Fuzzy Logic Approach for Evolutionary Modeling of Principal Meteorological Variables

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ABSTRACT: The opportunity of fuzzy set approach for study of joint diurnal distribution of principal coupled atmosphere-land variables (temperature of air and soil, humidity of air and soil, atmospheric precipitation, pressure, short-wave radiation, cloudiness) is investigated. Ten years data sets of one hour temporal resolution for several meteorological sites of Russian north-west region are used. Known and novel interrelationships between various atmospheric and linked soil variables are reviewed. The revealed relationships between solar downward radiation fluxes and soil temperature diurnal patterns allow to simulate all principal elements of surface energy exchange : long-wave outgoing radiation fluxes in the atmosphere, soil heat fluxes, sensible, turbulent and latent heat fluxes. It was found out that the most complicated links take place for fuzzy sets, corresponding to fractional cloudiness diurnal patterns. There is an asymmetrical relationship between solar daily sums of radiance for half cloudy day and mean soil temperature values. That is a main cause for simulation of meteorological and heat balance component diurnal cycles in most ecological models. Introduced stationary and transition modes for main meteorological variable diurnal patterns represent the background for simulation of all known weather phenomena. This modes are used also as a neural network's nodes for hidden layers. Implementation of neural networks (back propagation algorithm) allows to perform several modeling experiments. Problem of optimum network configuration (number of nodes in hidden layers) is discussed. For example, it is possible to reconstruct the diurnal cycles of some meteorological variables with sufficient (at the observational error levels) precision for each of them, by using 1, 2 or 3 instantaneous meteorological observations. Adapted non-linear mapping of one group variables (and its diurnal distributions) on another one allow to investigate the possibility of application of this approach for diagnostic aims. Potential applications of the developed approach are : regional models; nested models and downscaling in global models; spatial field reconstruction in case of missing observational data (for some variable(s)); parameterization of energy exchange processes at the surface of the Earth.

KEYWORDS: PARAMETERIZATION OF ATMOSPHERE-LAND ENERGY EXCHANGE, FUZZY SETS, NEURAL NETWORK

INTRODUCTION

Various approaches and methods of simulation of meteorological processes at the surface of the Earth have been actively developed in recent years (e.g.Randall (1991)). The principal stimulus for these researches are linked with activation of regional and global climate change investigations, and also of complicated processes, occurring in ecosystems (Kondratyev (1996), Pokrovsky (1995), Pokrovsky (1996)).

The head stone for such researches is the study and simulation of diurnal cycle of basic near-surface meteorological parameters (air and soil temperature, humidity, pressure, precipitation, wind, cloud cover). In connection with necessity of description of energy exchange processes it is essential to consider also radiometric parameters (downward, reflected and net SW radiation, albedo, outgoing LW radiation) (Cherveny (1991), Kubota (1991)). During many years experts investigated specific features of a diurnal cycle of these parameters on the base of empirical data (Cherveny (1992); Williams (1992)). Some examples of classification of diurnal or daily cloud cover distributions are represented in the literature (Berlyand (1961)). The given problem for atmospheric temperature and humidity was traditionally considered at a qualitative level during many years. We mention some publications of last time (Mass (1991); Ruschy (1991)). The examples of a classification of radiation characteristics at the surface of the Earth, mainly determined by distribution of a cloud cover, are presented in two works (Flach (1951); Flach (1952)). In last years activity at study of a diurnal cycle of precipitation amount is exhibited (Haldar (1991)). It has allowed the authors to determine basic types of distributions and to make definite qualitative conclusions. Unfortunately, the majority of researches in this area is connected with study of a diurnal cycle of separate meteorological parameters. However, for simulation of complicated processes, taking place at the surface of the Earth, characterised by natural topography, it is necessary to investigate joint distribution of several parameters simultaneously.

Many model studies (see review : Betts (1996)) have shown the importance of the surface boundary condition over land in controlling weather and climate processes of different time-scales. The radiation fluxes over land as well as soil temperature and soil moisture are not routinely observed or are not used as input boundary condition in global forecast models. Instead , they are evaluated from full system of parameterized equations at the surface, involving the surface radiation budget, strongly influenced by solar diurnal cycle and poor model representation of the cloud field. The impact of land surface processes in general circulation models has been reviewed by Garratt (1993). The solar terms are dominant in radiation budget, at least during daytime and in summer. Reflection and absorption by clouds and aerosol reduce the incoming radiation at the surface. It is well known that many models underestimate the atmospheric absorption and reflection of solar energy and as a result overestimate the incoming short wave radiation at the surface (Garratt (1993)). The excessive net radiation at the surface leads to excessive surface evaporation and dried out soil moisture. The mentioned study concerns the daily mean values. But it is of interest to get insight into the deviation statistics for diurnal resolved values because of substantial daily amplitude of main meteorological parameters .

In our opinion for solving this problems it is necessary to refuse from conventional methods of statistical analysis (calculations of moment, correlation functions, regression analysis and etc.), which ensure exposition only of linear relations. At the same time the most of meteorological processes and relationships should be referred (by their nature) to non-linear. So our final goal is to describe this non-linear processes by modern mathematical methods. The first step on a path should be the classification of basic meteorological parameter diurnal patterns by means of fuzzy logic (Jain (1988); Kohonen (1989)). Their diurnal cycles should be the object of the first phase of researches. Then it is necessary to proceed to classification of synoptic variability not only of single meteorological parameters, but also of their joint distribution to study their actual feedbacks. All mentioned above type of patterns are considered as state vectors in multidimensional space. Principal method issue is the revealing of its fuzzy sets. We suggest that most of the weather phenomena could be simulated by sequences of its conservation inside some fuzzy set and transition from one fuzzy set to another. The more fuzzy sets are used the more wide set of weather phenomena could be described by this approach. Important key point here is the development of the transition rules.

In the first section of the paper the description of the used cluster analysis method is presented. The problem of classification of diurnal cycles of major meteorological parameters under condition of their statistical sample independence is further considered. In the third section the most actual problem - the study of joint probability distribution of several meteorological parameters for synchronised periods of observations and appropriate classification of linked diurnal cycles is considered. At the final section researches on classification of joint distribution of meteorological parameters on a time scale equal to two days are presented.

FUZZY LOGIC ALGORITHM

In meteorology the large attention is given to the analysis of statistical relations between separate parameters. For study of their space and temporal distributions it is necessary to use methods of a multidimensional statistical analysis. One of the important direction is a combination of cluster and discrimination analysis. In the given research diurnal distributions of meteorological parameters will be considered. However, the offered approach can be applied to distributions of other temporal scales (monthly, seasonal, annual and etc.).

We shall assume that it is necessary to investigate a time scale, containing p - references (for example, instants of observations), and we arrange n - realisations of measurements in an indicated time interval. In this case measurement data can be presented as a matrix:

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots. & \dots & \dots & \dots \\ x_{p1} & x_{p2} & \dots & x_{pn} \end{bmatrix} = (\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_n). \qquad (1)$$

Each realisation of the investigated process, represented by the vector - column X_j,(j=1,..., n), can be interpreted as a point in Euclidean multidimensional space of size p. Using notation (1), it is possible to introduce several characteristics, describing scattering of data inside classes and a distance between classes. We define a matrix of size p * p

$$S_x = \sum_{i=1}^{n} (Xi - \overline{X}) (Xi - \overline{X})^*, \qquad (2)$$

(* - sign of a transposition)

It is named by a matrix of scattering of a observational set X, and $\overline{X} = \sum_{i=1}^{n} X_j / n$ - is a vector of mean values. The trace of a matrix S_x, equal to a sum of diagonal elements, is named by statistical scattering of a set X.

The cluster analysis is based on partition of an initial set X on subsets, distance between which should be maximum. Now let us assume that there are two data sets X and Y. It is necessary to introduce a measure of a statistical distance between classes, formed by observational data matrixes X and Y:

$$D = \alpha (\overline{X} - \overline{Y})^* (\overline{X} - \overline{Y}), \qquad (3)$$

where α = n1 n2 / (n1 + n2), n1, n2 - number of realisations in each class.

We shall enter into consideration a combined class Z= (X, Y). Relationship between scattering of observations inside class Z and corresponding values inside classes X and Y:

$$S_z = S_x + S_y + ((\overline{X} - \overline{Y})^* (\overline{X} - \overline{Y})), \qquad (4)$$

is fundamental, as is used in any cluster analysis.

The equation (4) can be interpreted as follows: total scattering of two joint classes of realisations is equal to a sum of scattering inside classes and a distance between these classes(i.e. between its mean values). There are several fuzzy logic algorithms (Jain (1988)). This algorithms are distinguished by that in one case the partition of a set of input object set into classes begins from one class, contained all objects, and in other, on the contrary, joining of separate objects into classes are performed by a selection of «nearest neighbours ". We have used a method, concerning to the second group. The iterative algorithm implements under conditions of beforehand prescribed number of classes . Its essence is reduced to sequential search of objects from their initial distribution and to trial its transposition from one class to the other to archive both a minimum of inside class scattering and a maximum of centre to centre class distance

MAIN METEOROLOGICAL PARAMETER DIURNAL CYCLE MODELING

A basis for our researches were archival hourly observational data for several sites of north-west region of Russia for 1984-93. The input data arrays, concerning to various meteorological parameters, were synchronised on time and presented separately for each of months. The calculations were carried out for several stations. The results of the classification have appeared similar. Therefore results for only one characteristic site Voejkovo (60 N, 30 E) are presented below.

Originally diurnal distributions, obtained by an independent way for atmospheric temperature and humidity, downward total (scattered plus direct) SW irradiance, atmospheric pressure, precipitation, direction and velocity of wind, were considered. Then rows of X-type matrix were performed. Each row contains diurnal distribution for a certain day. Thus for each parameter and each month a matrix was formed and the calculations on a partition of initial sample on a number of classes by means of cluster analysis, described above, were carried out. Calculations allowed to allocate each class as a set of distributions, minimum deviating in a Euclidean distance sense from average diurnal cycle (in a given class). As has been mentioned above the applied algorithm is aimed to maximise an Euclidean distance between mean value vectors, appropriate to diurnal pattern distributions of different classes. Despite a formal character of this algorithm, it has appeared, that the obtained outcomes have the reasonable physical interpretation.

We shall begin from reviewing diurnal cycle of total solar downward radiation. Its diurnal cycle in summer is the most significant due to amplitudes. Average (for 6 classes) distributions are shown at Fig.1. The obtained results suppose the simple interpretation. The upper curve corresponds to conditions of clear sky, and lower one to overcast cloud cover. Intermediate curves correspond to conditions of a fractional cloud cover, which can vary during a day (Table 1). For example, at forth class in the first half of a day the fractional cloud cover is of .3, and in the afternoon is of .7 and at fifth class the diurnal pattern has an opposite structure. It is necessary to note, that results of empirical classification of a day time cycle of cloud cover, presented in works (Flach, 1951; Flach, 1952), are closely interlaced with data from Table 1. To substantiate

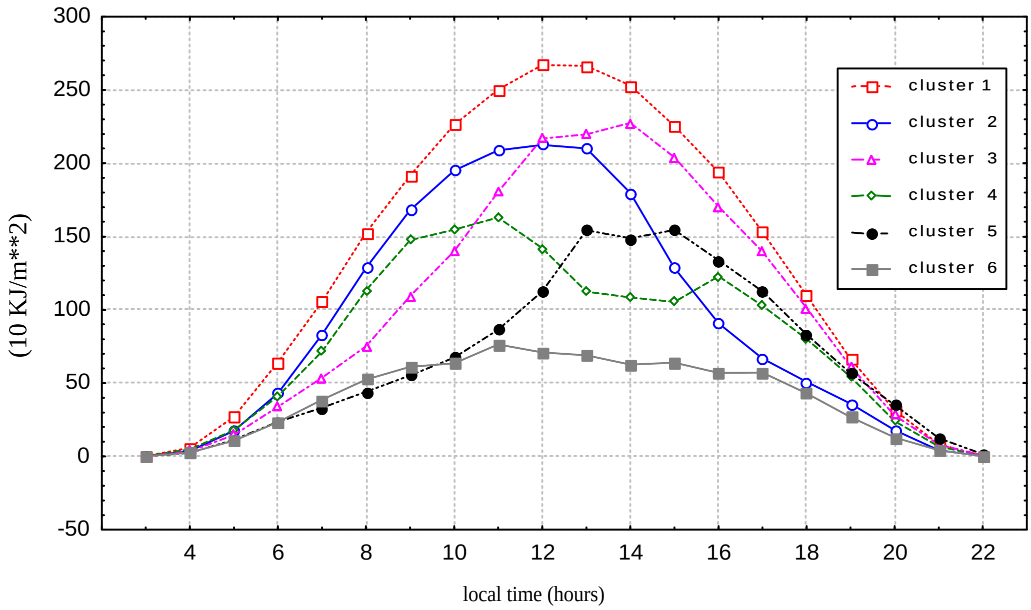

Fig.1. Diurnal patterns of surface total downward irradiance(6 clusters), July

the interpretation of classification results presented in Table 1, parallel calculations of day time distribution of downward SW radiation for the latitude 60° and height of the Sun, adequate to appropriate month of the year, were performed. The calculations were carried out on the base of the Delta-Eddington approximation technique for homogeneous cloud model, with optical thickness equal to 30, the albedo of single scattering equal to 0.99 and asymmetry factor of the phase function g=0.85 . The version of this technique for conditions of a fractional cloud cover, described in (Schmetz (1984)), was used. The values of fractional cloud cover given in Table 1 were selected by minimisation of a divergence between calculated and empirical distributions of a day time cycle of radiation fluxes. It is interesting to note that cloud diurnal pattern classification results obtained in previous studies (see review at Berlyand (1961)) are closely linked to data given in Table 1. The distributions show that net radiation diurnal patterns have the structure analogous to that obtained for surface solar irradiation. This fact explains rather strong links between diurnal distributions of surface solar irradiation and surface air temperature and other parameters, which will be discussed below.

Cluster Number	Cloudiness distribution

1	Clear sky - during a day
2	Clear sky -in the morning , fractional cloud cover of 0.3 - in the noon and the afternoon
3	Fractional cloud cover of 0.3 - in the morning and the noon, clear sky -in the afternoon
4	Fractional cloud cover of 0.3 - in the morning , fractional cloud cover of 0.7 - in the noon and the afternoon
5	Fractional cloud cover of 0.7 - in the morning and the noon, fractional cloud cover of 0.3 - in the afternoon
6	Overcast cloudiness - during a day

Table 1. Classification of cloudiness and solar radiation diurnal patterns

Since a mathematical classification method is used, the question concerning the structure of each class can be arisen. Fig.2 shows the bands including the diurnal radiation distributions for two (from six) clusters (their «centres'» are given at Fig.1). It is clear that classification can be considered a representative one not only if the class elements have minimal deviations from the centre diurnal distribution
(here it is mean values), but also if they have the same structure: coordinates of maximum and time gradient values. The given results demonstrate the fact that the proposed classification method guarantees precisely this similarity for most elements from the same class.

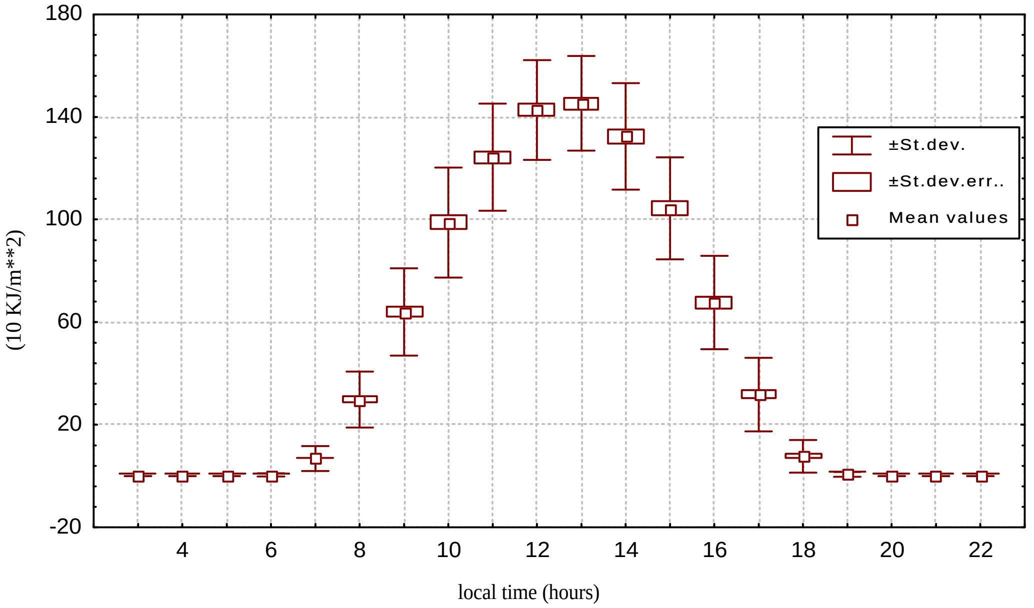

Fig.2. Statistics of total SW surface irradiance, July :

Let's consider a diurnal cycle of other meteorological parameters. For simplicity we will discuss the case of partition of initial sample onto 4 classes. Results of calculations (Fig.3,4) have shown, that in this case the obtained classes for temperature and humidity as well as for downward solar irradiance can be referred to two different groups. The first group includes distributions for which both parameters correspond to a stationary condition of atmosphere (i.e. during a day a considerable decrease or increase of parameter values deviations from multiannual average diurnal cycle is not observed). Proceeding from these it is possible to name the appropriate average diurnal distributions as stationary modes. They are two and they correspond to keeping warm or cold weather pattern during the day. The second group includes classes, the average distribution of which, on the contrary, changes during the day compared to corresponding average diurnal cycles. Such distributions are possible to name as transient modes, as they follow the modifications of temperature and humidity in the course of the day. These modifications are connected with increasing or decreasing values of considered parameters. Curves, adequate to indicated types of modes, are showed on Fig.3, 4. Four classes considered above allow to simulate closed loop variations of meteorological parameter during several sequential days, for example, synoptic variability. It is necessary to note that transient modes for solar radiation are mainly due to cloud cover varying in the course of the day.

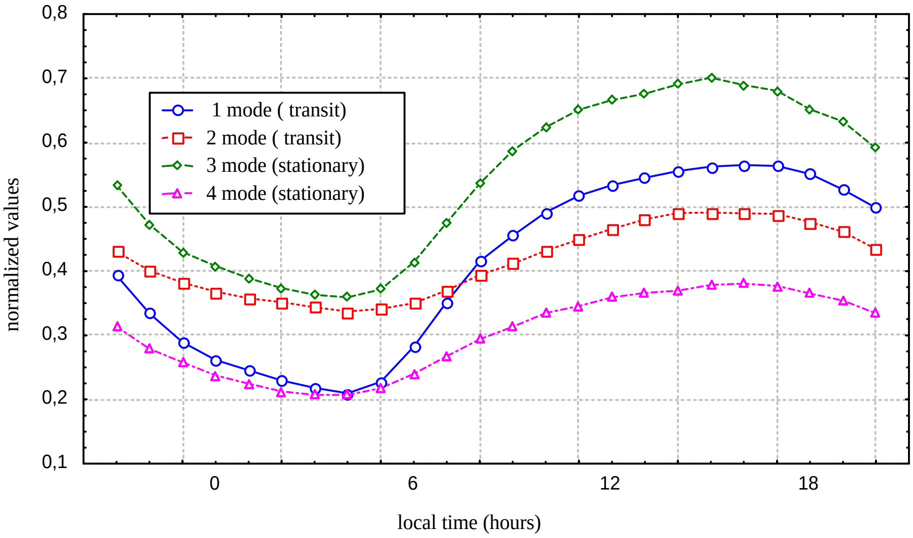

Fig.3. Classification of joint diurnal patterns : temperature

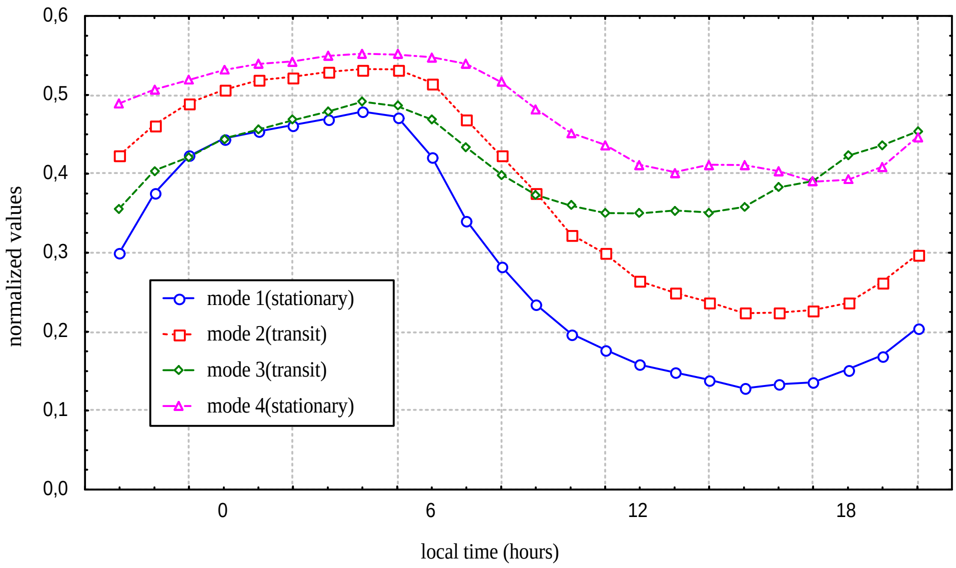

Fig.4. Classification of joint diurnal patterns : humidity

Typical diurnal patterns for other meteorological parameters shown on Fig.5, 6 demonstrate the unlike characteristic type of relationships.

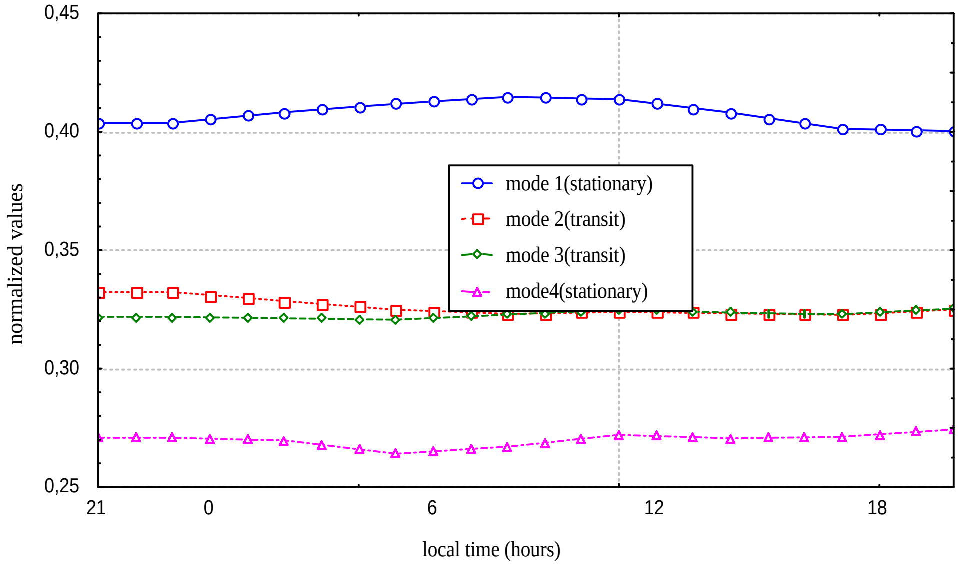

Fig.5. Joint patterns : atmospherical pressure, July

So, for example, in case of low or high pressure(cluster 1 and 4) diurnal oscillations (Fig.5) are more often observed. A study of precipitation has shown that rainfall before dawn, after midday and in the evening is the most probable. Moreover, the rain intensity increases in the indicated sequence and reaches a maximum at 19 o' clock of local sun time (Fig.6).

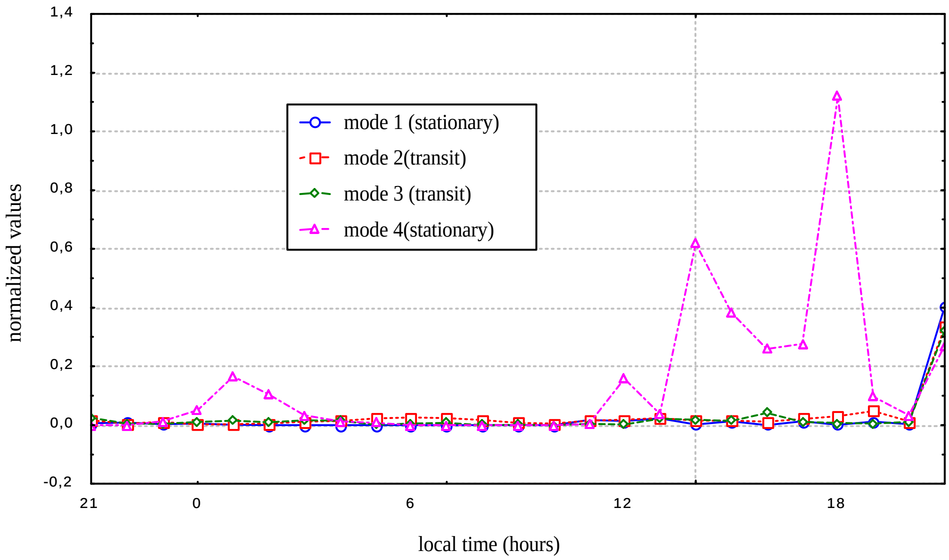

Fig.6. Joint patterns : precipitation , July

Direction of wind is one of the most changeable and informative for the meteorological parameter forecasting. Our study shows that the direction of wind is seldom saved during a day. The most probable modification time intervals are before dawn, in the morning, after midday and in the evening. In addition, the most intensive and quick are the changes from north-west wind to north-east, east and southern. Changes of southern wind to western are less intensive.

DIURNAL CYCLE PATTERNS OF JOINTLY DISTRIBUTED METEOROLOGICAL PARAMETERS.

For a long time the problem of joint probability distribution of meteorological parameters attracts attention of meteorologists. However, till now in majority of studies authors limited themselves by only revealing of cross-correlation and constructing of regression models. Taking into account, that feedbacks in the atmosphere - Earth surface, atmosphere - cloud cover and other systems, determined by energy exchange processes have a non-linear character, the above mentioned traditional statistical approaches, which involve only linear relations, give rather approximate conception on the essence of occurring processes.

The diurnal pattern of one or several meteorological parameters, corresponding to the given day can be represented as a point in a phase space of appropriate size. Our research has shown, that the points of such multidimensional phase space can be rather good classified, i.e. the input sample of points, adequate to empirical data, are splitted into an easily separated groups. It means that in the course of time a point, belonged to one cluster (adequate to one type of weather) is transferred to another cluster. For some time between these transpositions the point stays in the former cluster. It means that at this period the weather processes were stabilised. It is clear that the mentioned processes could not be accurately described by linear models.

Let's consider outcomes of performed calculations. Results of joint diurnal patterns of three meteorological parameters: solar radiation, air surface temperature and humidity are similar to patterns, presented at fig.1, 3, 4. The chosen average distributions were divided rather conditionally into two groups of modes: stationary and transient ones. The sense of introduced terminology is obvious. Stationary modes correspond to the points in phase space, that are staying in the same cluster. Transient modes correspond to a transitional position of these points. The minimum number of clusters for this case is equal to 4. Stationary modes in a diurnal temperature and humidity cycles correspond to distribution of the clear sky radiation : maximum temperatures and minimum humidity and also maximum diurnal cycle amplitudes. Similarly other types of stationary modes of temperature and humidity correspond to radiation under conditions of continuous cloud cover. The difference is connected with minimum values of diurnal cycle amplitude. A varying fractional cloud cover corresponds to transient modes of temperature and humidity distribution. The indicated transient modes describe passages from large to small values of meteorological parameters (temperature and humidity) and on the contrary.

The joint distribution of total solar radiation, precipitation and atmospheric pressure demonstrates their coherence. At the clear sky conditions high pressure and temperature , low air humidity and absence of precipitation are observed.

In this case one finds two distributions corresponding to conditions of overcast cloud cover . Thus, curve 2 corresponds to distribution, associated with decrease of pressure (Fig.5). On the contrary, continuous cloud cover (Fig.5, the curve 4) at low pressure corresponds to the curve 4 on Fig.6, revealing the presence of precipitation. Pattern, describing increase of pressure and absence of precipitation corresponds to distribution of radiation at a fractional cloud cover. Practically it is possible to speak about two classes of distributions for precipitation: days with rainfall and without rainfall.

The cluster determination of joint distribution of main meteorological parameters - pressure, precipitation and wind direction also gives characteristic correlation of a diurnal cycle. High pressure is accompanied by the lack of precipitation and western direction of a wind with passage to southern and south-eastern direction. At lower pressure (curve 3 at fig.5) the precipitation is also absent, and the wind has mainly western direction. At a further drop of pressure (the curve 2 at fig.5) wind has mainly south-eastern direction. At low pressure (the curve 4 at fig.5) precipitation is observed, and wind changes from southern to western direction. In July the increasing pressure curve corresponds to «no» precipitation and to probable change of wind from west to south and south-west direction. Providing lower pressure, precipitation is absent too, but wind has prevalent south-east or north-east direction. The decreasing pressure curve corresponds to higher probability of precipitation and wind changes from south to west direction

Mentioned results allow to make some conclusions. The typical diurnal cycle of basic meteorological parameters is characterised by consistent distribution of either stationary or transient modes. Fundamental influence of solar radiation on atmospheric temperature and humidity becomes more clear. Characteristic pressure distributions and appropriate distributions of precipitation and wind directions specify certain weather conditions and their modifications. Analogue conclusions are obtained for relations between cloud cover and precipitation. The number of clusters could be enlarged for more detail description of other weather conditions. The obtained classification could form a basis for a solution of both fundamental and applied problems. To the first group it is possible to refer the problem of modelling of a diurnal cycle of meteorological parameters, and the problem of the short-term weather forecasting or automatic monitoring of observational data could be referred to the second group.

MODELLING OF THE MULTIDIURNAL VARIABILITY OF JOINTLY DISTRIBUTED METEOROLOGICAL PARAMETERS.

Modifications of weather conditions occur not only during day period, but also consecutive days on a synoptic temporal scale. Therefore the problem of cluster determination of two and three-diurnal joint distributions of basic meteorological parameters was considered. Here as well as above we are interested to study the stationary and transient modes . Therefore only 4 classes for joint distribution of solar radiation, temperature, humidity and precipitation were selected for a minimum model. The major interest represents a role of joint distribution of parameters. Fig.7, 8 demonstrates the cluster discrimination results of two-diurnal patterns of joint radiation, temperature and humidity distributions. As it was mentioned above the stationary modes illustrate preservation of two types of distributions at passage from the first day to the second. There are two modes of such kind: keeping cold or warm weather types(curve 1 and 3).

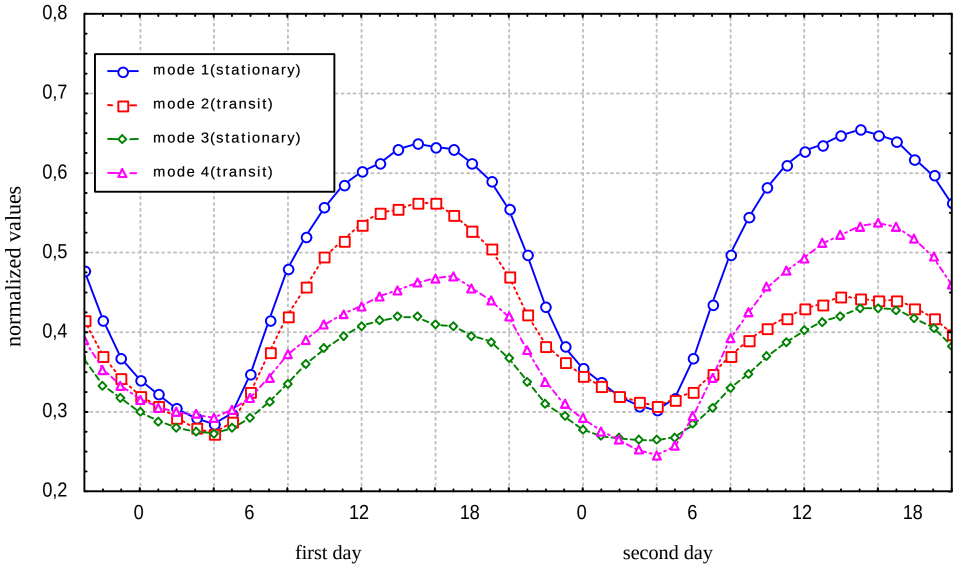

Fig.7. Joint bi-diurnal meteorological patterns : temperature, July.

On the contrary, the transient modes describe modifications of weather conditions. Passage from the clear sky conditions (to the overcast cloud cover results in the decreasing of temperature (curve 2, Fig.7) and increasing of relative humidity (curve 2, Fig.8). Passage from the continuous cloud cover to the clear sky leads to the inverse variations of the rest parameters, i.e. raise of temperature and drop of humidity(curve 4, Fig.7, 8). Once again it proves the determining role of radiation processes, controlled by a cloud cover.

Independent distribution of basic meteorological parameters on an interval equal to two days looks similar to considered above case of joint distribution of parameters. However, obtained modes are not completely logically matched. It means, for example, that transient modes of one parameter can fit similar modes of another parameter, more appropriate by physical reasons to other modes.

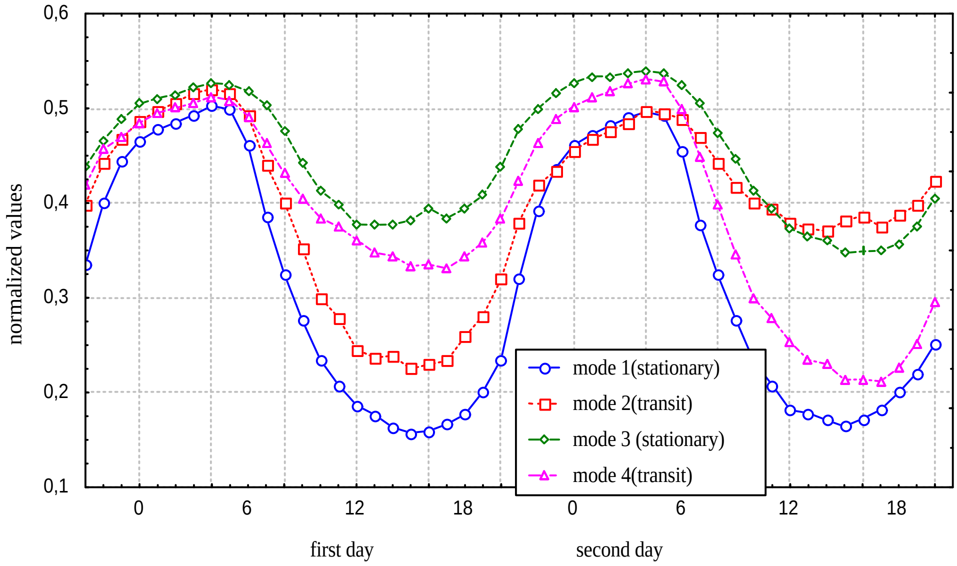

Fig.8. Joint bi-diurnal meteorological patterns : humidity, July.

CONCLUSIONS

The obtained results principally differ from conventional studies on statistical features of meteorological parameters widely represented in scientific literature. The conventional approaches are usually based on application of correlation or regression analysis techniques, which are linear by their nature. These methods usually deal with norms of meteorological parameters and statistical estimates of deviations from these norms. In this case it is possible to get estimates of deviations of some parameters as a linear function of the other. It concerns both diagnostic, and prognostic problems. However, determination of an area of applicability of linear methods and emerging of new techniques of non-linear process modelling, developing in parallel to significant progress of computer facilities, give stimulus for application of non-linear methods for statistical description of meteorological values and fields. Here first of all we mean the " neural network" techniques, which originally emerged from the problems of an artificial intelligence and obtained broad spreading at a solution of many applied problems in various branches of science and engineering. Applying «neural network» methods (Allen (1994); Bankert (1996)) it is necessary first of all to define cells or nodes of such network. The purpose of the given work consists not only in study of non-stationary diurnal and multidiurnal oscillations (modes), but also in the definition of elementary neural network for modelling diurnal cycles and multidiurnal patterns of main meteorological parameters. Thus, it is possible to consider the present research as the introduction to the application of new computing techniques for simulation of non-linear meteorological processes observable at the surface of the Earth.

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