis of the realized one-dimensional parametric model SMFE was the principle permitting to represent the snow column as a number of finite elements, which are in thermal and mechanical interaction with each other (fig. 1). Number of elements depends on the height of column. The column height is a snow height, measured at the meteorological stations. Each finite element has the form of cuboid with the height of 1 cm, length and width of 100 cm. I.e. if, for example, the measured snow height is 50 cm, this means that the column consists of 50 finite elements.

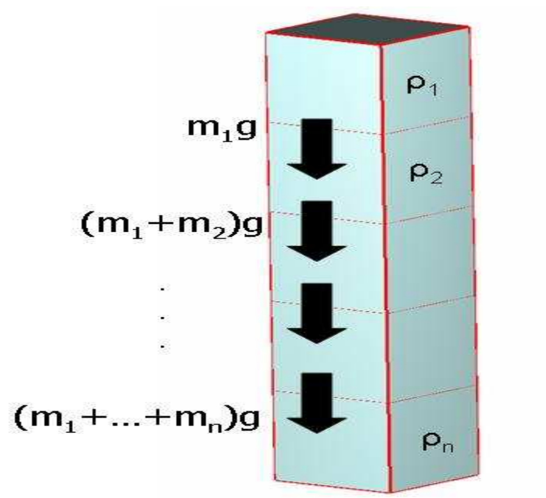

Figure 1: Representation of snow column in the snow model.

In the model the process of snow metamorphism due to gravity is taken into account according to dependence, suggested [17]. Thus, according to Yosida and Huzioka data Young modulus of snow E (Pa) as a function of snow density at temperatures from -1 to $-3°C$ and from -5 to $-13°C$ can be distinguished from formula (1) (we used the simplified condition for temperature: greater then $-5°C$ or less):

$$E_1 = (0.0167\rho - 1.86) \cdot 10^6 \ and \ E_1 = (0.059\rho - 10.8) \cdot 10^6 \tag{1}$$

It is supposed that finite elements experience only elastic deformation. The easiest elementary deformation is a relative elongation of some element:

$$e = \frac{l_n - l_0}{l_0}$$

where e - deformation, l_n - the length of an element after deformation, l_0 - the initial length of the element.

According to [1], in the capacity of fluidity limit the value of stress at permanent deformation $0.2\%(\sigma_{0.2})$ is chosen.

Thus for our case we have:

$$\frac{l_n}{l_0} = (1 - \sigma_{0.2}) = 1 - 0.002$$

Consider that following finite element experiences the pressure of the overlying layers the finish formula for snow density calculations take on form:

$$\rho = \frac{\dfrac{mg}{10^6(1-\sigma_{0.2})} + 1.86}{0.0167}, T > -5°C; \ \rho = \frac{\dfrac{mg}{10^6(1-\sigma_{0.2})} + 10.8}{0.059}, T < -5°C$$

where $m = (\rho_1 + \rho_2 + \ldots)H, H = 0.001\mathcal{M}$.

In many models for weather or climate forecasts in fresh-fallen snow description is used the assumption that fresh snow density is approximately equal to $100 kg/m^3$. Yet according to numerous researches (for example [5], [15]) fresh snow density can differ from this value. The dependence on air temperature for fresh snow density calculations was proposed in paper [2] (formula (2)), which were used in the developed one-dimensional model:

$$\rho_{s,f} = 67.92 + 51.25 e^{\frac{T_a}{2.59}}, T_a < 0°C; \ \rho_{s,f} = min(200, 119.2 + 20T_a), T_a > 0°C \tag{2}$$

where $\rho_{s,f}$ - fresh snow density, T_a - 2 meters temperature.

Depending on average daily temperature in model it is defined what kind of snow is fallen on the generated snow cover. If the temperature is positive, it is assumed that wet snow lies above the snow column (formed since the previous day), which will give snow density increase to the column "top" due to contained water. If the temperature is negative then dry snow is falling on the column, and further redistribution of density in snow column will depend on of what density and how much snow fell and whether can the snow cover existing from the previous day sustain the pressure of newly-fallen snow according to elastic deformation approach or considerably transform under its weight.

Daily temperature fluctuations according to formula (2) define whether density in the column is changing uniformly or there are sections with higher or lower density ("intrusions").

In case of snow depth decrease vertical distribution of liquid mass in elements of all "intrusions" is provided.

During snow melting processes and its water loss the runoff is included, which value depends on relief.

The case of so called blowing snow is taken into account, which is defined by the condition $100\% - (\frac{H_{new} \cdot 100\%}{H_{new}}) > 40\%$, where H_{new} - current snow height, H_{old} - snow height at previous day.

It is suggested that the maximum snow density in model cant be more then $700kg/m^3$ (conditionally equal to porous ice density).

For evaporation calculation from snow surface the widely known formula by P.P. Kuzmin ([8]) was used:

$$F = (0.18 + 0.098u_{10m})(e_{pot} - e_{2m})\ \mathcal{MM}/day \tag{3}$$

where F - evaporation rate, u_{10m} - wind speed at 10-m height, e_{pot} - saturated vapor pressure over snow, e_{2m} - air vapor pressure at 2-m height.

For saturated vapor pressure calculations on 2 meters and on snow surface (snow roughness length) the use of formula ([10]) is needed, with a glance of tables ([9]):

$$e^* = 10^{[c + b/T]}T^a$$

a, b, c - constants, depending on whether evaporation is held over water or ice, T - 2-meters temperature or snow surface temperature.

Vapor pressure at 2-m height is:

$$f = \frac{e(T)}{e^*(T)},\ e(T) = e_{2\mathcal{M}}(T) = e^*(T) \cdot f$$

where f - relative humidity, calculating with the use of dew point values:

$$f = 10^{[(c - c_1) + b/D - b_1/T]}D^a T^{-a_1}$$

D - dew point temperature, a_1, b_1, c_1 - constants.

If the value of dew point is higher then a freezing point, then relative humidity is calculated according to formula:

$$f = (\frac{D}{T})^a 10^{b[1/D - 1/T]}$$

In case of absence measurements of snow temperature (or - as an additional option of model) the following relation for its definition is used ([8], [12]):

$$T_{snow} = T_{2\mathcal{M}} - \frac{1}{\mathcal{K}}\sqrt{\frac{\tau_0}{\rho}}ln\frac{z}{z_0}$$

where $\mathcal{K} = 0.4$ - constant von Karman, τ_0 - shear stress, $\rho = 1.293kg/\mathcal{M}^3$ - air density, $z = 2\mathcal{M}$ - the height for standard observations at meteorological station, $z_0 = 0.001\mathcal{M}$ - aerodynamic roughness for snow ([11]).

The formula for wind shear stress τ_0 mostly used in practice of engineering calculations ([18]) looks as:

$$\tau_0 = \rho c|u_{10\mathcal{M}}|u_{10\mathcal{M}}$$

where $c = 0.003$ - a typical value of friction coefficient [18], which is got through substitution of the height of surface friction $z = 2\mathcal{M}$ and aerodynamic roughness $z_0 = 0.001\mathcal{M}$ in formula for friction coefficient calculation:

$$c = (\frac{k}{ln(\frac{z}{2z_0})})^2$$

The output parameters of the model for each station are snow density and snow water equivalent (average values), density distribution in the snow column (values for each finite element), snow surface temperature.

Model testing was held for some stations of the European part of Russia (fig. 2). Three seasons with snow cover were analyzed: 2009-2010, 2010-2011 and 2011-2012. Hydrological station observations of snow water equivalent and snow height with the frequency of once in 10 days, during snow melting - once in 5 days were used for comparison with the received model results of snow density and snow water equivalent. Initial fields of snow water equivalent for period February-March 2012, received from DWD modeling-assimilation global system (with the help of the global model GME), were also used for comparison. In this continuous data assimilation system the model snow parameterization coupled with aging functions is used - rather typical approach for problems like this. Particularly exactly such an information is used nowadays as initial data for weather conditions modeling in mesoscale model COSMO-RU ([13], [14]). A comparison between values of snow surface temperature received due to one-dimensional model and station SYNOP observations and initial field for the model COSMO-RU was held.

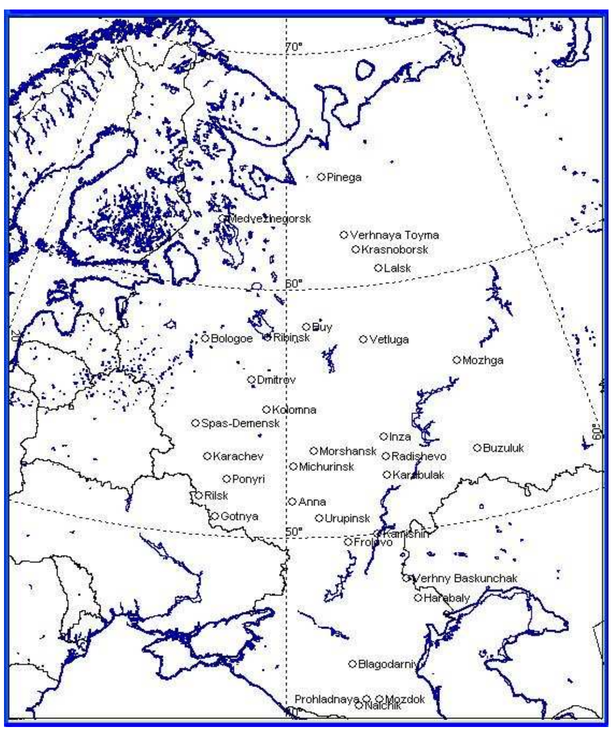

Figure 2: The researched region - European part of Russia.

Also the developed snow model was tested on the region of Sochi Olympic Games. The automatic meteorological stations data include measurements (temperature, relative humidity, wind speed, snow height, snow temperature) with the time interval of 30 minutes. The data of winter season 2011-2012 was available (fig. 7).

4 Results and Discussion

By comparing model results and hydrological observations it was revealed that the developed one-dimensional multi-layer snow model simulates well the snow evolution during the whole period of its existence (fig. 3, 4, 5). RMSE for water equivalent values for stations situated in different zones in the European Part of Russia is 1,5-8 mm by relative error of $15 - 20\%$. For example, for station Dmitrov RMSE is 1,3 mm by average absolute error of 7,6 mm and average SWE equal to 48 mm.

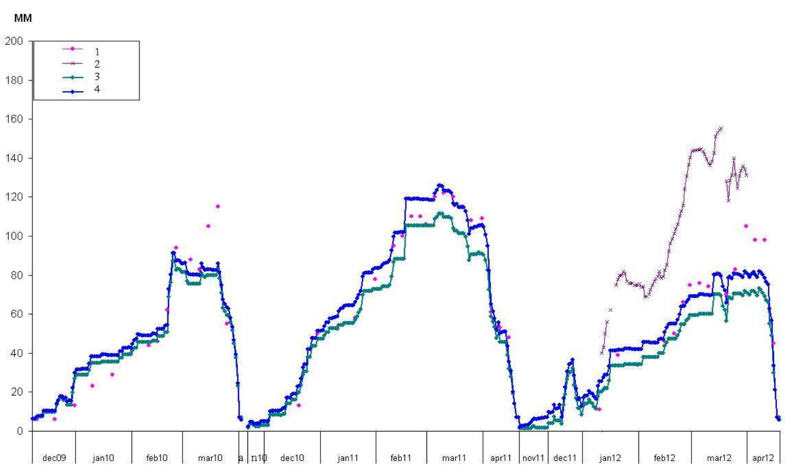

Figure 3: Snow water equivalent distribution during winter seasons 2009-2010, 2010-2011 and 2011-2012 for station Dmitrov: (1) hydrological station data; (2) initial field from the model GME, prepared for the model COSMO-RU; (3) model SMFE results; (4) model SMFE results with using formula (3).

As an example of successfulness of SWE modeling two stations can be examined: the first one - situated in the north of the European part of Russia, with predominance of low temperatures during snow falling (Medvezhegorsk), the second one - situated in unstable snow cover conditions, with predominance of temperatures near 0^oC during snow period (Nalchik). The analysis of model data makes it possible to conclude that in both cases the model simulates snow cover characteristics realistically.

It is much more smaller then discrepancies of the analogue values, calculated by GME (in the last case differences can reach $200 - 300\%$, and can change from 10 mm for southern regions to 130 mm - for northern) ([6]).

For station Medvezhegorsk the results of the model have more deviation in comparison with observations than for central and southern stations. It should be noted that this station is situated in forested area, and during cold season snow on trees can experience changes. These tiny changes can't be described in the model using only SYNOP data.

Thus the developed one-dimensional model accurately reproduces SWE evolution in time. This is achieved through using numerical finite-element scheme which allows taking into account the main principles of physical theory of elasticity.

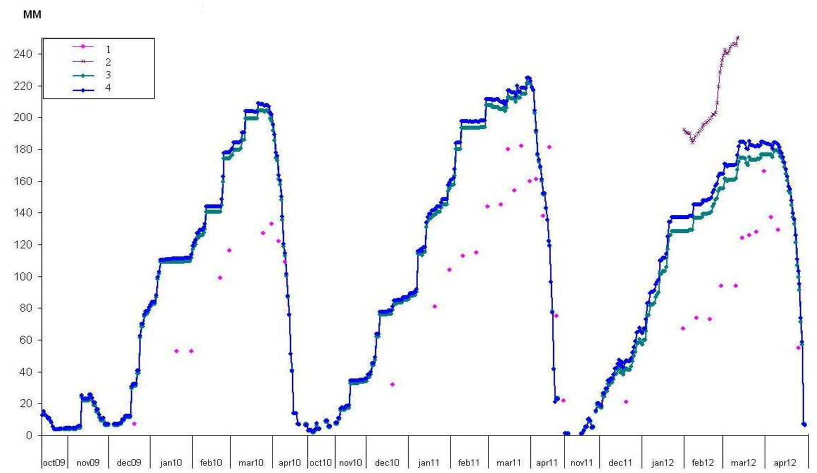

Figure 4: Snow water equivalent distribution during winter seasons 2009-2010, 2010-2011 and 2011-2012 for station Medvezhegorsk: (1) hydrological station data; (2) initial field from the model GME, prepared for the model COSMO-RU; (3) model SMFE results; (4) model SMFE results with using formula (3).

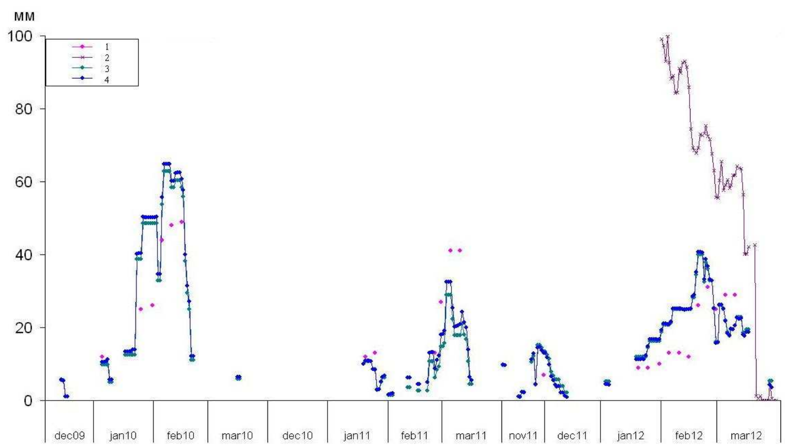

Figure 5: Snow water equivalent distribution during winter seasons 2009-2010, 2010-2011 and 2011-2012 for station Nalchik: (1) hydrological station data; (2) initial field from the model GME, prepared for the model COSMO-RU; (3) model SMFE results; (4) model SMFE results with using formula (3).

Snow surface temperature can be calculated in the model as an additional option. It is comparable with meteorological stations data (fig. 6). RMSE for the parametric model is less than 6^oC for 00 UTC for period 1 February - 31 March 2012, for snow surface temperature initial fields from GME-system - less than 5^oC. The same values are got for the developed model for periods of snow cover existence in different years 2009-2010, 2010-2011 and 2011-2012 for 00 UTC and 12 UTC. Some extreme low values can be observed (fig. 6), and it can be explained by using formulas for temperature calculations only for stable conditions (which are not always observed in nature).

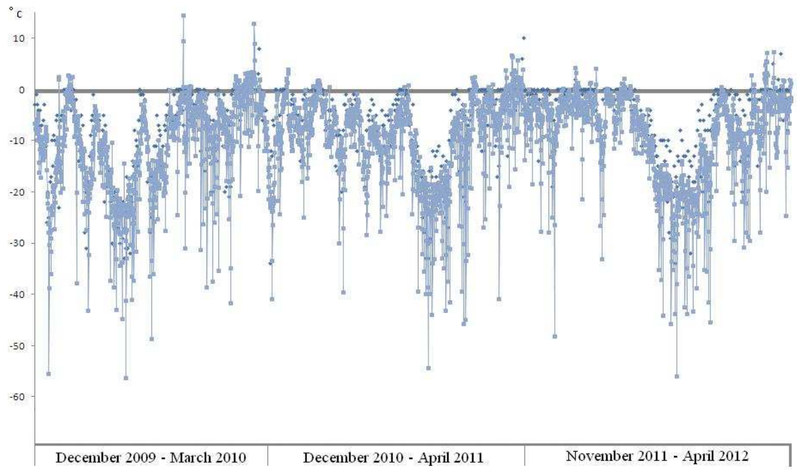

Figure 6: Snow temperature during winter seasons 2009-2010, 2010-2011 and 2011-2012 for station Poniri: blue dots - station data, gray dots - model results.

In order to calculate snow cover characteristics for the region of Sochi Olympic Games we use data with 30-minutes time interval from automatic meteorological stations. For winter period 2011-2012 we use stations, situated on the sports facility (fig. 7). As can be seen from the figure, snow height in mountain region can reach the value of some meters to the end of winter season.

The snow model makes it possible to calculate snow characteristics for the layer of snow. For providing meteorological forecasts during winter Olympic Games it is important to have knowledge about snow cover in the upper layer. As an example, the distribution of snow water equivalent was calculated for the upper 10 cm of snow cover for station 11 (fig. 8), as well as snow density (fig. 9). The model design allows receiving information about snow cover for any layer the user is interested in (so, it can be 50 cm or 20 cm or whatever).

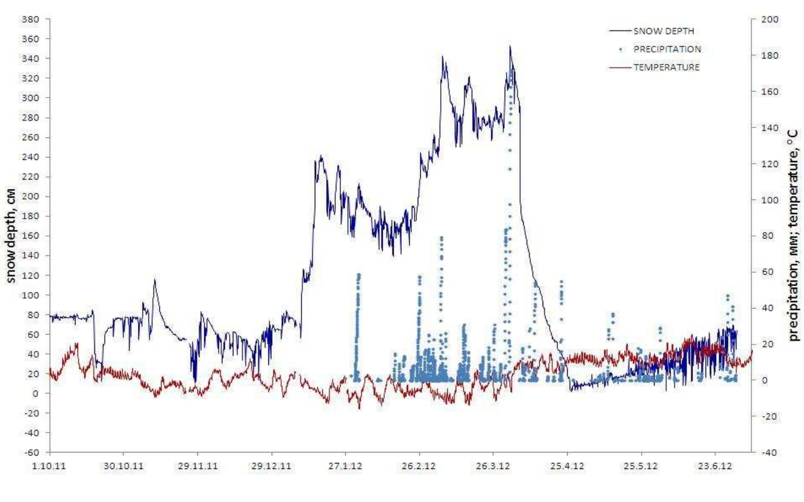

Figure 7: Distribution of snow depth, 2m temperature and precipitation for period 1 October 2011 - 1 August 2012 for automatic meteorological station 11 in the region of Sochi Olympic Games. The station height is 1580 m.

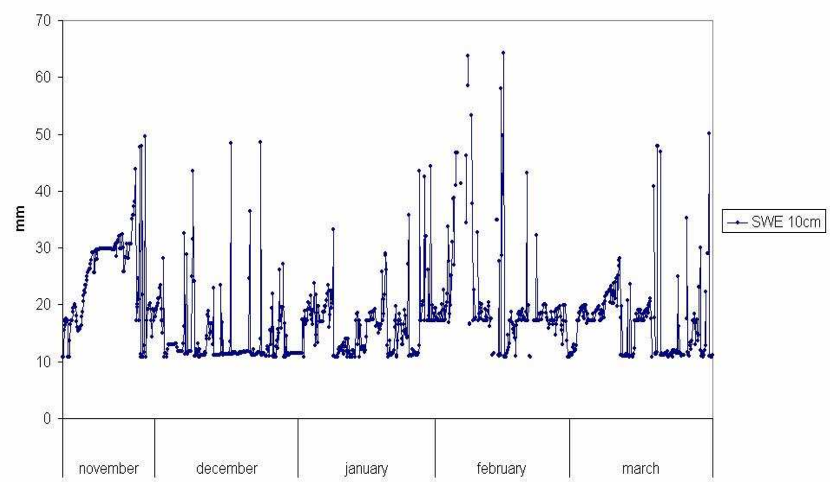

Figure 8: Distribution of snow water equivalent for the upper 10 cm for station 11 in the region of Sochi Olympic Games. 1 November 2011 31 March 2012.

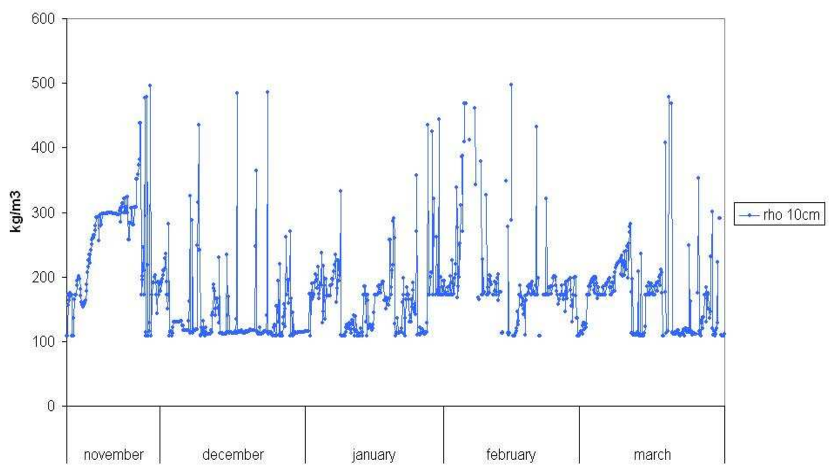

Figure 9: Distribution of snow density for the upper 10 cm for station 11 in the region of Sochi Olympic Games. 1 November 2011 - 31 March 2012.

5 Conclusion

The developed one-parametric numerical multi-layer model SMFE working with standard meteorological station data in SYNOP-code is realized. The structure of the model allows calculating of snow cover characteristics (SWE and snow density (average values for a snow column), snow density for each element, snow surface temperature) for each station with a discreteness, which is defined by snow depth measurements frequency (once a day - in case of stations situated at the European part of Russia, once in 3 hours - for automatic stations in the region of Sochi Olympic Games). Testing of SMFE based on physical elasticity principles by Russian meteorological stations situated in different climatic conditions is revealed that with its help realistic values of SWE and snow density can be obtained. The developed model was also tested for the region of Sochi Olympic Games according to automatic stations observations with high time discreteness. It is shown that snow characteristics can be calculated for any snow layer needed for a user. For that moment there is no such an observed data (SWE, snow density for snow period) in this region to compare with the model results. It is planned to develop the technology of operational making of analysis fields for snow cover in territories based on interpolation methods and combining the model results with satellite data and to enter the technology in the data assimilation block for mesoscale model COSMO-RU.

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