ТРАНСПОРТНЫЕ СИСТЕМЫ
2.9.1 – Транспортные и транспортно-технологические системы страны, ее регионов и городов, организация производства на транспорте;
2.9.4. – Управление процессами перевозок;
2.9.6 – Аэронавигация и эксплуатация авиационной техники;
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Substantiation of source data on the parametric algorithms for the classification of weather hazards

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Abstract: The meteorological situation is one of the decisive factors determining the safety and frequency of civil aviation flights. Weather hazards (WH), associated with cumulonimbus clouds, such as a heavy shower, thunderstorm, hail, combined with high atmosphere turbulence, quite often lead to aviation events and even accidents. Currently, a domestic weather radar system of the near airfield zone (WR) “Monocle” has been developed and successfully operated. The criteria for the classification of meteorological phenomena (MP), used in the WR, have been developed individually for each phenomenon and have some heuristic character. These criteria are cumbersome and complicate the process of automating the WH classification. In this case, there is a natural desire to generalize the criteria and optimize them in accordance with the theory of distinguishing statistical hypotheses. This article discusses the application of the Bayesian approach to the WH classification. The statistical Bayesian decision theory assumes decision-making in terms of the probability theory when all significant probabilistic values, so-called sufficient statistics, are known. In order to obtain statistical descriptions of the probability distributions of reflectivity and the eddy dissipation rate (EDR), an analysis of radar signals, reflected from such MP as a rain shower, thunderstorm, hail was carried out. The article provides brief descriptions of the methods of conducting experiments to form statistical database and its analysis. Based on the above methods, the statistical parameter H(EDRmax) analysis for a rain shower, the amplitude distribution of reflectivity parameters and the EDR (Zmax, EDRmax) for thunderstorms and hail was carried out, which showed the low distinguishing ability of each individual parameter when solving the problem to classify MP within the assigned alphabet. The obvious solution is dictated by the theory of recognition. To increase the classification confidence, it is essential to share information parameters, for example, in the form of multidimensional distribution densities of the probabilities of random parameters. The article presents a parametric description of the MP “rain shower-thunderstorm-hail” classification features. An analysis to evaluate the probabilistic characteristics of the WH classification for the adopted empirical classification criteria in the WR shows that the adopted criteria are far from optimal in terms of the probabilities of the correct classification, especially in the rain shower case. It is obvious that a problem solution of the assigned classification confidence is associated with the optimization of the feature space and classification criteria. Based on the data obtained, it is necessary to build an algorithm to classify the WH “rain shower-thunderstorm-hail”.

Key words: weather radar, near-airfield zone, weather hazards, weather phenomena classification, statistical data analysis.

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Обоснование исходных данных параметрических алгоритмов классификации опасных метеоявлений

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Аннотация: Метеорологическая обстановка является одним из решающих факторов, определяющих безопасность и регулярность полетов гражданской авиации. Опасные метеорологические явления (ОМЯ), связанные с кучево-дождевой облачностью, такие как ливень, гроза, град, в сочетании с сопровождающей их высокой турбулентностью атмосферы нередко приводят к авиационным событиям и даже авиакатастрофам воздушных судов (ВС). В настоящее время разработан и успешно эксплуатируется отечественный метеорологический радиолокационный комплекс ближней аэродромной зоны (МРЛК БАЗ) «Монокль». Критерии классификации метеоявлений, используемые в МРЛК БАЗ, разработаны для каждого явления отдельно и носят некоторый эвристический характер. Данные критерии громоздки и затрудняют процесс автоматизации классификации ОМЯ. В этом случае возникает естественное желание обобщить критерии и оптимизировать их в соответствии с теорией различения статистических гипотез. В данной статье рассматривается применение Байесовского подхода к классификации ОМЯ. Статистическая теория принятия решений, разработанная Байесом, основана на выборе решения в рамках теории вероятностей, когда известны все представляющие интерес вероятностные величины, так называемые достаточные статистики. С целью получения статистических описаний вероятностных распределений отражаемости и удельной скорости диссипации турбулентной энергии был проведен анализ радиолокационных сигналов, отраженных от таких метеоявлений, как ливень, гроза, град. В статье приведены краткие описания методики проведения экспериментальных исследований для формирования базы статистических данных и ее анализа. На основании приведенных методик был проведен статистический анализ параметра H(EDRmax) для ливня, а также амплитудного распределения параметров отражаемости и удельной скорости диссипации турбулентной энергии (Zmax, EDRmax) для гроз и града, который показал невысокую различительную способность каждого отдельного параметра при решении задачи классификации метеоявлений в пределах заданного алфавита. Очевидный выход из создавшейся ситуации диктует теория распознавания. Для повышения достоверности классификации необходимо совместное использование информационных параметров, например, в виде многомерных плотностей распределения вероятностей случайных параметров. В статье приведено параметрическое описание признаков классификации метеорологических явлений «ливень – гроза – град». Анализ оценки вероятностных характеристик классификации ОМЯ для принятых эмпирических критериев классификации в МРЛК БАЗ показывает, что принятые критерии далеки от оптимальности с точки зрения вероятностей правильной классификации, особенно в случае с ливнем. Очевидно, что решение задачи заданной достоверности классификации связано с оптимизацией признакового пространства и критериев классификации. Далее, на основании полученных данных, необходимо построить алгоритм классификации опасных метеоявлений «ливень – гроза – град».

Ключевые слова: метеорологический радиолокатор, ближняя зона аэродрома, опасные метеорологические явления, классификация метеорологических явлений, статистический анализ данных.

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Introduction

A meteorological situation is one of the decisive factors determining safety and flight regularity of civil aviation. Weather hazards (WH) [1], more specific for the European part of Russia and associated with cumulonimbus such as a rain shower, thunderstorm, hail coupled with high atmospheric turbulence, quite often cause aviation events and even accidents of aircraft (A/C) [2]. The phenomena are the most hazardous during takeoff-landing procedures [3].

Currently, a revolutionary domestic X-range weather radar complex of the near-airfield zone “Monocle” [4, 5] of low mass-dimension performance, which complies fully with the modern international and domestic requirements, has been designed, tested and in-service.

The criteria of the classification of meteorological phenomena, used in the WR [6], were formulated in conformity with the regulatory documents[1] [7], in which, universally applicable parameters to define a weather event class in weather radars with various performance. Significantly, that all the legislatively adopted criteria of the weather event classification ranging from clouds to waterspout based on long-term observations, which has commanded respect, have been individually developed for each phenomenon and bear some heuristic character.

In this case, it is a natural desire to generalize the criteria and optimize them in accordance with the theory of differentiation of statistic hypotheses [8–11]. It is practical when probability distributions of information atmospheric parameters [12] are parametrically described.

In the WR “Monocle”, the WH classification is based on knowledge about the altitudinal distribution of radar reflectivity [1], atmosphere temperature (freezing level, freezing level −22°) as well as values of low and high radar echo boundary [6]. The data is cumbersome and hinders the process of automation for the WH classification.

The authors initiated to set an end to heuristics with respect to the depicted problem, and transfer to parametric methods, expand an alphabet of classes to enhance the WH classification confidence. The basic ways of criteria optimization of the CB-related WH classification have been found:

- the use of information about altitude distribution not merely of reflectivity but also of atmosphere turbulence in the WH classification criteria;
- the formation of parametric descriptions of maximum reflectivity distribution densities and turbulence by values and altitude;
- the development of WH classification algorithms (of decision-making threshold formation) in compliance with the single chosen criterion to differentiate statistic hypotheses.

This paper is a logic continuation.

Bayesian approach to the classification of meteorological phenomena

The Bayesian decision theory constitutes the foundation of a statistic approach to the problem of natural phenomena, image, signal classification [8]. The problem statement of identifying MP in the case under consideration assumes the solution of the following integrated tasks:

- forming the class alphabet, i.e., a combination of classified phenomena, in our case, a rain shower-thunderstorm-hail-another phenomenon (the term “another phenomenon” is used in a rigorous problem statement, as the alphabet should form a complete group of events);
- selecting feature space, i.e., information parameters which are emitted from a reflected radar signal and allow the phenomena classification with the assigned reliability;
- defining the sufficient statistics, i.e., the probabilistic description of features and phenomena, which will be used while identifying (the substantiation of the loss matrix, availability of a priori information, density of distribution of information parameter probabilities, extent of feature correlation, etc.);
- selecting the identification criterion (Bayesian, maximum of likelihood function, Neyman-Pearson, etc.) and the confidence requirements, which determine a value of decision-making threshold.

In the general case, the given sequence of problems is iterative and assumes the correction of alphabet, features, and criteria to achieve the required validity to identify under limitations on various type-resources.

Thus, the classification problem essentially poses the partition problem of the feature space into domains for each class. The partition in terms of forming decision-making thresholds should cause the maximization of right decisions and/or the minimization of erroneous ones.

Let us denote a weather event by a symbol ω, whereby ω = SHRA for the rain shower, ω = TS

[1] The Guide to make observations and apply information-from not automated weather radars WR-1, WR-2, WR-5. RD 52.04.320-91. (1993). St. Petersburg: Gidrometeoizdat, 342 p. (in Russian)

for the thunderstorm, ω = GR for the hail. The value ω is regarded as a random value in the sense that nature state is unknown. In our case, let us assume that a priori probabilities of events are not known as well. In order to simplify a problem without losing the quality of its solution, let us assign an obvious assumption: conditional distribution density of a factor x while observing a weather event ω_i $p(x/\omega_i)$, where $i \in \{SHRA, TS, GR\}$ is the sufficient statistics in the case under consideration. The statistics allows us to solve based on the method of the maximum likelihood: the solution ω = i is chosen for which

$$p(x/\omega_i) > p(x/\omega_k) \quad \text{for all} \quad k \neq i. \qquad (1)$$

Sufficient statistics, formed without using data, which are contained in a priori distribution and the loss function, determine the structure of an optimal decision and an optimal method of data processing [13]. It is indicative of their versatility and adequacy while solving a diversity of applied information system synthesis problems within the conditions of expected uncertainty [10].

The conducted experimental analysis of radar signals showed that for the assigned class alphabet, it is feasible to search for probabilistic descriptions of the maximum reflexibility distribution density Zmax and EDR which reflects turbulence by values and altitude in the form of $p(Zmax/\omega_i)$, $p(EDRmax/\omega_i)$, $p(H(Zmax)/\omega_i)$, $p(H(EDRmax)/\omega_i)$, where $i \in \{SHRA, TS, GR\}$.

The degree of the expected uncertainty can be different. At the first stage, the authors considered the problem with the complete expected uncertainty, when neither types nor parameters of laws of information parameters probability distribution are known. It should seem that under the complete expected uncertainty, the statistic synthesis is not practical because we cannot either formulate or compute the optimality criterion. However, instead of unknown distributions, empiric data, which are referred to as learning samples, can be used.

The [10] demonstrates the problem of overcoming the complete expected uncertainty can be solved by means of three stages:

- at the first stage, the class of possible probability distributions, limited by some aggregate with arbitrary parameter values (in our case, a distribution aggregate close to Gauss one), is determined stemming from the physical existence of the problem solved;
- based on the distribution-free test of fit (of Kolmogorov, Smirnov, χ^2 Pearson, etc.), adopted in the statistic theory, hypotheses about the compliance of observation data with one of the aggregate-assigned theoretical information parameter probability distributions are being checked [14];
- at the third stage, already parametric uncertainty is eliminated using, as true values, the parameters of their optimal evaluations (in our case, sampling mathematical expectations (ME) and mean square deviations (MSD).

The materials, describing as the methodology itself to conduct a full-scale experimental investigation for the purpose of obtaining learning samples as the results of their statistical analysis to form probabilistic descriptions of information parameters in order to solve the CB-related WH classification problem, are presented below.

Statistical analysis of experimental weather hazards data “rain shower-thunderstorm-hail”

With the aim of obtaining statistic description of the probabilistic reflectivity distributions and EDR, an analysis of radar signals, reflected from such weather events as the rain shower, thunderstorm, hail, was carried out. The studies were carried out in the Upper Volga Region over a warm period of 2021, 2022. As a tool of obtaining source data, radar data, derived at the output of WR “Monocle”, using signals of the horizontal polarization within X-wave-length range, was used.

The methods of conducting experimental studies to form statistic database were formulated as follows (fig. 1). The validation of derived data about the classified weather events in the WR was carried out by correlating with the reliable meteorological sources: ground meteorological stations, located in the towns of Staritsa,

1. The WR installation in the research area
2. Selecting a meteorological station in the area of the WR surveillance to validate data
3. A signal record from the WR with WH
4. The comparison of the WR data with sources of reliable and additional information
5. An automatic cutting of height layers of justified meteorological phenomena
6. The calculation of a maximum value at each height
7. The formation of a database of height parameter distribution

Fig. 1. Methods of conducting experiments

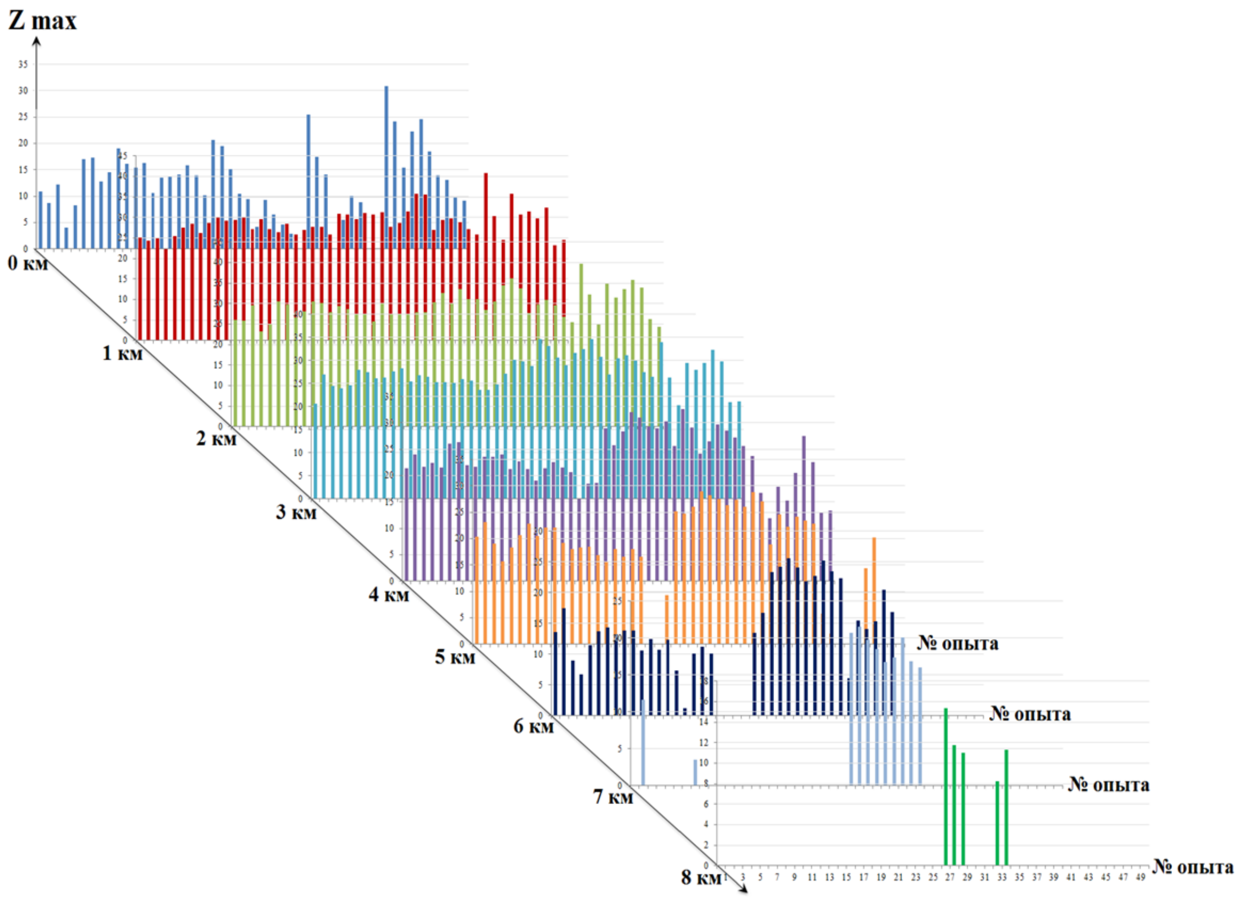

Fig. 2. Example of experimental data on the distribution of the maximum reflectivity by height for a heavy shower

Volokolamsk, Mozhaisk and Gagarin, and the certified DMRL-C type radars of the Rosgidromet network. In the event of observing a phenomenon on the WR and the MRLS maps over the given span of time, the phenomenon is considered confirmed in accordance with the WR map if it coincides in space with the phenomenon on the MRLS map, to the contrary, the phenomenon

1. Normalizing the parameters under consideration
2. Building histograms of empirical parameter distribution
3. Selecting a theoretical distribution
4. The determination of selective characteristics (μ, σx)
5. Hypothesis testing about a distribution type by the criterion χ2

Fig. 3. Methods of the experimental data statistical analysis

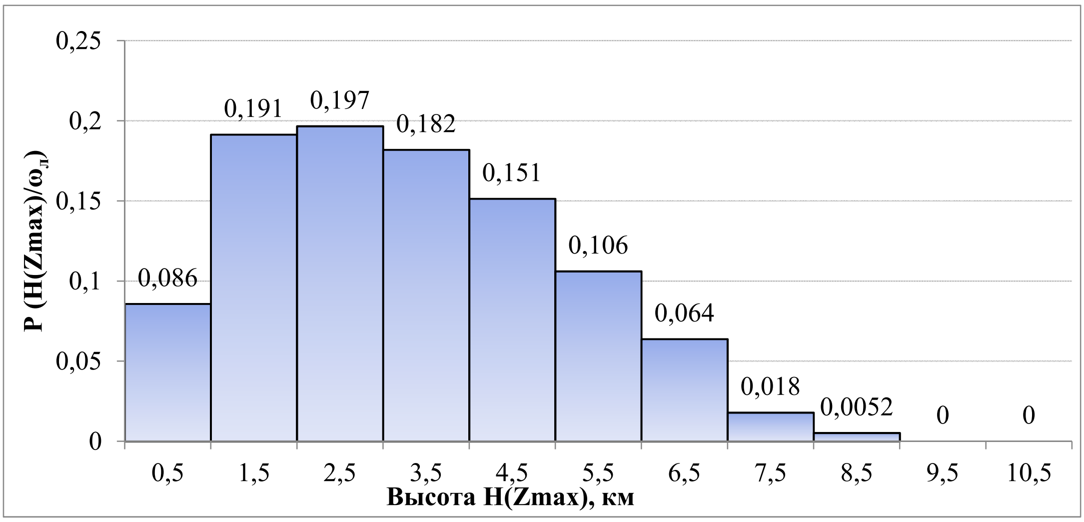

Fig. 4. Histogram of relative frequencies of the maximum reflectivity height

is considered not confirmed. On the whole, 50 confirmed experiments were conducted for each WH.

In order to derive the atmospheric parameters of distribution at each altitude with the discrete of 1 km, the following values: the maximum reflectivity in the cloud of Zmax as well as the maximum EDR value in the cloud of (EDRmax), were evaluated. An example of the maximum reflectivity distribution for the series of experiments for a rain shower is presented in Figure 2.

The methods of statistical processing experimental data are presented in Figure 3 [15].

A histogram of relative H(Zmax) value frequencies is presented in Figure 4, as an example.

The check of various hypotheses concerning the type of distributions by the Pearson criterion of χ^2 for the level of significance 0.01 showed the maximum compliance of experimental relative frequencies with the generalized Rayleigh-Rice distribution

$$f(x|\mu,\sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2+\mu^2}{2\sigma^2}} I_0\left(\frac{x\cdot\mu}{\sigma^2}\right), \qquad (2)$$

where $I_0(z)$ – the modified zero-order Bessel function of the first kind,

μ = 2 – ME and σ = 2.5 – MSD. The histogram approximation result by the theoretical law is presented in Figure 5. The parameters μ and σ in the strict sense are not ME and MSD, however, they appropriately reflect the shape of distribution[2] [16, 17].

[2] Approximation based on the type distribution. *Approximation of experimental data law*. Available at: https://poznayka.org/s97706t1.html (accessed: 12.05.2023). (in Russian)

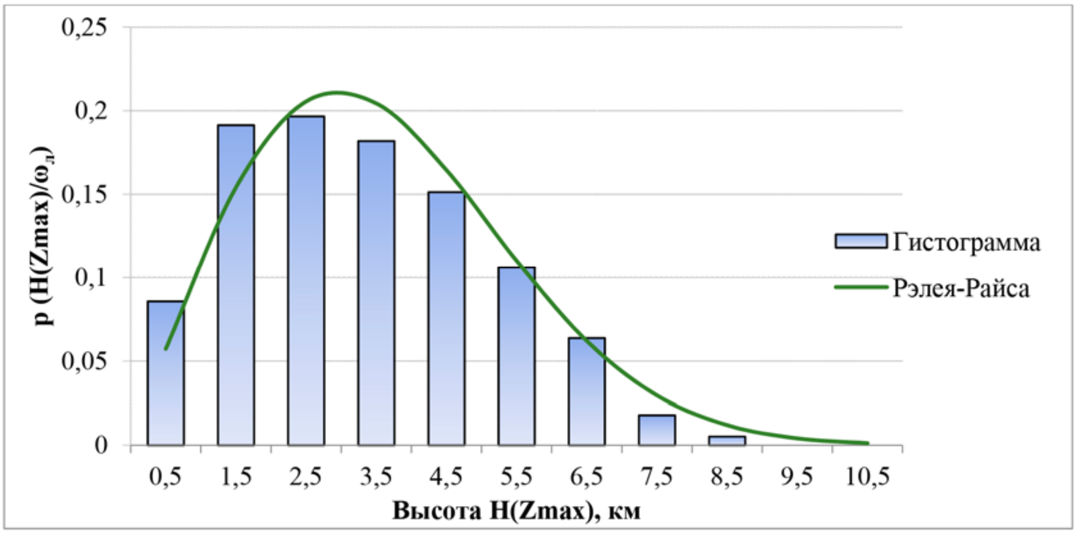

Fig. 5. Approximations of the histogram by the theoretical Rice law

To be based on the developed methods, the statistical parameter H(EDRmax) analysis for a rain shower was conducted as well as of the amplitude distribution of reflectivity parameters and EDR (Zmax, EDRmax) for thunderstorms and hail. Rice distributions for the parameters H(Zmax), H(EDRmax), Zmax and EDRmax of meteorological phenomena under consideration are shown in Figures 6 and 7.

The practical identity of distribution densities of p(H(Zmax)), p(H(EDRmax)) is observed in Figure 6. It points out to the high height correlation of reflectivity and turbulence in CB [18]. In the event of the maximum values distribution, the difference is obvious. However, in all the cases, distributions are quite severely overlapped. It points out to the insignificant distinctive ability of each individual parameter while solving the problem of the meteorological phenomena classification within the assigned alphabet. The theory of recognition prompts an obvious alternative. A combined use of information parameters, for example, in the form of multidimensional probabilities distribution densities of random parameters [17] is essential to enhance confidence of the classification, as Figures 8 and 9 show.

The derived Rice distributions parameters μ, σ_x, based on the computational results of height distribution of the reflectivity parameters and EDR for a rain shower, thunderstorms and hail, are indicated in Table 1. In fact, the table presents a parametric description of the classification factors for the MP “rain shower-thunderstorm-hail”.

Thus, the statistical analysis of full-scale experiment data showed that the distribution densities of the maximum reflectivity and turbulence by values and altitude possess the unique character described by a generalized Rice law.

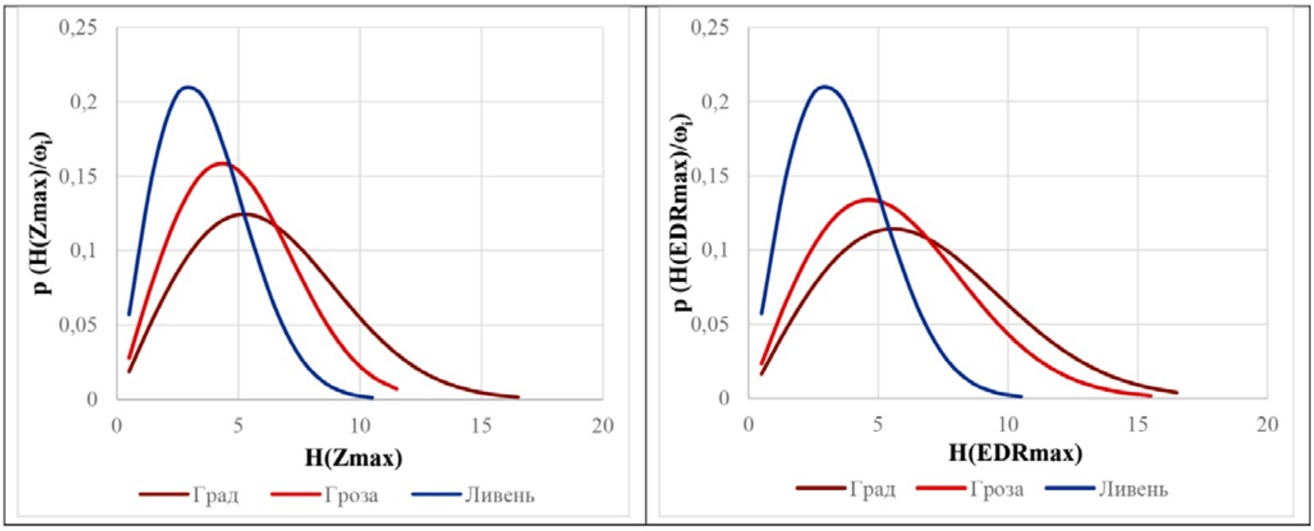

Fig. 6. Density of the probability distribution Zmax and EDRmax by height for the meteorological phenomena under consideration

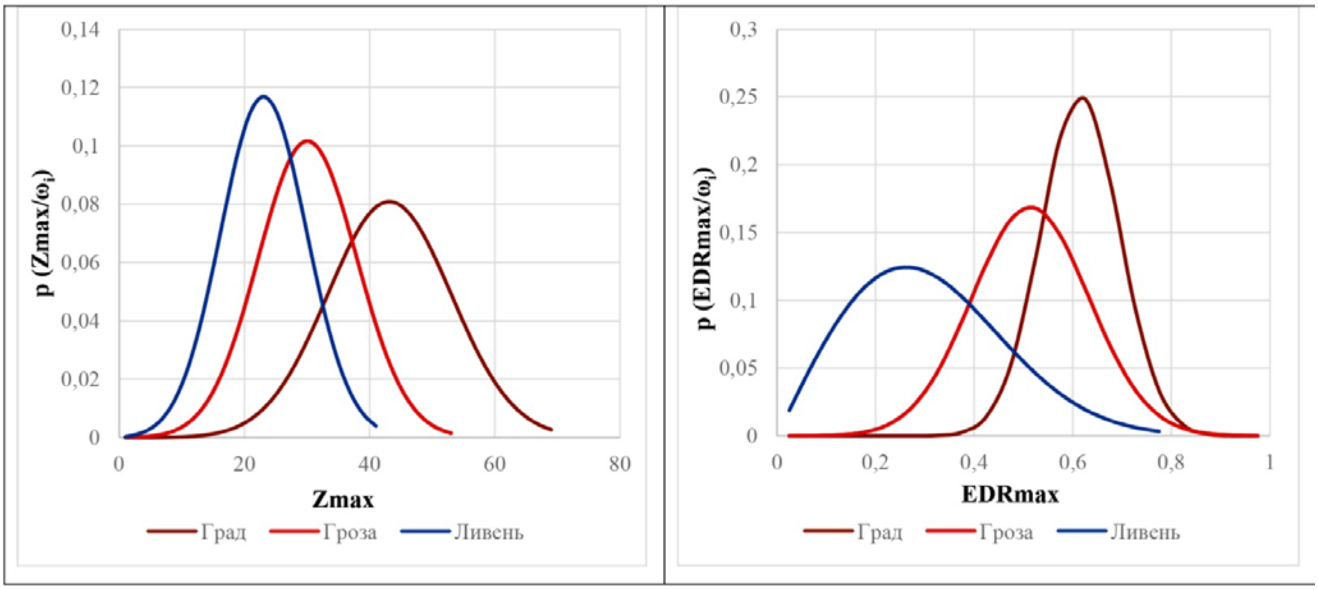

Fig. 7. Probability distribution density of Zmax and EDRmax by values for the meteorological phenomena under consideration

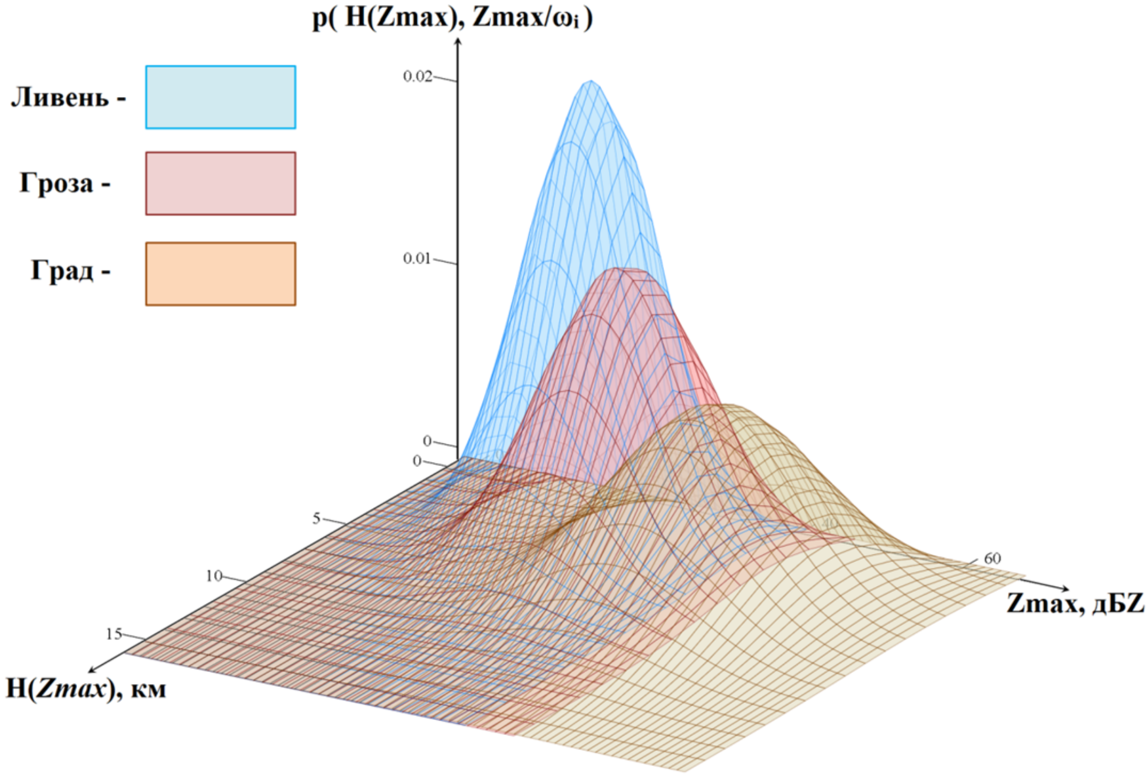

Fig. 8. Surface of the two-dimensional probability density of the radar reflectivity

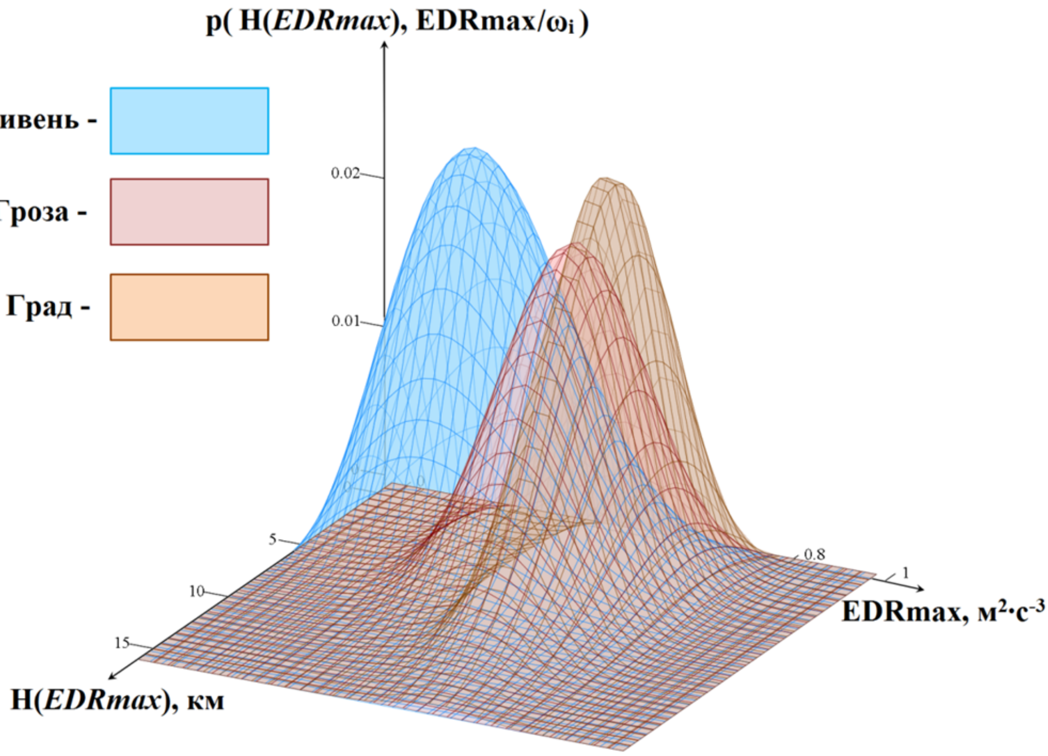

Fig. 9. Surface of the two-dimensional EDR probability density

Table 1

Rice distribution parameters for a rain shower, thunderstorm and hail

Parameter	**Rain shower**	**Thunderstorm**	**Hail**
	H(*Zmax*)		
ME	μ= 2	μ = 3.5	μ = 4
MSD	σ_x = 2.5	σ_x = 3	σ_x = 4
	H(*EDRmax*)		
ME	μ = 2	μ = 3	μ = 4
MSD	σ_x = 2.5	σ_x = 4	σ_x = 4.5
	Zmax		
ME	μ = 22	μ = 29	μ = 42
MSD	σ_x = 7	σ_x = 8	σ_x = 10
	EDRmax		
ME	μ = 0.2	μ = 0.5	μ = 0.61
MSD	σ_x = 0.2	σ_x = 0.12	σ_x = 0.08

Evaluation of the probabilistic characteristics of the weather hazard classification for the specified empirical criteria of the classification in the WR

Let us define decision-making confidence for specified criteria considering newly obtained statistical data to determine some reference point.

As we mentioned before, the criteria for the MP classification: a rain shower-thunderstorm-hail are adopted by the entire arrays of the range of reflectivity distribution by height. Subsequently, in order to specify in conformity with cumulative statistics over a span of time which determines decision-making confidence at the level of 0.9, the classification criteria were determined in the software WR "Monocle" as follows[3]:

1) the threshold value of radar reflectivity at the height of 0–2 km for the (MP) – Rain Shower **Zпор = 27 dBZ**;

2) the threshold value of radar reflectivity at the level of $H_3 = H_0$ + 2500 m = 5.2 km for the MP – Thunderstorm **Zпор = 26 dBZ**;

3) the threshold value of maximum radar reflectivity over the entire cloud volume for the MP – Hail **Zпор = 45 dBZ**.

In case of a rain shower, in accordance with the adopted criterion, a value of height does not influence decision-making. Therefore, let us restrict ourselves by considering the reflectivity value **Zпор = 27 dBZ** (fig. 10), as a threshold.

The expression for the probability calculation of the correct rain shower classification [19] takes the form

$$P_{Л} = \int_{Z_{пор}}^{\infty} \frac{x}{\sigma^2} e^{-\frac{x^2+\mu^2}{2\sigma^2}} I_0\left(\frac{x\mu}{\sigma^2}\right) dx. \quad (2)$$

For the values μ = 22 and σ = 7, the probability amounts to the value of 0.29, but the probability of a rain shower missing – 0.71. The similar approach is applicable for the case with hail, setting a threshold at the level of Zпор = 45 dBZ. As a result, for the values of μ = 42 and σ = 10, we will obtain a value of probability of the correct classification of hail – 0.42, of missing – 0.58. In the case of thunderstorm, a threshold value of Zпор = 26 dBZ reflectivity is additionally determined by the value of a minimum height of its availability – 2.5 km above a freezing level. Let us calculate the correct classification probability of thunderstorm, similar to the first two cases, as an additional condition will result in its decreasing in the case under consideration. For the values of μ = 29 and σ = 8, we will obtain a probability value of the correct classification of thunderstorm – 0.70, of missing – 0.30.

[3] Maintenance Manual. Weather radar system of nearair-field WR. (2016). Moscow: Standartinform, 19 p. (in Russian)

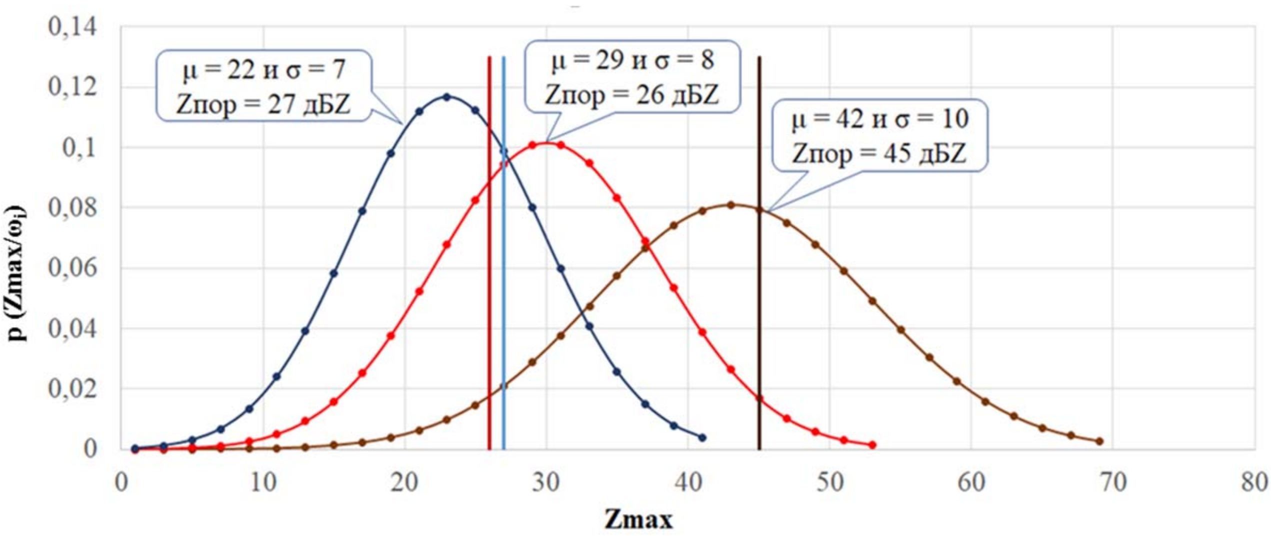

Fig. 10. Example of setting decision-making thresholds for the existing classification criteria

Even such a simple analysis shows that the adopted criteria are far from optimality in terms of the probabilities of the correct classification, specifically in the case of a rain shower. According to the authors, thresholds must ensure the correct classification probabilities not worse than 0.8. It is quite obtainable for the parametric criteria. MP data probabilities of the correct classification of 0.81, 0.82, 0.82 appropriately ensure the correction of Zпор thresholds for the level of 17, 23, 34 dBZ for a rain shower, thunderstorm and hail.

It is obvious that the problem solution of the assigned classification confidence is associated with the optimization of the feature space and classification criteria.

Conclusion

In the WR "Monocle", the WH classification is based on knowledge about the height distribution of radar reflectivity, atmosphere temperature (height of zero-degree isotherm, isotherm −22°), as well as about values of lower and upper boundaries of radio echo. The criteria are far from optimal, cumbersome and make the process of the WH classification automation difficult.

The basic ways of the WH classification criteria optimization associated with CB: the use of information about the height distribution of not only reflectivity but also of the atmosphere turbulence, forming parametric descriptions of classification features in the WH classification criteria.

The WH classification must be based on Bayesian approach under which a problem of choosing a decision is formulated in terms of the probability theory and all the significant probabilistic values, so-called sufficient statistics, are known. Whereby, for the assigned alphabet of classes, it is necessary to seek probabilistic distribution density descriptions of maximum reflectivity and EDR by values and height.

The basic ways of overcoming the complete expected uncertainty of probabilistic classification features description, based on the use of the learning sample, are shown.

For the purpose of obtaining statistical descriptions of probabilistic reflectivity distributions and specific velocity of turbulent energy dissipation, the analysis of radar signals reflected from such MP as a rain shower, thunderstorm, hail was conducted. As a tool of deriving learning samples, radar data, obtained at the output of the WR "Monocle", was utilized. The methods of conducting experiments and the statistical analysis of their results were developed.

The statistical data analysis of a full-scale experiment showed that distribution densities of maximum reflectivity and turbulence by values and height have the unique parametric character described by a generalized Rice law. The parametric feature descriptions of the MP classification "rain shower-thunderstorm-hail" have been obtained.

The following step is the substantiation of a single probabilistic criterion of the CB-related WH classification and the development of decision functions, decision-making thresholds determined by the assigned classification confidence.

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