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Intelligent Monitoring of Air Temperature by the DATA of Satellites and Meteorological Stations

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ABSTRACT Climate models are the primary tools for investigating the response of the climate system to various forcings and for climate predictions. The combined use of the data from remote sensors and meteostations allows taking into account the spatial and temporal components of monitoring. In this study the temperature forecasting technique was improved by using the data from thermal imaging satellites and weather stations. This technique uses for this purpose the model of dependence of temperature received from satellite imagery on the temperature obtained from existing meteorological stations. During the investigation of the variables selected from the input data array, it was shown that satellite imagery data can be used in regional models of temperature prediction, and temperature traces obtained from satellite imagery and weather stations at similar points show similar dynamics. The effectiveness of the group method of data handling using multi-row algorithm for forecasting temperature for areas with no meteorological stations is shown.

KEYWORDS climate models; intelligence monitoring; thermal imagery; Landsat satellites; machine-learning; group method of data handling; temperature.

I. INTRODUCTION

THE technologies of the Internet of Things provide new opportunities to address modern environmental problems [1]. Prediction of weather and climate change is essential for science and economy. It is possible only as a result of systematic long-term observation of it. Temperature, as one of the leading climatic indicators of the territory, is used to analyze climate change and create climate models of different levels [2]. Now, regular temperature data of the specific area are obtained, primarily from meteorological stations. At the same time, the grid of meteorological stations is not sufficiently branched throughout the territory of Ukraine. Also, as a source of temperature data, thermal imaging of satellites can be used to obtain temperature data for each surface point (accuracy is determined only by the resolution of space images). However, the frequency of thermal imaging is not regular, and in general, it is much lower than the frequency of obtaining data from meteorological stations. Thus, the use of space images allows us to take into account the spatial component of monitoring and data from meteorological stations – temporal component, and their combination will allow creating a complex system of the temperature monitoring of specific territory [3, 4]. There are already comprehensive studies that demonstrate the connection between Remote Sensing and the creation of climate models, but they also indicate some limitations when using such data [5].

Simulation by observed data is a necessary condition for monitoring since it allows us to evaluate the current situation quickly and predict its development. In particular, the effectiveness of the use of inductive modeling methods for modeling of climatic parameters, one of which is temperature, is proved. Thus, the development of the method of forecasting the temperature of air based on the establishment of functional dependencies between the investigated parameters is relevant.

The purpose of the study is to develop an information system for intelligent monitoring of the temperature conditions of the territory by satellite images and data of meteorological stations.

II. RELATED WORK

Nowadays some studies prove the efficiency of using the thermal imaging data for forecasting and analyzing the temperature of the air. In particular, papers [6, 7] demonstrate a set of approaches to the determination of air temperature based on space images. Quite often, this definition of temperature is given to solve practical problems [8]. Often, time series analysis algorithms are used to analyze the temporal dynamics of temperature. This is possible since data from most satellites have been available on average from the eighties of the last century [9].

Many studies show the use of thermal channels for the determination of thermal anomalies in cities, plants, or water bodies. Some works demonstrate methods for detecting and predicting the distribution of forest fires by thermal imaging from satellites [10, 11].

There are different approaches to how data can be obtained and processed. In particular, the study [12] used a model to approximate the annual temperature cycle and obtain periodic parameters to describe annual changes in surface temperature, including average and maximum values, both during daytime and at night.

The effectiveness of using the group method of data handling (GMDH) for forecasting climatic indicators is shown in many studies. Notably, the paper [13] demonstrates approaches to modeling and predicting average wind speed per hour. Several studies offer integrated algorithms for creating climatic models. Thus, the article [14] proposed a method that was obtained by integrating the kernel principal component analysis method with the locally weighted group method of data handling, which can be obtained by combining GMDH with the method of local regression and weighted least squares regression. The paper [15] presents another example of the frequent use of several algorithms. In particular, in this case, GMDH was used for creating a climate model, neural network – for predicting wind speed and wind power in the short term and wavelet noise reduction – for filtering high-frequency emissions in wind speed data, providing a smooth neural network training.

The work [16] proposed the use of inductive simulation methods for the recovery of incomplete or short-term data recorded in large regions and the creation of prognostic climatic models on their basis.

This paper improves the methodology for evaluating the air temperature in hard-to-reach places, using the model of the temperature dependence of the determined by thermal imagery on the temperature obtained at existing weather stations, and creating a monitoring information system.

III. JUSTIFICATION OF THE RESEARCH METHODOLOGY SELECTION

As it is known, monitoring is a technology for providing information to decision-making processes [17, 18]. The requirements for this information technology are determined by the kind of information that the super-system needs to support the formation of control actions in managing systems. In the case of environmental monitoring, these will be ecosystems [18]. Mainly, the identification of patterns in the temperature regime of the territory is necessary to predict possible undesirable events and to introduce, if necessary, adjustments to economic and other activities. The solution to numerous problems associated with the study of the laws of the temperature regime requires the acquisition, processing, and conversion of large volumes of data – the results of observations. Today, the processes of acquiring and processing various climate characteristics are an extremely complex process.

The features of the climate system introduce significant restrictions on the choice of methods and tools suitable for climate prediction. Therefore, the assessment of future climate change is fundamentally possible only in the form of a specific probability distribution; thus, the task of predicting climate is reduced to determining the probability distribution functions of various characteristics of the climate system.

Climate models are trying to explain climatic processes with the help of only fundamental parts of the system – they are simplified versions of reality. The consequence of this simplification is small on a planetary scale; however, they are noticeable when predicting climate "on the ground". At the same time, the global climate can only predict general trends; however, they are not very suitable for practical use. Due to the "gross" spatial resolution, global climate models poorly reproduce the regional climate. Regional models are one of the ways to clarify data according to local features of the orography, atmospheric circulation, etc. The usage of regional models makes it possible to identify the effects associated with local characteristics of the underlying surface more accurately [2-4].

We have chosen the temperature as the main climatic parameter for further work among climatic indicators. The list of indicators of the temperature regime of the territory and the frequency of observations allows displaying the state of the studied system in the obtained data array. Processing of the results of the observations was carried out by statistical methods (for indicators of meteorological stations) and classical methods of geospatial analysis for data obtained from satellite images. Conversion of processing results into information about the parameters of the temperature regime of the territory is a combination of the two mentioned above groups of methods. The monitoring results are obtained in the form of two-, three-dimensional dependencies. However, the indicators of the temperature regime of the territory are determined by a large number of factors (primarily the dynamics in space and time). The possibilities of statistical modeling methods for displaying multifactor effects are limited [3].

The problem investigated in this article arises when creating monitoring information systems (MIS). The proposed solution eliminates the existing contradiction between the need to reflect the properties of a complex climate system in the structure of the model and the limited capabilities of the modeling methods used for this. As a result, information about the features of observational objects are not reflected in the model structure and are not used in the decisions making by monitoring results. Therefore, there is a need to develop and implement new methods for identifying and studying these factors, processing and analyzing the received information, which should be based on a combination of research results using traditional climatology and meteorology methods combined with modern methods of processing big data and modeling complex systems. There is a need to reduce the time for receiving conclusions by automating routine work by widespread using of MIS. The primary goal of this work is to study the processes of using the information technology of temperature monitoring based on the data of weather stations and thermal satellite imaging on the example of the territory of Chernivtsi and Ivano-Frankivsk regions.

According to the methodology for creating automated systems for socio-environmental monitoring at the first stage of the formation of the MIS, the super-system formulates requirements for the content of information that must be obtained from the monitoring results. In this case, monitoring information is needed to determine the dependence of temperature values at a certain point in space on a temperature at other points in space, which are characterized by the presence of weather stations. The problem of climate change is currently extremely relevant as in the field of basic research, so far in practice. The development of reliable estimates and objective forecasts of environmental impacts related to climate dynamics determined the researcher’s interest in this topic, in particular, the intensity and nature of climate transformations. The task of accurate prediction of temperature values cannot be realized. Therefore, a justified choice of the most significant and informative elements available for sufficiently detailed research is needed.

The study of existing climatic models of different levels allows us to assert that the temperature depends more on its dynamics in space and time. Also, cloudiness makes a significant influence on temperature values. During the day, the earth’s surface is warmed by the sun. If the cloudiness is low, then much more heat gets to the surface of the earth. It leads to increasing temperature. At night, the influence of cloudiness is exactly the opposite. On condition of low cloudiness, the heat reflected by the surface of the earth is lost more intensively, since it freely gets into the Universe. As a result, the temperature of the air decreases. Besides, significant stable cloudiness reduces the daily temperature amplitudes, and the absence of cloud cover has a reverse effect. Thus, during the processing of space images, not only the date but also the specific time of the shooting is essential. It is taken into account when conducting atmospheric correction, which is one of the necessary procedures for the preparation of the analyzed data [6].

The use of thermal satellite images for temperature prediction is relevant also because they contain information about cloudiness, and the location of study points and even altitudes, which is also one of the crucial factors affecting the resulting value. Also, by satellite images, the type of underlying surface is taken into account, which makes a noticeable effect on the temperature regime [6].

That is why, the requirement for MIS in this case is to describe the dependence of temperature values at a certain point of the space (with specific characteristics of the location, altitude, and the nature of the underlying surface), determined by space images on the values of this indicator at other points determined by meteorological stations and cloudiness. In the second stage of the MIS formation, the number of levels of information conversion, and the local tasks for each of the levels is determined. In this case, it is necessary to form two levels of information transformation. At the first level, the signs of the state of the climate system are converted into digital characteristics by the results of observations. Means are measuring instruments for determining the temperature (both directly and with the help of thermal images) and regular maintenance of these processes. At the second level, the information is transformed from the form of the array of numerous characteristics into the form of analytical models, the structure of which reflects the change in temperature values at a certain point of space based on satellite images, from its values at other locations where there is a meteorological station. Table 1 presents the features, numerical characteristics of the first level of monitoring implementation results for the analyzed area during 1985-2016. They are used as components of the initial description of monitoring objects and as variables for the synthesis of second-level models.

Table 1. List of attributes of the input data array

№	Feature’s name	Variable
1	Air temperature determined on meteorological stations (48)	Y
2	Air temperature determined by thermal satellite imaging (48)	X1
3	Cloudiness, determined by satellite imaging (48)	X2

Y is a set of the dependent variables (modeled indicators):

$$Y = \{y_1, y_2, ..., y_n\} . \quad (1)$$

Variables 2-3 are independent variables and form the set X:

$$X = \{x_1, x_2, ..., x_n\}. \quad (2)$$

To determine the nature of the influence of air temperature values received from meteorological stations and cloudiness index with air temperature measured by the thermal imaging camera, we have to identify functional dependence:

$$Y = f(X). \quad (3)$$

Here presented the results of studies whose purpose was to determine the nature of the influence of air temperature values determined at meteorological stations and cloudiness index on air temperature, determined by thermal imaging using MIS air according to satellite and methane stations. At the same time as the studied indicators used the value of changing it for a specific geographic location. The study was conducted for three meteorological stations in the Chernivtsi and Ivano-Frankivsk regions (Chernivtsi, Vyzhnytsia and Kolomyia meteorological stations). For each city, 16 points were selected with specific coordinates for which air temperature can be determined in two ways (at the weather station and on a satellite basis). Also, as a control, the territory was removed from the meteorological stations, for which it is possible to determine only the temperature by thermal imaging. Since sweeping advancement was to establish the possibility of predicting the territory temperature with no meteorological stations, the temperature was chosen as the dependent variable based on the result of the thermal imaging. Since it allows determining the temperature at any point on the earth's surface, and the detail of its determination is due only to the resolving power of the cosmic reference. Thus, it is necessary to solve the identification problem:

$$\boldsymbol{y_1} = f(x_1, x_2, ..., x_n). \quad (4)$$

At the third stage of building the MIS, the structure of its information transformation subsystem is formed. The method of ascending model synthesis and tools of the information system of multi-level data transformation is used. Under the given dependent and independent variables, models are synthesized at each level of information transformation; models of a separate level are combined into executions. The output signals of the models of the lower penalty form arrays of initial data for the synthesis of the models of the upper penalty [17, 18]. For the integration of models of the second level of information conversion of the MIS temperature based on the satellite of the material stations, a multi-row GMDH algorithm was used [19, 20]. In the process of synthesizing the model, data obtained during 1985–2017 were used for the territory of the weather station. For testing the model, we used the results of observations obtained during the same period for the lands where there are no meteorological stations.

Since the structure of the model contains a characteristic of the time, it reflects the pattern of forecasting. Also, by examining the model for sensitivity to the dynamism of variables of the set X, one can assess the influence of factors and describe the pattern of association [17, 19]:

$$\boldsymbol{W}_1 = \frac{\boldsymbol{y_1'}}{\sum_{i=1}^{m} \boldsymbol{y_i'}}, \quad (5)$$

where y_1 – is the value of the partial derivative of the model to the variable x1; m is the number of variables included in the structure of the model.

After confirming the usefulness of the models obtained, the whole subsystem of data conversion of the MIS as a whole is tested by an expert assessment of monitoring information at the system output.

IV. RESULTS OF THE MODELING

The input data in the study were medium-resolution Landsat images of medium resolution provided by the US Geological Survey [21], and temperature data were recorded at meteorological stations that were received from meteorological servers [22, 23]. Terrestrial meteorological stations are used to assess the reliability of temperature measurements from remote sensing data for Landsat satellites. Since spatial data were obtained from different sources, they were in different cartographic projections. For the purpose of unification, all of them were transformed into a UTM projection, in which all the coordinates given in the work are presented.

The main disadvantage of this approach is the effect of changes in the shadows and illumination of the earth's surface, vegetation, and objects when analyzing satellite images limits the use of the space-time approach. However, the development of a methodology for modeling, detecting, and removing shadows on images allows, after additional processing, to carry out the comparison of multi-time images.

To compare the values of temperature measurements, according to the data of ground-based weather stations and the results of the thermal field from satellite images, we selected images from the Landsat-4, -5, -7 and -8 space satellites. The choice of satellites is due to the presence in the imaging equipment of the so-called heat channel (electromagnetic waveband 10.4–12.5 μm) and data from these satellites, which were received over a long time. Data from satellites of the Landsat series are presented from 1982. For studies, images from the Landsat series satellites for 1984-2018 are most often selected. Another advantage of Landsat satellites over competitors is that the data from these satellites are free for access.

Starting with the Landsat-4, -5 satellites in the heat channel 6 or the channels 6.1 and 6.2 for the Landsat-7 and -8 satellite, we obtain digital data that do not have physical dimensions. It is necessary to convert the space data of the heat channels to the temperature value. For Landsat 8 Thermal there is a ten channel. All the required information about the input data is contained in the metadata file supplied with each image (scene).

All input images have resolution 30 m per pixel and are sufficiently accurate to predict climate indicators. When comparing meteorological and satellite data, the concept of the effective forecast radius of a meteorological station (the experimentally established territory for which the proper temperature can be measured at the meteorological station) was used. It is known that on average, such a radius is about 30 km. In this case, 16 points from satellite images closest to the weather station were used to restore weather data.

Also, an important aspect that had to be considered when planning an experiment was the frequency of data acquisition. The fixation of temperature indicators at meteorological stations occurs several times a day (from 4 to 12 times, depending on the type of meteorological station). However, fully satisfying the time component of the weather station research is almost devoid of spatial (in case of working with many stations model would not still be regional). At the same time, another source of input data, namely, satellite images, is an entirely satisfactory spatial component of the analysis; however, the Landsat satellite captures 16-18 days, that is, the time during which the satellite turns around the Earth and how often it records. Also, the cloudiness value of more than 50% makes it almost impossible to use a specific scene to an image, which further reduces the frequency of data acquisition. So, one of the tasks of creating an MIS within this research was the development of methods for the common use of all these types of input data.

We tested the established monitoring system for the territory of Chernivtsi and Ivano-Frankivsk regions. In particular, a series of satellite images from 2000 to 2017 inclusive was taken for analysis. To compare the data obtained from the meteorological stations and by satellite images, we selected three meteorological stations: Kolomyya, Vyzhnytsia, and Chernivtsi. The primary data contained 205 values characterizing each of the points at different dates for the period under investigation.

Preliminary analysis of the initial data array shows that the graphs of the course of temperatures obtained by both methods are almost identical, which suggests the expediency of using this approach in the future. However, absolute values at specific points are different, which may depend on many factors. In particular, cloudiness, that was considered in the model. Moreover, also from the type of underlying surface that affects the temperature determined by the image, while in the meteorological stations the temperature indicators are measured at a level of 2.6 m above the surface of the earth. The account of these disagreements is possible by preliminary classification of satellite images with the comparison of spectral and thematic classes and the introduction of correction coefficients for each of them. However, such an approach will not be universal since changing the study area will need to start the entire procedure from the very beginning. As a more comprehensive tool for the solution of the problem of temperature prediction based on the analyzed data, it was suggested to use methods of inductive modeling.

Thus, further research could be carried out in the temporal and spatial aspects, but the non-periodicity of obtaining data makes such studies ineffective. It is possible to use different methods of “restoration” of time series; however, this would decrease the informativeness of an array of initial data.

Therefore, it was decided to construct models in a spatial aspect. In particular, the establishment of functional dependencies between the temperature indices on satellite images at each specific point of space was made from the temperature values obtained at meteorological stations, taking into account the values of satellite images in the area nearby meteorological stations and their indicators of cloudiness. For each city in the array, there were 16 points, with coordinates nearest to the meteorological station.

As a result of modeling by the synthesizer of the intelligent monitoring system, 48 models were constructed (for each point where the temperature of the weather stations is known). The data array for training models contained one dependent variable (Y), which used the results of a satellite image from a specific point. The Xs were meteorological data from all other locations. The meteorological data on the modeling point was not used in building the model but was used to assess the quality of the temperature prediction. It must be noted, that the models were tested on data that did not participate in the creation of the model; thus the obtained results characterize the model’s stability. Such a choice of parameters for modeling and forming the array of input data is determined by the need to avoid multicollinearity, to the coherence of two or more variables in the regression equations. The temperature value at the meteorological stations and beyond the satellite images on the same territory is not satisfied with the requirement of multicollinearity.

GMDH is the first approach of modeling, and the accuracy criterion of the selection series was used for finishing of the selection series generation. In this case, the absolute error of the exact polynomial of the series was used as the criterion. The number of polynomials, performed as inputs for each subsequent row of selection was equal to the number of original variables. The primary polynomial for model generation is quadratic. The weights were calculated as the ratio of the partial derivative of the model in a separate variable to the sum of the partial derivatives of this model to all variables. Tables 2-4 give initial test results of some of the created models.

Analysis of the obtained results indicates a relatively accurate forecast of these temperatures in areas with no meteorological stations. Unlike all previous algorithms, in this case, the main number of significant relative errors belongs to high positive temperatures. However, a comprehensive analysis of dependencies is possible only by models for all the points studied, which should be contained in the model knowledge base.

Table 2. Example of the model test results for the Chernivtsi point (longitude 421650, latitude 5343300, altitude 222,02) – Model 1

№	RT, °C	PT, °C	AP, °C	RE,%
1	21,060	20,505	0,555	-2,64
2	15,640	14,595	1,045	-6,68
3	24,540	24,381	0,159	-0,65
4	23,680	23,417	0,263	-1,11
5	22,380	22,449	0,069	0,31
6	12,360	10,592	1,768	-14,30
7	-1,850	-1,721	0,129	6,95
		…		
40	20,550	24,381	3,831	18,64
41	16,670	16,578	0,092	-0,55
42	23,970	24,381	0,411	1,71
43	23,250	23,417	0,167	0,72
44	6,030	6,538	0,508	8,43
45	8,670	7,557	1,113	-12,84
46	22,990	19,528	3,462	-15,06
47	21,600	22,449	0,849	3,93
48	25,744	22,449	3,294	-12,80

Note to table 2-4: RT – real temperature, PT – predicted temperature, AP – absolute error, RE – relative error

Table 3. Example of the model test results for the Kolomya point (longitude 355110, latitude 5378250, altitude 288,51m) – Model 2

№	RT,°C	PT, °C	AP, °C	RE,%
1	21,060	22,205	1,145	5,44
2	14,250	17,269	3,019	21,19
3	24,970	24,258	0,712	-2,85
4	-9,770	-7,417	2,353	24,09
5	25,400	22,921	2,479	-9,76
6	22,820	22,921	0,101	0,44
7	-2,390	-1,973	0,417	17,46
		…		
40	23,400	26,023	2,623	11,21
41	25,400	21,458	3,942	-15,52
42	23,680	24,258	0,578	2,44
43	19,730	15,389	4,341	-22,00
44	25,830	23,606	2,224	-8,61
45	19,080	24,258	5,178	27,14
46	24,660	22,921	1,739	-7,05
47	18,380	18,166	0,214	-1,16
48	20,720	21,458	0,738	3,56

Table 4. Example of the model test results for the Vyzhnytsia point (longitude 363480, latitude 5345400, altitude 335,99) – Model 3

№	RT,°C	PT, °C	AP, °C	RE,%
1	17,020	18,589	1,569	9,22
2	12,840	12,610	0,230	-1,79
3	23,250	22,676	0,574	-2,47
4	12,360	8,730	3,630	-29,37
5	-8,020	-8,446	0,426	-5,31
6	20,620	21,647	1,027	4,98
7	21,500	20,623	0,877	-4,08
		…		
40	25,010	22,676	2,334	-9,33
41	14,569	14,582	0,013	0,09
42	23,723	22,676	1,047	-4,41
43	21,061	21,647	0,586	2,78
44	3,999	4,939	0,940	23,49
45	19,410	17,579	1,830	-9,43
46	17,441	20,623	3,182	18,24
47	19,340	20,623	1,283	6,63
48	-6,769	-5,878	0,891	13,16

General characteristics of the models under consideration (Table 5) confirm that the obtained values of the weight coefficients can be explained primarily by the distance between the plotted points and by comparisons of their absolute heights. By comparing models for the first three points, it was found that the difference was in indicators (longitude, latitude, and altitude) between the simulated point and the variable that showed a change in the function direction approximately at the same level. It allows predicting that for each point for which the temperature is modeling can be set a point (or points) that have the most significant impact on the resulting value.

Table 5. Characteristics of the obtained models

№	Model	The variable name, showing reliable changing of function's value	WC	MinV	MaxV	DFC
1	Model 1	Temperature from meteorological station (Chernivtsi, longitude 421650, latitude 5343300, altitude 222,02)	1	–20	30	Increasing
2	Model 2	Temperature from meteorological station (Kolomya, longitude 355110, latitude 5378250, altitude 288.51m)	1	–14	31	Increasing
3	Model 3	Temperature from meteorological station (Vyzhnytsia, longitude 363480, latitude 5345400, altitude 335.99)	1	–20	30	Increasing

Note to table 5: WC – Weight coefficient, MinV – Min value, MaxV – Max value, DFC – Direction of function's change

Thus, to improve the accuracy of modeling, more research points should be chosen, which should represent different physical and geographical conditions.

V. CONCLUSION

The method of temperature prediction based on thermal satellite imagery and weather station data is improved, using this model of dependence of temperature received from satellite imagery on the temperature obtained from existing meteorological stations.

1. The analysis and synthesis of existing approaches, methods, and means of temperature prediction, including by satellite imagery, in particular, by thermal imaging, is carried out. It is revealed that the most effective means of solving the problem is the use methods of inductive modeling.

2. During the investigation of the variables selected from the input data array, it is shown that satellite imagery data could be used in regional models of temperature prediction, and temperature traces obtained from satellite imagery and weather stations at similar points show similar dynamics.

3. The effectiveness of GMDH using of the multi-row algorithm for forecasting temperature for areas with no meteorological stations is shown.

4. Thus, a system of intelligent monitoring of air temperature based on satellite imagery and weather station data is developed and implemented, in particular, demonstrated during the testing of the system for the territory of Chernivtsi and Ivano-Frankivsk regions. The results can be widely used for solving both global and local problems, in particular, to monitor climate change and create climate models, or to identify the state of vegetation and the presence of traces of human activity in the studied territories.

This monitoring information system is promising for future development, in particular, due to the use of OLAP technologies and the inclusion of new indicators in the input data array, which can be obtained based on satellite images and data provided by modern cyber-physical systems that use IoT devices connected to the Internet. The amount of data delivered by IoT is enormous. According to paper [12], more than 132 million Internet-connected IoT devices are deployed and used worldwide in the first half of 2019. Therefore, a complex mechanism is needed that combines OLAP technology and IoT search mechanisms, which will affect the final result, for example, taking into account the features of the underlying surface or the presence of "heat islands" over cities.

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