Automatic meteorological measuring systems for microclimate monitoring

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Abstract. The paper presents a description of the atmospheric-soil measuring complex (ASMC) intended for mobile and stationary long-term automatic measurements of the basic parameters of the atmosphere, soil and water. The device developed by the Institute of Monitoring of Climate and Ecological Systems of the SB RAS has a number of differences from analogues. To substantiate the possibility of using the device as a meteorological value meter, the data of measurements of air temperature and humidity, soil temperature, snow cover depth were verified. The data obtained by ASMC were compared with standard meteorological instruments. As a result of the analysis, high correlation coefficients between the time series were obtained. The average error of air temperature in the ASMS measurement is less than 0.2°C, and 91% of the measurements are within ±1°C. The average air humidity error is 5%, 70% of the measurements are within 5% of the error, and 95.5% of the measurements are within 10% of the error. The average error in soil temperature measurements during the warm period is 0.5°C, during the cold period is 1.5°C. The average error in measuring the snow cover depth is 5 cm and 90% of the measurements do not exceed it.

1. Introduction
Systematic observation of the climate system is usually carried out by national meteorological centres and other specialised bodies. They take measurements and make observations at standard preset times and places, monitoring atmosphere, ocean and terrestrial systems. Since national monitoring systems all form part of a global network, it is vital that there is as much consistency as possible in the way measurements and observations are made. This includes accuracy, the variables measured and the units they are measured in [1].

The existing network of meteorological stations of Russian Hydrometeorological service has more than 1500 stations, but their density decreases from west to east. Measurements at meteorological stations in Russia began more than a hundred years ago [2], but massive observations began in Russia in 1930-1950 [3]. Current rates and scale of climate change form new conditions for the existence of the natural environment [4]. For their control, it is necessary to have a developed network of climate monitoring stations covering large areas with high spatial resolution.

A unique atmospheric-soil measuring system (ASMS) was developed at the Institute of Monitoring of Climate and Ecological Systems of the SB RAS (Tomsk) [5]. ASMS is designed for mobile and stationary long-term automatic measurements and recording of the main parameters of the atmosphere,
soil and water. ASMS is different from existing measuring systems with low power consumption, a wide range of connected sensors, an autonomous mode of operation, operability in a wide range of environmental conditions and a low price.

Currently, more than 200 different modifications of ASMS operate on the vast territory of Siberia and the Far East.

2. Models and Methods
The atmospheric-soil measuring system can be equipped with soil and air temperature sensors, the depth and temperature of the snow cover, the level of bog or ground waters, the sum of atmospheric precipitation, wind speed and direction, soil and air humidity, solar radiation characteristics, carbon dioxide concentration, etc.

There are two types of ASMS - with the use of concealed installation loggers ("anti-vandal") and stationary non-masked stations.

Vandal proof ASMS designed for hidden installation which determines the inability to use unmasking structures: antennas, solar panels and many types of air sensors. As a result of these limitations, a controller with ultra-low power consumption (battery power) was developed with large internal non-volatile memory for data recording and USB interface, using a special cable with a sealed connector to connect to the logger, and maximum degree of protection of the enclosure IP68 (possible operation below groundwater level). Only underground sensors can be used in vandal proof ASMS: soil temperature, moisture, conductivity, as well as, water level, in some cases, snow depth and air temperature sensors (table 1).

| Table 1. Main characteristics of vandal proof ASMS. |
|-----------------------------------------------|
| **Value** | **Characteristics** |
|---|---|
| Size of non-volatile memory | 4 MByte |
| Recording interval | (1 000 000 records) |
| Maximum number of connected digital temperature sensors, pcs. | 90 |
| Number of inputs 10-bit for analog-to-digital converter | 7 |
| Current consumption in stand-by mode, mA | 0,07 |
| Average current consumption in active mode, mA | 10 |
| Average battery life, years | 5 |
| Operating temperature range of the recorder unit, °C | from −55 to +65 |
| Interfaces | USB, SDcard, 1-Wire, I2C |
| IP Code | IP67, IP68 |

The microcontroller (ATMEGA1284) is used in the logger, which through the digital interface (1-Wire) interrogates temperature sensors (DS18B20), analog inputs and stores data in non-volatile memory (AT45DB321) with reference to the measurement time, using a clock (PCF8563T). In the memory of the logger, the supply voltage is also fixed (table 2). The USB interface (FT232RL) allows the ASMS to communicate with the computer to configure its operation and read data.

The atmospheric-soil measuring system, with an autonomous controller-registrar (ACR) as a base element, is designed to create monitoring networks [6]. ACR, in contrast to the hidden installation recorder, is supplemented with additional analog and digital interfaces (RS485, RS232 - 2 pcs.), and most importantly, it can connect to GSM, Wi-Fi, and satellite Internet networks through expansion modules. The power of the recorder is provided by the lead–acid battery 12FGHL48, which, through a circuit with a temperature correction of the charge voltage, is powered by a low-power solar battery.

Temperature and humidity sensors located at a level of 2 m are protected from sunlight and atmospheric precipitations by a plastic shield. In the wind speed and direction sensor, a variable resistor and reed switch are used. The total solar radiation sensor (2 channels) is placed on a mast at a...
height of 1.5 m. The radiation flux, passing through the PTFE protective filter falls on two blackened and two shiny aluminum plates heating them and by attaching them to the back side platinum thermoresistors determine the flux density of solar radiation from the difference in resistances.

According to the sensor-profile of the height of the snow cover the snow level is calculated from the temperature difference at the air-snow interface. Liquid precipitations collected by the inlet section of the precipitation sensor funnel are poured into one of the rocker cups, which, after filling the cup (0.2 mm of precipitation), is tilted, substituting another cup for the funnel, while the magnet fixed to the rocker passes past the reed switch, causing its closure.

The probe of the soil temperature is located at a distance of more than 1 meter from the other sensors and the logger, and contains digital temperature sensors at different levels (from a surface up to 10 m deep into the soil). The probe is made in the form of a three-wire printed circuit board with soldered high-precision digital thermometers, protected by a shrink tube. The soil moisture sensor measures the ratio of the volumetric water content to the volume of the substance by the specific permittivity. The water conductivity is measured by the bridge circuit at the ultra-low frequency of the alternating current. The electrodes are made of stainless steel.

The ASMS software makes it possible to visualize the time series of data. The data is exported to text format. ASMS allows receiving on-line information on the atmospheric and soil climate characteristics, to compile a database for analysis of information.

Due to the use of original plastic mast constructions, the modularity of the constructs and the use of hermetically sealed connectors, it was possible to achieve simplicity in assembling, installing and repairing the complex in remote and inaccessible places (figure 1, figure 2).

3. Results and Discussion

Based on the results of parallel synchronous measurements of the atmospheric soil measuring system and the meteorological station Tunka (Republic of Buryatia), a comparative assessment of the data and an analysis of the correctness of ASMS use for autonomous monitoring were carried out. At the moment, the air temperature, soil temperature, air humidity and snow depth sensors have been compared within the period 2012-2018.

According to the Manual on Hydrometeorological Stations and Posts [7], measurements by thermometers and hygrometer are carried out 10 minutes before the end of the period, that is, measurements of the air temperature at the weather station should coincide with the ASMS

Table 2. Main sensors used in ASMS.

| №  | Component part                           | Measuring range       | Accuracy   |
|----|-----------------------------------------|-----------------------|------------|
| 1  | Temperature sensor DS18B20              | from -55 to +55°C     | ±0,1°C     |
| 2  | Air humidity sensor HIH-5031            | from 0 to 100%        | ±3,5%      |
| 3  | Soil moisture sensor TRIME-PICO32       | from 0 to 100%        | ±2%        |
| 4  | Atmospheric pressure sensor MPL3115A2  | from 500 to 1100 hPa  | ±4 hPa     |
| 5  | Wind speed and direction sensor Davis   | from 0,9 to 78 m/s    | ±5%        |
| 6  | Liquid precipitation sensor Davis 7852M| from 0 to 1000 mm/h   | ±5%        |
| 7  | Pyranometer 2 channel (albedometer)     | Range from 0,35 to 9 μm| ±10%      |
| 8  | The level of groundwater sensor         | from 0 to 10,5 m      | ±1%        |
| 9  | Snow cover depth sensor                 | from 0 to 2 m         | ±0,05 m    |
| 10 | Ultrasonic sensor of snow cover depth MB7384| from 0 to 4 m  | ±0,015 m   |
measurement 15 minutes before the end of the period. With allowance for inertia correction, the smallest difference between measurements was obtained when measured 30 minutes before the end of the period.

Figure 1. Hidden vandal proof monitoring station (Tunka National Park, Republic of Buryatia)  
Figure 2. Open monitoring station (Davsha passage, Barguzin National Park 30 km from Baikal)

Measurements of air temperature by a psychrometric thermometer in a Stevenson screen are made every three hours, and automatic measurements are made every 15 minutes. To understand the reasons for the deviations in the measurements of different instruments, four periods were recorded by ASMS: 15 minutes and 30 minutes before the end of the period, at the end of the observation period (on time) and 15 minutes after the end of the period.

Correlation coefficients between weather station data and data for all four periods of ASMS are more than 99%. The maximum correlation with the data of the weather station in time "for 30 minutes" (99.9%). Mean deviations in all terms were 0.1-0.2°C. The smallest differences were found between weather station data and ASMS data 30 minutes before the end of the observation period at the weather station. The absolute mean deviation is 0.5°C, the amplitude and dispersion are 0.6°C. Analysis of the deviations showed that within ±1°C there were 88% of measurements.

For comparison of air humidity observations, similar studies were conducted. The main method for determining air humidity at a meteorological station is a psychrometric one, which is based on measuring the air temperature and the temperature of a water-moistened thermometer. An additional method for determining air humidity is sorption, or hygrometric, based on the change in the length of the sensing element (skim hair) when the humidity of air is changes. The absolute average error of ASMS when compared with the data obtained at the meteorological station was 5%, the maximum overestimation – 28% and the maximum underestimation – 30%.

For a more accurate comparison, all measurements were divided into two periods: warm (T> 0°C) and cold (T <0°C). When comparing, it was revealed that the deviations between the data were higher in the warm period - an absolute error of 6%, while in the cold – 4%. The maximum overestimation in the warm period is 28%, in the cold period - 19%. The maximum underestimation in the cold period is 30%, in warm - 14%.

Regression equations for different temperature ranges were derived to improve ASMS data. Analysis of the data showed that after correction 54% of measurements fit to the range of deviations of ±3.5%, 70 % of data are within ±5% of error and 95.5% of measurements are in ±10% range of deviations (making the error of the hygrometer at the weather station).

The resulting differences and errors are partly due to poor air exchange in the Stevenson shield, which prevents rapid response to changing conditions in the atmosphere. In automatic equipment, radiation protection is made of plastic. It protects a little worse from direct solar radiation, but the
design itself allows the sensor to respond better to atmospheric changes and measure the air temperature and humidity almost without a delay.

Measurements of soil temperature at weather stations by extracting deep soil thermometers are carried out at depths from 80 to 320 cm once a day and, therefore, are not averaged. While the data at depths from 20 to 40 cm in the warm half of the year measured 8 times a day were brought to average daily values. ASMS data on soil temperature for the period from April 1, 2013 to April 1, 2016 with 1 our step were also averaged to daily values.

Correlation coefficients have high values at all depths for each month (from 90% and higher). But at a depth of 240 cm in September, low correlation values were recorded - 66 (2014), 69 (2013), and 83% (2015). In September, the soil temperature, measured with the help of an atmospheric soil measuring system at a depth of 240 cm, is higher by an average of 0.5°C. Such differences were observed in all years. In addition, low values of the correlation coefficient were also observed at a depth of 320 cm and fall in April-May. The values of the correlation coefficient in these months vary from 55% in April 2015 to 6% in April 2014. Comparison of the temperature at these depths during these periods shows a difference of 0.1-0.2°C. Such differences are within the limits of the error (0.2°C) of the extracting thermometers. Thus, we claim that it is possible to neglect the low values of the correlation coefficient, referring to small annual temperature fluctuations at a depth of 320 cm.

So the greatest deviations in soil temperature from ASMS observed at a depth of 20 cm (higher by 1.8-2.0°C) in the cold season. Differences in soil temperature values decrease with the transition from the cold period to the warm one, in summer at a depth of 20 cm they are minimal and average 0.5-0.8°C.

With increasing depth, there is a decrease in deviations between the ASMS and the extracting thermometers. So at a depth of 160 cm, the soil temperature in the ASMS is more by 1.0-1.5°C in spring and summer and less by 0.1-0.3°C in autumn and winter.

Thus, the obtained results show that soil temperature sensors are suitable for monitoring the temperature regime of soil and have small errors at depths of 20 to 320 cm in the autumn, spring and summer periods. Large errors arising in the winter period are partly due to the features of temperature measurement by soil extracting thermometers. At the same time, it is possible to make an additional correction to the temperature in the winter period in order to neutralize the data inaccuracies.

The increase in air temperature has a significant impact on the state of soils in the permafrost zone, which occupies more than 65% of the territory of the Russian Federation. The most important climatic parameters that determine the temperature of the soil and its freezing / thawing, are air temperature and snow cover depth [8].

To solve the problem of automatic measurement of snow cover depth, the method for determining the air-snow boundary was chosen for finding temperature extremes in the vertical temperature profile. The depth of the snow cover is determined by exceeding the preset threshold value of the difference in readings between two neighboring thermometers, starting from the upper one. The measurement period is 1 hour. The number of temperature sensors in the measuring rail is 20, the distance between the sensors is 25 or 50 mm.

To verify the calculation of the height of the snow cover, the meter was equipped with an ultrasonic height sensor, which corresponds to the data of the snow measuring rod. For calculation, the time interval was selected from 09.09.2017 to 31.03.2018.

The correlation coefficients between the sensors for the entire period were more than 90%. At the beginning of the cold period (September-October) ASMS overestimates the depth of the snow cover by 5 cm, which is within the declared error. During the period of active accumulation of snow (October-January), 90% of the measurements are within the limits of the error, the remaining 10% of the ASMS underestimates the snow cover depth by 6-10 cm. At the end of the cold period (February-March), the ASMS lowers the depth of the snow cover by 5 cm, which is also within the measurement error of the instrument.
Using the methods of mathematical modeling of the measurement of depth and temperature of the snow cover, it is possible to calculate the effective thermal diffusivity of snow and determine its density.

4. Conclusion
The atmospheric soil measuring system (ASMS) developed at the Institute for Monitoring of Climate and Ecological Systems of the SB RAS allows to conduct microclimatic and meteorological measurements to be made in difficult-to-access landscapes. The ability to install diverse systems - hidden vandal proof and open, as well as a flexible sensor connection system gives the consumer the opportunity to realize their needs.

In addition to sensors, ASMS can be equipped with modern communication and data transmission systems, and can also be powered by various types of energy carriers (solar panels, batteries). A relatively low price and simple, but high-quality materials allow the consumer to create networks of automatic monitoring in many landscapes, including water bodies [5,9].

Verification of ASMS sensors with standard meteorological data showed that sensors for air temperature, air humidity, soil temperature and snow depth can be used to measure the corresponding meteorological quantities. The series of air temperature data have a correlation of more than 99%. The average deviation in all terms does not exceed 0.2°C. Within ±1°C there are 91% of measurements.

The humidity sensor has an average error of 5%. After correcting the data, 54% of measurements entered the deviation range of ±3.5%, 70% within ±5%, and in ±10% (making the error of the hygrometer at the weather station) have 95.5% of the measurements.

The soil temperature data series have correlations of 90% or more for different soil profiles in winter-spring, the soil temperature according to ASMS is higher by an average of 1.0-2.0°C, in summer and autumn it is lower by an average of 0.1-0.8°C.

Snow depth data have an error of 5 cm, which includes 90% of all values. The maximum error is 10 cm.

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References
[1] WMO 2016 The Global Observing System for Climate: Implementation Needs p 303
[2] Pavlov A V 2008 Monitoring of Permafrost Zone (Novosibirsk: Geo) p 229
[3] Gilichinskii D A, Byhovec S S, Sorokovikova V A, Fedorov-Davidov D G, Barry R G, Chang T, Gavrilova M K and Alekseeva O I 2000 Use of data from meteorological stations to assess long-term trends changes in soil temperature on the territory of the seasonal and permafrost cryolithzone in Russia Earth’s Cryosphere 4(3) 59-66
[4] The Second Assessment Report of Roshydromet on Climate Change and Their Consequences on the Territory of the Russian Federation 2014 (Federal service for Hydrometeorology and environmental monitoring) p 605
[5] Gruza G V, Rankova E Y, Rocheva E V and Smirnov V D 2015 Current global warming: geographical and seasonal features Fundamental and Applied Climatology 2 41-62
[6] Ciais P et al 2013 Carbon and Other Biogeochemical Cycles. In: Climate Change The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed Stocker T F and Qin D et al (Cambridge: Cambridge University Press) p 1535
Anisimov O A and Sherstiukov A B 2016 Evaluating the effect of environmental factors on permafrost in Russia Earth's Cryosphere 2 90-9
Golovatskaya E A and Dyukarev E A 2012 The influence of environmental factors on the CO₂ emission from the surface of oligotrophic peat soils in West Siberia Eurasian Soil Science 45(6) 588-97

[5] Kurakov S A 2012 Autonomous Environmental Monitoring System Sensors and Systems 4 29-32

[6] Bazarov A V, Badmaev N B, Kurakov C A, Gonchikov B-M N, Cibenov U B and Kulikov A I 2016 Measuring complex for automatic long-term monitoring of atmospheric and soil climatic parameters Instruments and Experimental Techniques 4 158-9

[7] Manual for Hydrometeorological Stations and Posts 1985 (Leningrad: Hydrometeo Pub.) vol 4 chapter 1 p 300

[8] Dyukarev E A 2015 Influences of air temperature and snow cover on the seasonally frozen soil layer characteristics Earth's Cryosphere 19(3) 39-45

[9] Kiselev M V, Voropay N N and Dyukarev E A 2017 The temperature regime of the soil sedge-sphagnum fen in the southern taiga of Western Siberia Geography and Natural Resources 1 110-7