AUTOMATED SYSTEM FOR METEOROLOGICAL SUPPORT OF THE LOCAL AND REGIONAL MONITORING OF THE ATMOSPHERIC POLLUTION

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Received December 29, 1996

We consider here the principles of construction, basic functions and the configuration of an automated system for meteorological support of local and regional monitoring of the atmospheric pollution. The system has been created at the Institute of Atmospheric Optics SB RAS and it is a part of the "GIS-ecolog" geoinformation system. The specifications of the system are presented.

1. INTRODUCTION

The experience compiled in organizing and performing of ecological monitoring of the atmosphere over different regions of our country is the evidence of the fact that planning and performance of the environmental protection measures on isolated administration formations should be based on the use of prompt, reliable and maximum full information on the state of air pollution not only near the pollution source, but also in the vicinities of great industrial centers and neighbor regions.

The system of ecological monitoring of the atmosphere over limited areas (for example, a big city, industrial center and region as a whole) existing in our country does not meet the requirements of the modern practice in full measure (especially if concerning the reliability of the data obtained and automation of the observation process and processing ecological data). This raises the question on creation of an effective automated system for local and regional monitoring of atmospheric pollution in the nearest future. Such a system should be developed not only based on the modern technical tools for monitoring of atmospheric pollution (first of all, the most promising and effective systems for laser sounding which provide obtaining profiles or fields of meteorological parameters with extremely high spatial resolution[1–3]), but also based on modern geoinformation technologies which are the computer technologies for complex processing of data distributed over space, and are widely used abroad when solving the problems of prompt estimation of the state of natural resources.[4,5]

Taking into account this fact, since 90th the Institute of Atmospheric Optics SB RAS carries out wide and regular investigations into the problem of creation of computer geoinformation systems (GIS)[6,7] which are aimed at processing the data of atmospheric ecological measurements with the sensors distributed over the territory under control. Such systems would certainly be helpful when the estimating and predicting spatial spread of pollutants and evolution of air pollution resulting from the big emergencies. An example of the functional block-diagram of the local and regional GIS of such a type is presented in Ref. 7. Figure 1 shows similar though revised version of the GIS-ecolog system aimed at solving applied problems of atmospheric ecology.

One should say that one of the most important element of a GIS is the subsystem of diagnosis and forecast of the atmospheric ecological situation, which includes the block of data assimilation and matching and the imitation modeling complex which is a mesoscale model of the pollution transfer (in particular, it is mentioned in Refs. 8–11) used for numerical assessment and prediction of the spatial distribution and evolution of the atmospheric pollution. To put the imitation modeling complex into operation, it is sufficient to enter the results of the objective analysis of meteorological fields (i.e. the fields with the characteristic size from tens to hundreds of kilometers[12]) and perform the procedure of initialization (matching) of the fields of meteorological parameters, as well as the initial characteristics of pollution and its sources. After this procedure it is possible (by numerically solving the transfer equation) not only to estimate the scale of the pollution spread, but also to predict the evolution of the pollution level of the air over the territory.

Since meteorological data mainly presented in the form of the results of objective analysis of the fields of meteorological parameters (first of all, temperature affecting the turbulent transfer conditions, and the wind characteristics determining the advection of pollution[13]) is important for estimation and prediction of the spread and evolution of atmospheric pollutions, the automated meteorological support system (AMSS) should be included (if autonomous) into a local and regional GIS aimed at solving the ecological problems. This system, implementing its own functions, provides the operation of a subsystem of diagnosis and prediction, as well as the expert system block of the GIS-ecolog.

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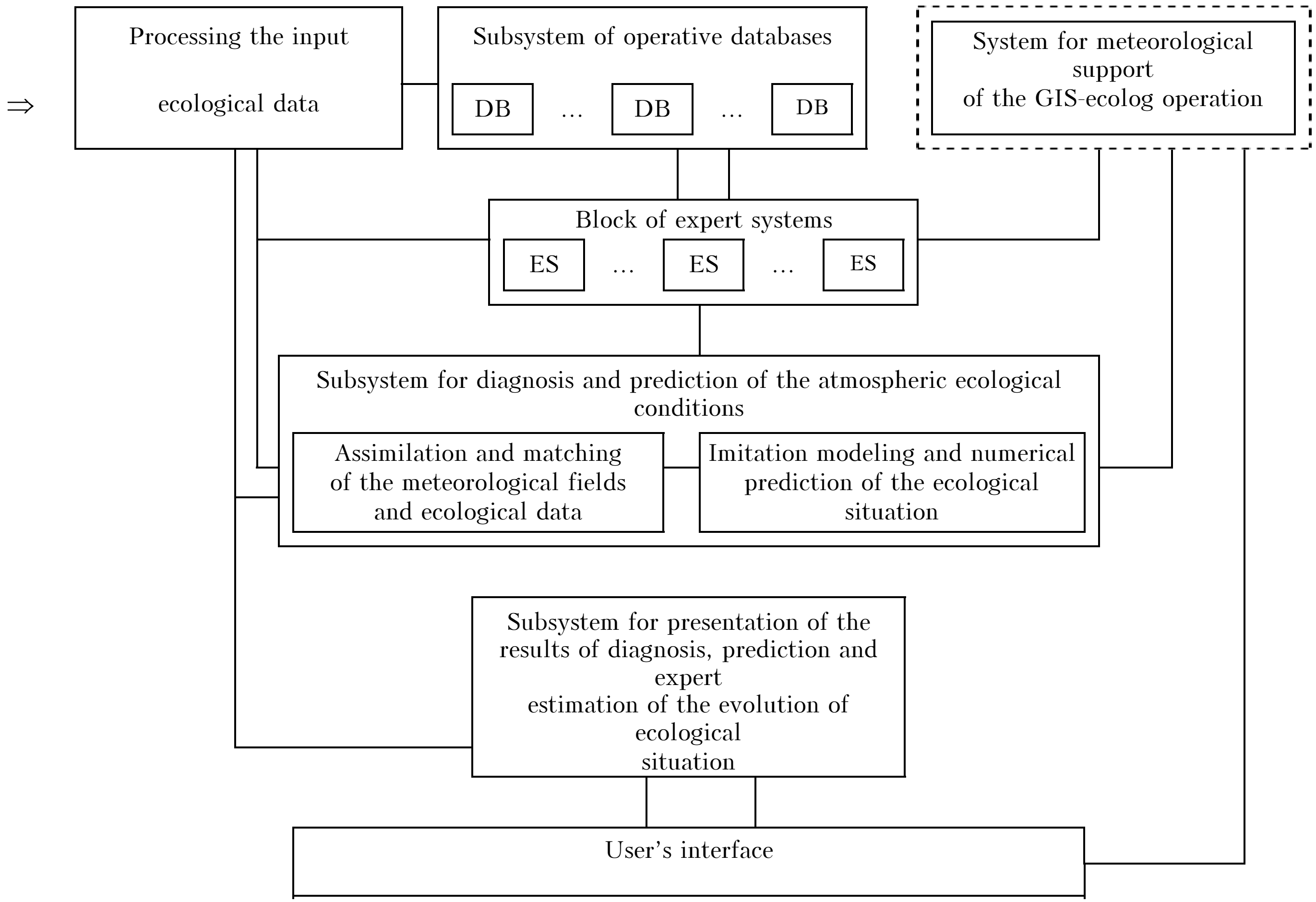

FIG. 1. The function block-diagram of the "Ecolog" GIS

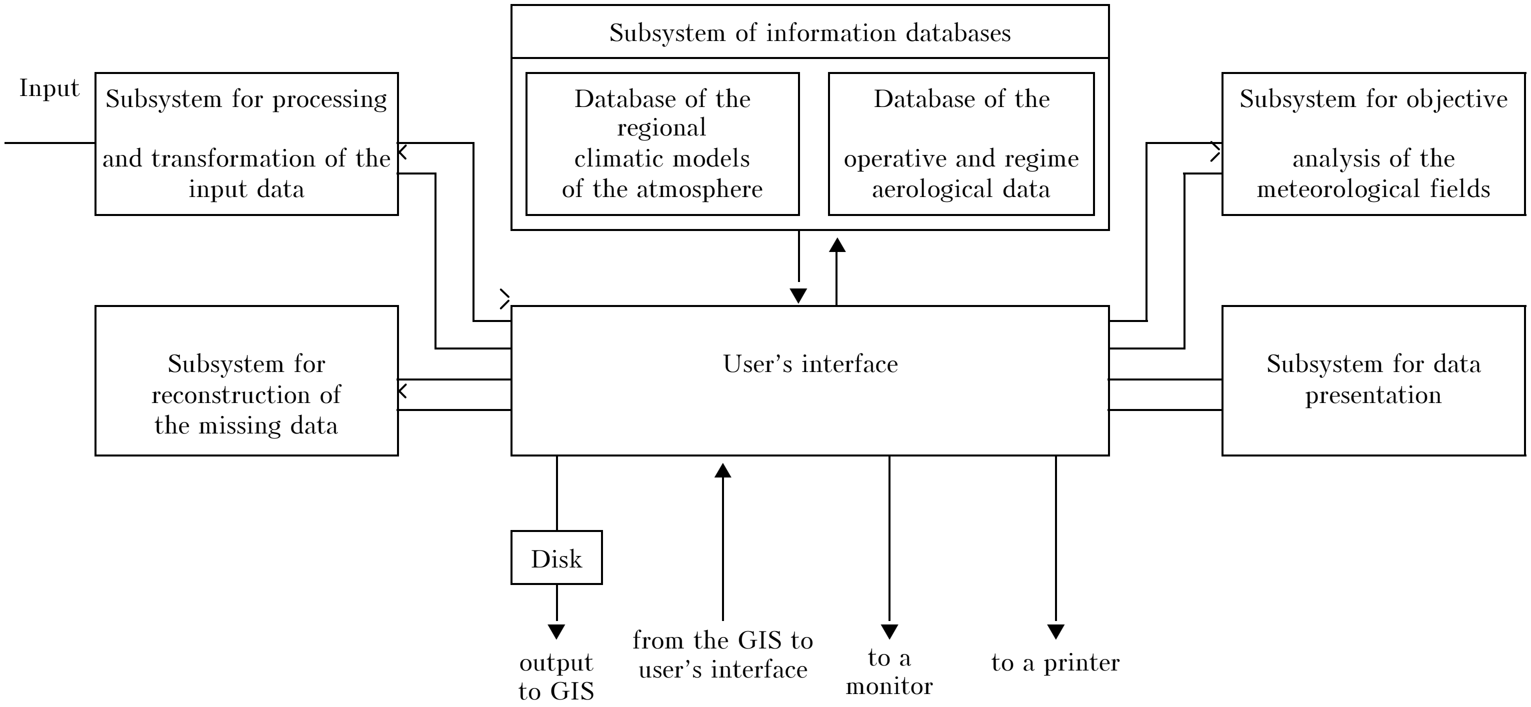

FIG. 2. Block-diagram of the meteorological support system for "Ecolog" GIS.

In this paper we summarize the outcomes of many-year investigations into the problem of developing of AMSS and discuss basic principles of the development as well as the structure and specific features of the first version of the system composed in 1995–1996.

2. BASIC PRINCIPLES OF CONSTRUCTING AUTOMATED METEOROLOGICAL SUPPORT SYSTEM, THE COMPONENT OF THE "ECOLOG" GIS

Taking into account the problems to be solved with AMSS and its purpose, one can formulate the following principles of constructing automated meteorological support systems:

– the AMSS should be designed based on the functions which this software should perform;

– an automated meteorological support system should be developed as a multifunctional computer complex created on the base of IBM PCs;

– the AMSS information software should contain a subsystem of information databases and a number of applied software packages for processing and transformation of the input data, solving the applied problems and presentation of the results numerically, graphically or in the form of tables;

– the AMSS should provide noncentralized principle of data processing and the principle of "openness" related to the composition of the meteorological data to be processed, as well as the possibility of operating in a dialogue mode;

– the AMSS system architecture should provide wide possibilities for high-rate data processing and solving the applied problems. It should follow the module principle of construction of this software complex, which would allow one to perform the subsequent integration of supplementary information and program modules into it;

– the algorithms and software of the AMSS should be based on the optimum complex of the classic (traditional) and non-traditional approaches to meteorological data processing and solving the applied problems;

– it should be possible to connect the AMSS to the automated systems for receiving and transmitting the data and transform the operative meteorological data presented in special codes to the format used by AMSS for formation of the operative and regime aerological database and solving the applied problems;

– the AMSS should be constructed so that, if necessary, can be incorporated into the ecological geoinformation system.

All the above principles were taken into account when developing the first version of the automated meteorological support system software.

3. PURPOSE AND BASIC FUNCTIONS OF THE AUTOMATED METEOROLOGICAL SUPPORT SYSTEM

The automated meteorological support system developed as a multifunctional and professionally oriented software complex is intended for the operative meteorological support of the local and regional ecological GIS. The AMSS is aimed at solving such applied problems as:

– construction of local statistical models of the vertical distribution of meteorological quantities important in the formation of the atmospheric pollution field as assessed from the data of operative observations at the network of radio-sondes and lidar stations situated on the territory of a mesoscale region and its vicinity;

– numerical filling of the gaps in data at some levels (or layers) of the atmosphere based on the results of sounding at the lower levels;

– objective analysis of a 3D structure of mesometeorological fields over a given territory to be performed using the data from the network of aerological (including lidar) stations and taking into account the possibility of changing the size and orientation of the regular grid of points, as well as its spatial resolution.

Let us now consider the functions, of an automated meteorological support system, taking into account the aforementioned applied problems. Let us use the block-diagram of AMSS presented in Fig. 2. As is seen from the figure, the system under consideration comprises as a number of modules (subsystems) each of which performs a certain set of functions. These modules are the following:

1) information database subsystem;

2) subsystem for processing and transformation of the input data;

3) subsystem for restoration of the missing data;

4) subsystem for objective analysis of a 3D structure of the mesometeorological fields;

5) subsystem for presentation of the output data;

6) user's interface.

These subsystems provide complete solving of all applied problems in meteorological provision of the "Ecolog" GIS.

4. BRIEF CHARACTERIZATION OF THE AMSS SUBSYSTEMS

Let us present brief characterization of the first version of the automated meteorological support system.

4.1. Information Database Subsystem

The subsystem of the information support of applied problems that have a need for restoration of missing data, and problems in the objective analysis of meteorological fields comprises two bases. One includes regional climatic models of the atmosphere, and the other one involves the operative information from aerological and lidar stations in the mesometeorological region. Let us consider each of these information databases separately.

Database of Regional Climatic Models of the Atmosphere

The database contains parameters of regional models of the atmosphere presented by the model profiles of the mean values and standard (rms) errors and the model correlation matrices of pressure p (hPA), temperature T (K), humidity q (g/kg), zonal u (m/sec) and meridional v (m/sec) components of the wind velocity obtained at the altitudes up to 30 km (with 1-km step) for some quasi uniform regions of the northern hemisphere revealed based on the objective classification of the climates of the free atmosphere.

The methodology and results of such a classification, as well as the information on the regional climatic models of the atmosphere may be found in Refs. 14–16, and the problems of designing the database of the regional models of the atmosphere are considered in Ref. 17. Let us note that complication of this database is based on the methodology of the DB DATAID–1.[18] Figure 3 shows the global operational scheme of the database of the regional models of the atmosphere which has been constructed on the stage of conceptual design. As is seen from Fig. 3, the database control system (DBCS) supports three groups of operations connected with the database supervision, displaying its current state and search for the regional models for the territory with a preset of geographical coordinates, respectively.

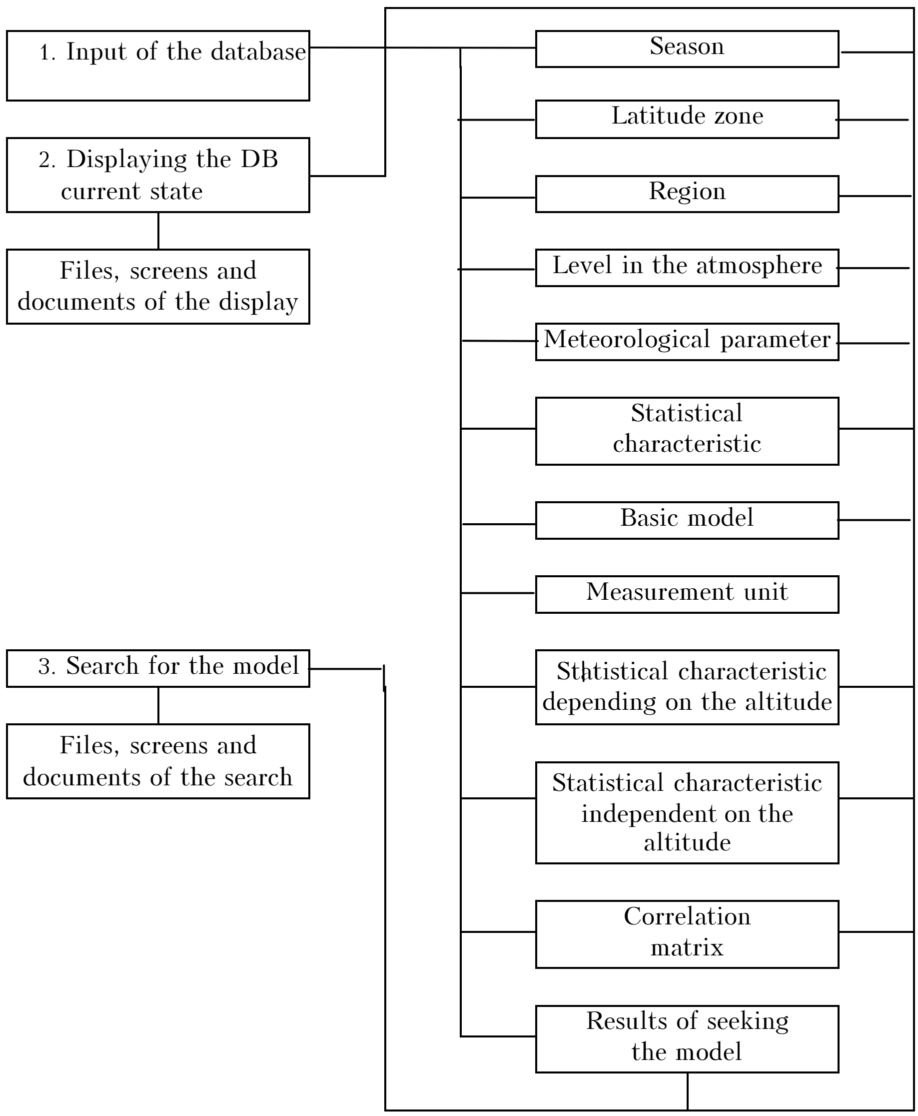

FIG. 3. Global operational diagram of the database of the regional models of the atmosphere.

The spatial structure of the database of regional models is the set of statistical characteristics of the aforementioned meteorological parameters corresponding to one of the quasi uniform regions of the northern hemisphere. The quasi uniform regions are the spatial areas presented by the ordered values of the coordinates of their units, and the models corresponding to them are considered as a set of the meaningful descriptors.

Database of the Operative and Regime Meteorological Information.

The database is the second functional block of the information database system and it is intended for:

– systematization and optimum organization of the storage and access to the archives of the operative data coming from the network of aerological stations on the mesometeorological area under consideration, as well as to the archives of the mean data containing vertical profiles of the mean values (norms) and variances of pressure, temperature, humidity and wind velocity components calculated for each of these stations up to 10 km using limited samples of operative observations (the number of observations was $N = k + 1$ for norms, where k is the number of levels, and $N \geq 30$ for variances);

– search for the data requested by the applied problem to be solved;

– presentation of the data from archive in a file for solving the problem of reconstructing missing values and objective 3D analysis of the mesometeorological fields.

The database of operative and regime aerological data was organized and designed, using the same principles as the database of the regional models of the atmosphere. So we do not consider them here.

4.2 Subsystem for Processing and Transformation of the Input Data.

This subsystem of AMSS is an auxiliary module and is aimed at solving such problems as:

– interactive input of operative aerological data coming from the balloon-sonde and lidar sounding stations in encoded or another form;

– selection, transformation and formation of the needed aerological data in the format required.

The result of operation of the subsystem is creation of the output file named METEORES that is a table, in the first row of which the station coordinates (latitude φ and longitude λ) are written, the year, month, day and time of the observation are written in the second row, the profile numbers is in the third row, and the corresponding set of meteorological parameters is written in the other rows in the order of increasing altitude H. The following altitudes were selected: 110, 540, 990, 1460, 1950, 2470, 3010, 3590, 4210, 4870, 5570, 6340, 7190, 8190, 9160, 10360, 11780, 13610, and 16180 m. Such a grid of altitudes makes it possible to divide the atmosphere into the layers that, according to the standard atmosphere, have the thickness of 50 hPa, that, according to Ref. 11, is necessary for the objective analysis of the mesometeorological fields and constructing the mesoscale model of the pollution spread. The data are transferred in this subsystem from the levels of the special point to these levels on the basis of linear interpolation.[14]

4.3 Subsystem for Reconstructing Missing Data

This subsystem is one of the main subsystems of AMSS and it is aimed at reconstructing missing meteorological data at some levels or in the layers of the atmosphere from the data obtained at the below levels, as well as from the data obtained at the previous time.

The algorithms and software of this subsystem are developed using original methodology based on the modified method of clustering of arguments (MMCA) that was described in detail in Refs. 19 and 20. Let us note here that the initial data and mathematical models of MMCA are the following:

– spatiotemporal observations of the form

$$\{\xi'(h, t), \quad h = 0, 1, \dots, h_k; \quad t = 1, \dots, N\},$$

$$\{\xi'(h, t), \quad h = 0, 1, \dots, \quad \bar{h} < h_k; \quad t = N + 1\}, \qquad (1)$$

where $\xi'(h, t)$ are the random deviations of any meteorological parameter from its norm $\bar{\xi}(h)$, h is the altitude, t is the time of observation, and N is the number of the vertical profiles;

– the mixed difference and dynamical-statistical model of the form

$$\xi(h, N{+}1) = \sum_{\tau=1}^{N^*} A(h, \tau)\, \xi(h, N{+}1-\tau) + \sum_{j=1}^{h-1} B(h, j)\, \xi(j, N{+}1) + \varepsilon(h, N{+}1), \qquad (2)$$

where N^* is the order of delay in time ($N^* < [N - h - 1]/2$); $A(h, 1), \dots, A(h, N)$ and $B(h, 0), \dots, B(h, h - 1)$ are unknown parameters of the model, and the value $\varepsilon(h, N + 1)$ is the discrepancy of the model.

Two methods were taken according to Ref. 21 for selecting the best model (2) and successful prediction of the meteorological parameters on its basis, namely:

a) method of directed group clustering used for the optimization of the structure of the model performed by means of :

– final error in predicting (H. Akaike) of the form

$$\mathrm{FRE} = \frac{(N - N^* - 1) + 1}{(N - N^* - 1) - 1}\, \mathrm{RSS}(s), \qquad (3)$$

where $\mathrm{RSS}(s) = \sum_{j=1}^{N-N^*-1} [\xi_{h,N-j} - \hat{\xi}_{h,N-j}(s)]^2$ is the remainder of the sum of squares when using current model $\hat{\xi}_{h,N-j}(s)$ containing s non-zero estimates;

– rms error in predicting by the control sample B

$$|\xi_{h,N} - \hat{\xi}_{h,N}(s)|^2 \to \min . \quad (4)$$

b) method of the minimax estimation used for obtaining the estimates of the parameters of the model, which makes it possible to provide the required quality of the corresponding prediction that is estimated by means of the inequality

$$E|E(\xi_{h,N+1}) - \hat{\xi}_{h,N+1}|^2 \le \delta_{h,N+1}\,(h = \bar{h}+1,\ \dots,\ h_k)\ , \quad (5)$$

where $E(\bullet)$ is the mathematical expectation operator, and $\hat{\xi}_{h,N+1}$ and $\delta_{h,N+1}$ are the minimax estimates depending on the variance of the observation errors and on the *a priori* information about the maximum permissible values of the prediction errors.

The subsystem for reconstructing missing data, the block-diagram of which is shown in Fig. 4, provides the construction (based on the matrix of spatiotemporal observations) and selection of the best prediction model MMCA, as well as the numerical reconstruction of a set meteorological parameter by means of this model up to the altitude required or at some level.

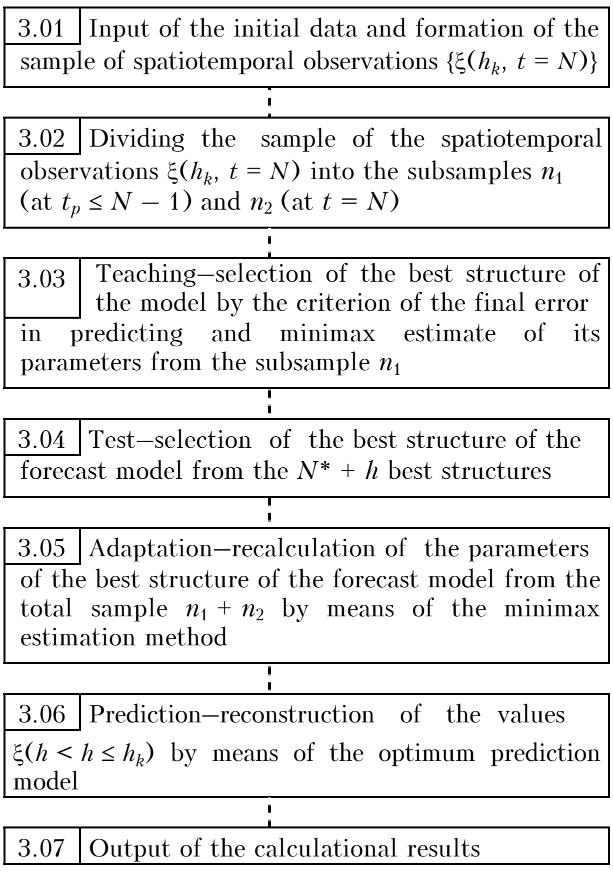

FIG. 4. Block-diagram of reconstructing missing data by means of the MMCA algorithm

The output data of the subsystem are written in the ASCII file named RESULT, which contains some reference information (the station number, its geographical coordinates, date and time of reconstruction) and the results of reconstructing the needed meteorological parameter at all necessary altitudes (including the highest altitude h_k) or at some level.

4.4. Subsystem for Objective Analysis of Mesometeorological Fields.

This subsystem is the second (main) and the most important subsystem of the AMSS, that enables one to perform objective analysis of the 3D structure of mesometeorological fields based on the data of observations at aerological (including lidar) stations located on the territory of a mesometeorological region. The results of this objective analysis are the basis for calculation of the spread and evolution of the atmospheric pollution, which is performed by the "Ecolog" GIS program.

The algorithms and software of this subsystem is developed based on two alternative methods of the spatial interpolation (extrapolation) of the fields of meteorological parameters, namely: MMCA and the optimum interpolation method based on the relationship[22,23]

$$\xi_0 = \bar{\xi}_0 + \sum_{i=1}^{n} p_i\, \xi'_i\ , \quad (6)$$

where ξ_0 and $\bar{\xi}_0$ are the sought and mean values of the meteorological parameter at the node of a uniform grid with the index 0, respectively,

$\xi'_i = \xi_i - \bar{\xi}_i$ is the deviation of the same meteorological parameter from the norm at the points with the index i, n is the number of stations used, p_i are the weighting coefficients, as well as the linear equation system (LES) of the form

$$\sum_{i=1}^{n} p_i\, r_{ij} + \eta_j\, p_j = r_{0j} \quad (j = 1,\ 2,\ \dots\ ,\ n), \quad (7)$$

where r_{0j} and r_{ij} are the correlation functions of the meteorological parameter calculated taking into account the distance l between the grid nodes and the stations and between the stations, respectively, and η_j is the measure of the measurement error.[22]

Such a complex approach to the objective 3D analysis of the mesometeorological fields and corresponding algorithm are described in more detail in Ref. 24.

The block-diagram of the configuration of the subsystem for the objective analysis of the mesometeorological fields is shown in Fig. 5.

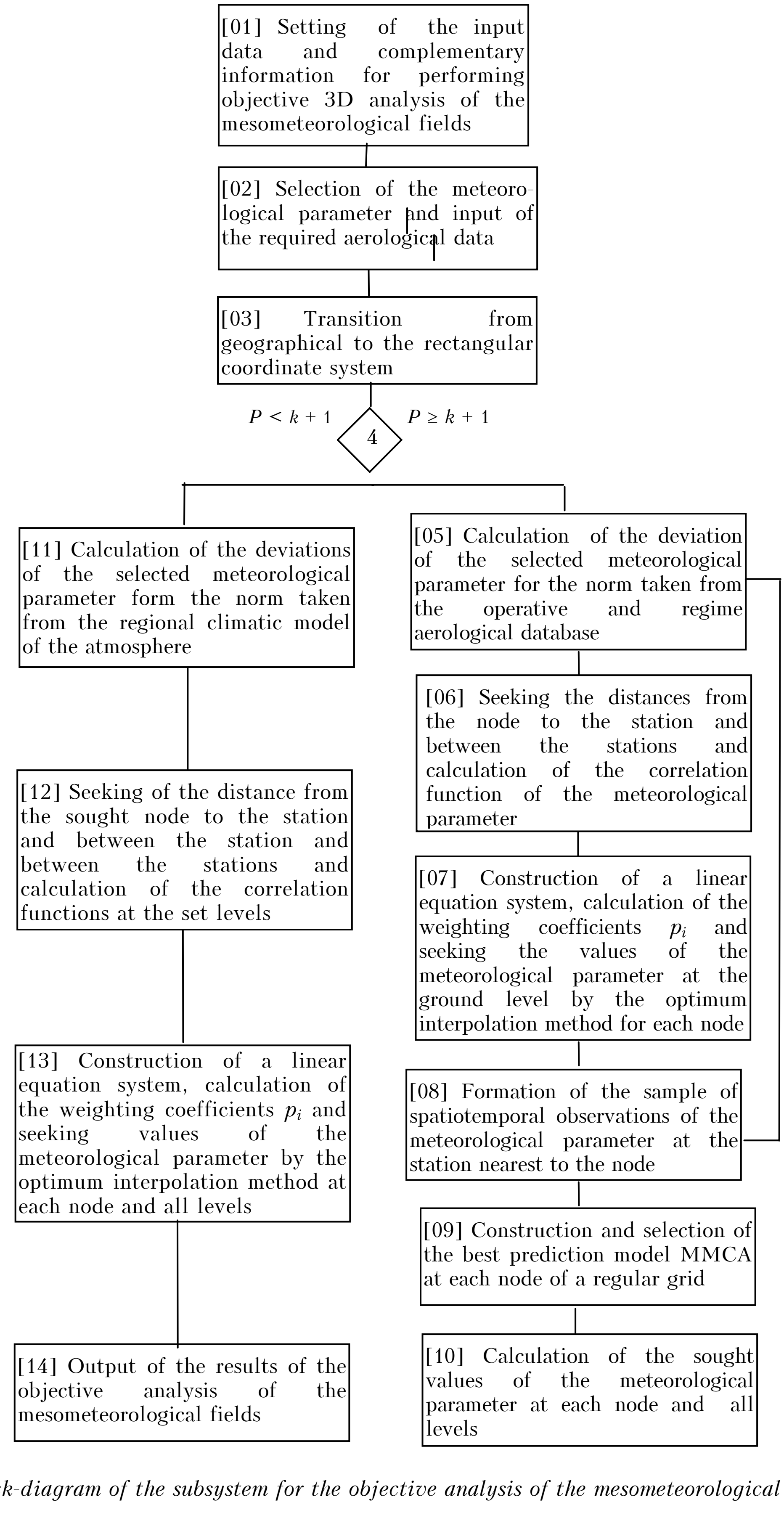

FIG. 5. Block-diagram of the subsystem for the objective analysis of the mesometeorological fields.

It is seen from Fig. 5 that the presence of a number of blocks, each of which performs some function, is characteristic of this configuration.

The block 1 provides for setting of the initial information containing the date and time of the objective analysis, the number of the reference stations N_c (for $N_c \geq 3$) and their geographical coordinates (latitude φ and longitude λ), the number of the profiles P and the number of the levels k, the coordinates of the left upper corner of a regular grid and the angle relative to the north-south axis, the horizontal and vertical size of the area and the step of the regular grid Δl and, at least, the azimuth angle between the lines connecting the left upper corner of the area and the reference stations, and the N–S axis.

The block 2 provides for the selection of the meteorological parameter and the input of the aerological data required.

The block 3 serves for the transfer of the coordinates of the stations and the area from geographical to rectangular coordinate system.

The block 4 examines the condition $P \geq k + 1$, where P is the number of the profiles, and k is the number of levels in it, that causes two calculation procedures. The objective analysis at $P < k + 1$ is carried out only by means of the optimum interpolation method, and at $P \geq k + 1$ it is carried out using a complex procedure, i.e. using the same optimum interpolation method and the MMCA algorithm.

The blocks 5–10 are the main blocks which provide the calculation of deviations of the meteorological parameter from the norm taken from the database of operative and regime aerological data at $P \geq k + 1$; determination of the distances (and correlation functions) from the node considered with the index "0" to the stations and between the stations, respectively; construction of a linear equation system and calculation of the weighting coefficients p_i; seeking the values of the meteorological parameter at the ground level at each node of the grid on the basis of optimum interpolation model (6); formation of the spatiotemporal observation taking into account the results of the reconstruction; constructing based on them and selection of the best prediction model MMCA for each node of the same grid, and, at least, calculation the sought values of the meteorological parameter on the basis of the MMCA model at the same nodes and at all missing altitudes.

The blocks 11–13 provides the calculation of deviations of the meteorological parameter from the norm taken from the database of the regional climatic models of the atmosphere at $P < k + 1$; determination of the distances (and correlation functions) from the node with the index "0" considered to the stations and between the stations, respectively; construction of the linear equation system and calculation of the weighting coefficients p_i; and, at least, calculation of the sought values of the meteorological parameter on the basis of the optimum interpolation model at the nodes of a regular grid and at all missing altitudes.

The block 14 provides the output of the results of the objective analysis. The output data are written in the ASCII file named RESULT containing reference information (the number m of the grid node, as well as the date and time of the objective analysis) and the values of the meteorological parameter calculated at all altitudes at each node of the grid.

4.5. Subsystem for Presentation of the Output Data

This subsystem of AMSS is an auxiliary one and it is intended at presentation (in the required format) of the results of objective analysis of the mesometeorological fields, as well as other (required for solving the ecological problems) information, which are transferred to the hard disk by means of the interface, and then all output data are delivered to the "Ecolog" GIS.

4.6. User's Interface

The user's interface provides the operation of all subsystems of the AMSS. Separate module (subsystem) is initiated to run from the user's interface program.

The software of the user's interface of the AMSS is realized as ASMP.EXE in Windows and it is oriented to operation in the Windows 3.1 medium that is the most perspective and effective (in comparison with DOS).[25]

5. SOFTWARE AND SPECIFICATIONS OF THE SYSTEM

When selecting the basic programs to be used for developing the AMSS software, we took into account the possibility of their incorporation into the Windows environment. The second aspect taken into account at the selection was the requirement of the best program compatibility of separate program blocks when operating in the general program package.

To meet the second requirement, all software applications included into the AMSS were developed based on the products of the same firm Borland Inc., which gained wide acceptance among the users and developers of different databases. On this basis, the database of the regional models of the atmosphere has been written in the Paradox 4.0 DBCS of Borland Inc. described in detail in Ref. 26. According to the expert estimate, this DBCS is one of the most powerful control systems of the relation database upon the criterion of the rate of operation.

The modern product of Borland Inc., Delphi system, which is related to the systems of fast development of applications, was used for the development of the AMSS Windows application. The new programming language of high level, Object Pascal equipped with the fastest compilator in the world, is used in the Delphi system. The important property of this language is the possibility to call the external functions of the C-style, that makes it possible to link the programs written in any language to the Windows-application developed in the Delphi system by creating the Dynamic Link Libraries (DLL). The latter are the set of the dynamically called programs (only for solving a particular problem) and are stored in a separate file.

When developing the DLL-libraries in the AMSS version realized, the programming system of the Microsoft Fortran 5.1 type was used, because historically the FORTRAN language was invented for solving complex scientific problems, with which we dealt when solving the applied problems of AMSS.

As for the specifications of the first version of the automated meteorological support system, it was realized on a PC/AT 386DX personal computer with RAM of 4 Mbyte and the hard disk of 80 Mbyte free memory.

It should be said for the conclusion that although the automated system described above is oriented mainly to the meteorological support of the "Ecolog" GIS, the principles laid in the development of this system can be successfully used for creation of other software complexes of that type.

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