Theoretical model of the volumetric heat content of moist soil

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Abstract. In the scientific literature, the thermal properties of soils are described by three indicators: heat absorption capacity, heat capacity, and heat conductivity. It is proposed to introduce into practice the prognostic equation of the volumetric heat content of moist soil, as its energy characteristic, by which it will be possible to judge not only the phase (ice, water, steam) state of the water in the soil, but also the nature of the soil-atmosphere heat exchange, that is important to know during seasonal thawing and characterizes the power of the process. Since the degree of saturation of the soil with water determines the thermal properties of the soil, the key point of this research is to prove the legitimacy of using the prognostic equation to calculate the moisture content of the soil. Calculations using the proposed equations are not difficult, since they are based on data from the available information of the state hydrometeorological services. The main advantage of prognostic equations is that they are not of statistical origin. Consequently, they are not related to a specific geographic point, which allows analyzing the parameter being studied by building the calculated indicators in one row and thus finding patterns in the soil-atmosphere system. Studies were conducted for three geographical points located on the same longitude, but at the same time located in different soil-climatic zones. Studies were conducted for conditions above 0 °C inclusive. The research analyzes the results of the calculation of the predicted soil moisture content using two equations. A mathematical analysis of the equation was conducted, where the predicted value is the moisture content of the soil; a variable, the coefficient of moisture according to Ivanov. The legitimacy of using the index of the predicted soil moisture content in the model of the volumetric heat content of moist soil is theoretically proved.

1. Introduction

The literature on how solar variability affects climate is extensive [2, 7, 10, 15]. A weak anthropogenic effect and a strong contribution of the sun to climate change were proved [13,15]. An assessment of the impact of the Sun on the global average temperature of the surface layer of air and ocean waters was carried out [16]. Changes in ocean tidal dynamics have been studied [16]. Detailed studies are being conducted to assess the impact of climate change on various parameters related to the state of water resources with a view to more realistic future planning and integrated water resources management [1]. For this purpose, ecohydrological modeling of water resources and land use is being developed [14]. A model of global warming, caused by pollution of the habitat, has been developed [3]. A disproportion in the development of the northern zones of Russia [4,5] has been statistically proven and an innovative method for the development of the extreme north [2,13] has been proposed.

However, all models were developed based on a statistical multivariate analysis of hydrometeorological changes and are tied to a specific point. In addition, all the parameters included
in the equation, have a different dimension, which makes it impossible to identify patterns of processes occurring in nature. At the same time, the only source of energy is the Sun and, probably, it is more correct to evaluate all changes occurring in nature by energy units of measurement.

In the previous researches of the author, it was proposed to introduce an integral agrometeorological indicator of air temperature and humidity — the heat content (enthalpy) of humid air, as an obligatory energy characteristic of a climate-forming factor [10].

Later, the author introduced prognostic equations for the heat content of the soil [11]. Heat content (enthalpy) is a property of a substance, indicating the amount of energy that can be converted to heat with some constant effect.

Consequently, based on the heat content of the soil, we can judge how the heat energy of the soil takes part in the phase transitions of soil moisture, being released during the formation and condensation of soil moisture and consumed during ice melting and evaporation.

In addition, the difference in heat content of the contacting media (atmosphere - underlying surface) characterizes the heat exchange between the media. The underlying surface can be soil or water. Moreover, the speed and direction of heat transfer changes in the soil and atmosphere depend on their humidity.

The higher the humidity of the air and the soil, the higher their heat capacity, and as the temperature rises, their heat content increases.

The purpose of the work is to show the possibility of using a new model of the volumetric heat content of moist soil, taking into account the predicted moisture content of the soil.

2. Theory and methods of research

Volumetric heat content is the amount of heat contained in a unit volume (1 cm$^3$) of moist soil (J / cm$^3$). The heat content, as an additive function of the system, is equal to the sum of all its components. Therefore, to calculate the heat content of the soil, the author proposes to use the model of volumetric heat content (ims) of a moist soil [11]:

$$i_{ms} = c_{sp}t_s v_{ds} + c_w t_s v_w + c_{air} t_s v_{air}$$

where $v_{ds}$ is the volume fraction of the solid phase of dry soil; $v_w$ is the volume fraction of water; $v_{air}$ - the volume fraction of air.

The volume fractions of all phases add up to 1. Each phase is characterized by its volumetric heat capacity.

$c_{sp}$ is the heat capacity of the solid phase. On average, the heat capacity of the solid phase of the soil is $1.7 \cdot 10^6$ J/m$^3$; $c_w$ is the heat capacity of water. On average, the heat capacity of water is $4.2 \cdot 10^6$ J/m$^3$; $c_{air}$ is the heat capacity of air. On average, the heat capacity of air is $1.5 \cdot 10^3$ J/m$^3$; $t_s$ is soil temperature, °C.

Reliability of calculations by the proposed equation is possible, provided that the characteristics of each phase are by volume with the corresponding heat capacity. At the same time, the units of measurement should correspond to the values - cm$^3$ / cm$^3$ and J / cm$^3$ · deg.

We will consider the basic details of the equation.

In the solid phase of the soil there are mineral and organic matters. For most soils, the proportion of the mineral part is much higher than the organic part and in this case as $c_{sp}$, the values of the dominant mineral part are used in the calculation. For soils with a high proportion of organic matter, the volume fraction of each part is taken into account (the total volume fractions are equal to the volume of the solid phase) with the corresponding heat capacity [12].

The negligibly low value of the heat capacity of air with respect to the other components of the equation makes it possible to neglect this value in the calculations.
The highest value of the heat capacity of water in relation to other components of the equation informs that the thermal properties of soils depend on the degree of their saturation with moisture, the quantitative characteristics of soil moisture content.

Unfortunately, there is no wide range of experimental studies on soil moisture, since research is time-consuming or local with a short overtake of research. In the studies [7, 8], two independent models were presented according to the soil moisture content forecast (kg/m$^3$), and the calculations are based on the available information from hydrometeorological services.

To achieve this goal, in this study the possibility of using prognostic values of soil moisture content is analyzed. The information reliability of the proposed equations was based on: comparing the results of the two equations among themselves, as well as with the generally accepted coefficient of moisture according to Ivanov; the breadth of the climatic zone; the length of the analyzed mathematical series.

The latitude of the coverage of the soil-climatic zones is provided by the calculations of the moisture content of the soil and the Shashko coefficient for points located along the same longitude, but of different latitudes (Arkhangelsk, Vladimir, Rostov-on-Don).

The proposed equations are not of a statistical nature, but are based on thermodynamic laws, which make it possible to analyze the parameter being studied, building the obtained indicators in one row and finding patterns in the soil-atmosphere system. Thus, each studied parameter calculated for three points (across Arkhangelsk, Vladimir and Rostov-on-Don) were combined into one row. The length of each row was 990.

A mathematical analysis of the reliability of prognostic equations was carried out by comparing the results of calculations using two equations [7, 8] and mathematical analysis $y = f(x)$, where $y$ is the predicted value, soil moisture content; $x$ is variable, the coefficient of moisture according to Ivanov. In the second case, the row length was reduced to 18 due to the formation of groupings according to the coefficient of moisture according to Ivanov, which characterizes the types and subtypes of the landscape [5]. Statistical accuracy is provided for the number of observations 990 - the number of groupings 18.

3. Discussion of the results

Discussion of the research results was held in three directions:
1. Discussion of the result of the prediction of soil moisture reserves in two prognostic equations [7,8].
2. Discussion of the result of a mathematical analysis of the parameters of the predicted soil moisture [7] and the coefficient of moisture according to Ivanov.
3. Discussion of the results of the first and second clauses.

Analysis of the predicted moisture content values obtained on the basis of two equations [7,8] showed their equivalence.

3.1. An example of a forecast of quantitative changes in soil moisture $\Delta g$ in a changing climate using the equations proposed by the author [7,8].

Given:
1) Soil porosity was measured in cubic meters. For one hectare with a capacity of one meter, the porosity is equal to 5000 ($g_{max}$).
2) Temperature was measured in degrees Celsius. The average monthly temperature increased by one degree from 15 ($t_1$) to 16 ($t_2$)
3) Absolute air humidity was measured in grams per kilogram of dry air and corresponded to values of 8,1 ($f_{t1}$) to 6,9 ($f_{t2}$).

Absolute maximum air saturation in grams per kilogram of dry air at air temperatures ($t_1$) and ($t_2$) correspond to values — 10,9 ($f_{t1_{max}}$) and 11,6 ($f_{t2_{max}}$).

3.1.1. Calculation of soil moisture content by the equation [7]:

...
The first stage of calculation. Translation of all components into volume fractions. We do the following reasoning:

The maximum values of the dimensionless parameter $d$ at temperatures $t_1$ and $t_2$ correspond to values:

\[ d_{max}^1 = 10.9 \times 10^{-3} \text{ kg/kg dry air} \]
\[ d_{max}^2 = 11.6 \times 10^{-3} \text{ kg/kg dry air} \]
\[ d_1 = 8.1 \times 10^{-3} \text{ kg/kg dry air} \]
\[ d_2 = 6.9 \times 10^{-3} \text{ kg/kg dry air} \]

The moisture content of air $f$ is related to the parameter $d$ by the ratio

\[ f = p_w d \]

Where $p_w = 10^3 \text{ kg/m}^3$ is the density of water.

Therefore, the maximum moisture content of air at temperatures $t_1$ and $t_2$ corresponds to values

\[ f_{max}^1 = 10.9 - \text{ kg/m}^3 \]
\[ f_{max}^2 = 11.64 - \text{ kg/m}^3 \]

The current moisture content of air at a temperature $t_1 = 15 ^\circ \text{C}$ and humidity of 75% is the moisture content of air $f_1 = 8.14 \text{ kg/m}^3$; at a temperature $t_2 = 16 ^\circ \text{C}$ and humidity of 60% $f_2 = 6.93 \text{ kg/m}^3$.

The maximum moisture content of the soil that does not depend on temperature is equal to the porosity of the soil $g_{max} = 5000 \text{ m}^3/\text{ ha}$.

We translate this value into kg/m$^3$: 5000 m$^3$ of water = $5 \times 10^6$ kg of water. 1 ha of soil 1 m thick = $10^4$ m$^3$ and thus $g_{max} = 5000 \text{ m}^3/\text{ ha} = 5 \times 10^5 / 10^4 = 500 \text{ kg/m}^3$.

The second stage of calculation. We will calculate changes in soil moisture content. From equation (1) it follows:

\[ \Delta g = g_2 - g_1 = \frac{g_{max}}{f_{max}^2} f_2 - \frac{g_{max}}{f_{max}^1} f_1 = g_{max} \left( \frac{f_2}{f_{max}^2} - \frac{f_1}{f_{max}^1} \right) = 500 \left( \frac{6.93}{11.64} - \frac{8.14}{10.9} \right) = -75.71 \]

Conclusion: due to climate change, soil moisture reserves of the studied point are reduced by 75.71 kg/m$^3$.

3.1.2. Calculation of soil moisture content according to equation [4] from the standpoint of changes in the heat content of air. The formula of heat content ($i$) of moist air:

\[ i = C_{dr} t + d(\lambda + C_v t) \]

where

- heat capacity of dry air is $C_{dr} = 1.005 \text{ kJ/kg deg.}$; steam heat capacity is $C_v = 1.807 \text{ kJ/kg deg.}$;
- latent heat of vaporization is $\lambda = 2500 \text{ kJ/kg}$; $t$ - air temperature; $d$ - moisture content.

We will calculate the change in heat content of air:

\[ \Delta i = i_2 - i_1 \]

Where

\[ t_2 = t_1 + \Delta t, \quad d_2 = d_1 + \Delta d \]

and will neglect the part $\Delta t \Delta d$, after that we will get the result:
\[ \Delta i = i_2 - i_1 = (C_{dr} + d_1 C_v) \Delta t + (\lambda + C_v t_1) \Delta d \] 

(5)

We will calculate \( \Delta d \) from the formula (2)

\[ \Delta d = \frac{1}{p_w} (f_2 - f_1) = \frac{1}{1000} (6.93 - 8.14) = -1.21 \times 10^{-3} \] 

(6)

After substituting all known values in (5) we will find

\[ \Delta i = -2,04 \text{ kJ / kg} = -2040 \text{ J / kg} \] 

(7)

We will calculate \( \Delta g \) from formula (3), for which we substitute \( f_1 \) and \( f_2 \) with their values from formula (2)

\[ \Delta g = pg^{\text{max}} \left( \frac{d_2}{f_2^{\text{max}}} - \frac{d_1}{f_1^{\text{max}}} \right) = pg^{\text{max}} \left( \frac{d_1 + \Delta d}{f_1^{\text{max}}} - \frac{d_1}{f_1^{\text{max}}} \right) = pg^{\text{max}} \left( \frac{f_1^{\text{max}} \Delta d - d_1 (f_2^{\text{max}} - f_1^{\text{max}})}{f_1^{\text{max}} f_2^{\text{max}} (\lambda + C_v t_1)} \right) \] 

(8)

Substituting value \( \Delta d \) of formula (5) into (8)

\[ \Delta d = \frac{\Delta i - (C_{dr} + C_v d_1) \Delta t}{\lambda + C_v t_1} \] 

(9)

We will find

\[ \Delta g = pg^{\text{max}} \left\{ \frac{f_1^{\text{max}} \Delta i - (C_{dr} + C_v d_1) \Delta t}{f_1^{\text{max}} f_2^{\text{max}} (\lambda + C_v t_1)} \right\} = -75.75 \] 

(10)

Conclusion: due to climate change, soil moisture reserves are reduced by 75.71 kg / m³

Thus, \( \Delta g \) calculated by the formula (3) and (10) coincide with the accuracy of the second decimal. This gives the right to prefer the choice of a simpler method for calculating the moisture content in the soil according to formula (3) for the subsequent use of this equation in the prediction of the heat content of the soil.

3.2. Discussion of the result of mathematical analysis.
The analytical dependence \( y = f(x) \) is best described by the logarithmic function, which is clearly seen from Figure 1. Where \( y \) is the predicted value, soil moisture content; \( x \) is a variable, the coefficient of moisture according to Ivanov [3].

\[
y = 7.2673 \ln(x) + 76.54
\]

\( R^2 = 0.9833 \)

![Figure 1. The logarithmic curve, where \( y \) is the predicted value, soil moisture content; \( x \) is variable value, the coefficient of moisture according to Ivanov, the coefficient of determination - \( R^2 \)](image)

The high coefficient of determination (\( R^2 \)) of the logarithmic regression demonstrates not only that the model accurately describes the original data, but the main conclusion is that the prognostic value of soil moisture content and the coefficient of moisture according to Ivanov are two interrelated values. The principal difference between these characteristics is: the predicted value according to equations (1; 10) is the moisture content of the soil - this is the quantitative value of the soil moisture, and the coefficient of moisture according to Ivanov is the relative value by which we qualitatively judge the degree of soil moisture.

4. Conclusion
The study proved the possibility of using a new model of the volumetric heat content of a moist soil, taking into account the predicted moisture content of the soil. The possibility of using the soil moisture prediction in the model of the volumetric heat content of the soil was confirmed by calculations of two prognostic equations and the result of mathematical analysis. The analysis of the predicted values of moisture content, obtained on the basis of two equations, showed their identity with an accuracy of the second decimal.

The high coefficient of determination (\( R^2 \)) of the logarithmic regression confirmed that the prognostic value of soil moisture and the coefficient of moisture according to Ivanov are two interrelated values. The volumetric heat content of a moist soil determines the entry of water and mineral substances into plants, growth, respiration, etc., and forms an ecosystem. The use of the prognostic model of soil moisture content provides a quantitative description of the influence of specific climatic conditions on the condition of the soil layer. The use of the predictive model of the volumetric heat content of a moist soil will make it possible to judge the phase transitions of water in the soil; heat exchange processes in the soil-plant-atmosphere system; spreading natural vegetation and choosing agricultural crops.
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