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RESEARCH ARTICLE

On monitoring and forecasting the dynamics of the development of the structure of tropical cyclones based on almost periodic analysis of satellite images

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Abstract

Objectives. The article sets out to identify the characteristics of tropical cyclones using almost periodic analysis of images of cloud dynamics of hurricanes in order to forecast the cyclone structure. Almost periodic analysis is applied in the processing and analysis of tropical cyclone structure images based on the obtained almost period values using a modified mathematical computational apparatus.

Methods. The main tool for processing and analyzing images of the tropical cyclone structure is almost periodic analysis, i.e., analysis of data with an ordered argument to identify dependencies that are close to periodic. By this means critical boundaries of changes in the trends of the studied data can be identified regardless of *a priori* assumptions. In the course of analysis the almost period information parameter, corresponding to the values closest to the periods, is determined. A modification of the known mathematical apparatus of almost periodic analysis is proposed for processing large and multidimensional datasets.

Results. In the course of the study, the characteristic almost periodic values of the structural zones at the moment of the beginning of the formation of the dynamics of the cyclone development were revealed on the example of the analysis of the frames of the dynamics of tropical cyclone Milton, operating from October 5, 2024 to October 10, 2024. Based on the identified values, forecast estimates of the tropical cyclone structure development were made to an accuracy of 95%.

Conclusions. Together with the results of studies published earlier, the results of this study support the conclusion that it is possible to apply almost periodic analysis to the identification of characteristic patterns of tropical cyclone structures and carry out qualitative forecast estimates of the dynamics of emergency situations caused by tropical cyclones.

Keywords: almost periodic analysis, image processing and analysis, tropical cyclone monitoring, tropical cyclone forecasting, technosphere safety, typhoons

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НАУЧНАЯ СТАТЬЯ

О мониторинге и прогнозировании динамики развития структуры тропических циклонов на основе почти периодического анализа спутниковых изображений

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Резюме

Цели. Статья посвящена проблеме идентификации характеристик тропических циклонов с использованием почти периодического анализа изображений облачной динамики ураганов и прогнозирования структуры циклона на основе полученных значений почти периодов. Цель статьи заключается в применении почти периодического анализа с использованием модифицированного математического аппарата вычислений при обработке и анализе изображений структуры тропического циклона с возможностью осуществления прогнозных оценок.

Методы. Основным инструментом обработки и анализа изображений структуры тропического циклона является почти периодический анализ – анализ данных с упорядоченным аргументом по выявлению зависимостей, близких к периодическим. Использование аппарата почти периодического анализа позволяет проводить выявление критических рубежей изменения тенденций исследуемых данных вне зависимости от априорных предположений. В ходе проведения такого анализа определяется информационный параметр – почти период, соответствующий значениям, наиболее близким к периодам. Предложена модификация известного математического аппарата почти периодического анализа, позволяющая обрабатывать большие и многомерные данные.

Результаты. В ходе исследования на примере анализа кадров динамики тропического циклона Милтон, действующего с 5 по 10 октября 2024 г., выявлены характерные почти периодические значения структурных зон в момент начала формирования динамики развития циклона. На основе выявленных значений составлены прогнозные оценки развития структуры тропического циклона, точность которых составила 95%.

Выводы. Полученные результаты совместно с результатами исследований, опубликованными ранее, позволяют сделать вывод о возможности применения почти периодического анализа к выявлению характерных паттернов структур тропических циклонов и составлению качественных прогнозных оценок динамики развития чрезвычайных ситуаций, вызванных тропическими циклонами.

Ключевые слова: почти периодический анализ, обработка и анализ изображений, мониторинг тропических циклонов, прогнозирование тропических циклонов, техносферная безопасность, тайфуны

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INTRODUCTION

Weather forecasting is important for ensuring the safety and sustainable development of human society. Among extreme weather events associated with ongoing changes in climatic conditions, one of the most potentially dangerous are tropical cyclones, comprising powerful atmospheric vortices that occur in tropical and subtropical latitudes over warm ocean waters. According to statistics from the Russian Ministry of Emergency Situations, more than 100 dangerous natural phenomena occur annually, causing total material damage exceeding RUR 50 bn.[1]

The increasing pace of life and enormous volume of information exchange demand prompt, balanced, accurate, and well-founded decisions based on relevant forecasts. In this regard, it is important to improve the speed of effective decision-making in emergency situations by obtaining improved forecasts of the dynamics of dangerous natural phenomena, which contributes to the timely adoption of measures to ensure human safety, as well as the preparation of measures to counteract emergency situations.

Traditional numerical weather models are based on solving systems of differential equations that describe the physics of the atmosphere. However, such models have limitations in terms of accuracy and require significant computing resources. The application of artificial intelligence and machine learning technologies has the potential to significantly improve the speed and accuracy of forecasting dangerous weather events and the dynamics of emergency situations.

In this context, it seems relevant to develop an approach to forecasting the dynamics of tropical cyclones based on an almost periodic analysis of images of cyclone structures. Images are one category of data with an ordered argument. Data with an ordered argument represent a set of measurements of some experimental quantity that depends on the argument, comprising an ordered vector of values.

Time or space can serve as examples of arguments. Currently, such data is analyzed and processed using special programming languages and their built-in libraries [1, 2]. The most common approach to analysis involves the use of machine learning methods [3–9]. Methods involving the study and identification of hidden patterns in data with an ordered argument are actively used in medicine, economics, and other fields [10–16].

It should be noted that the use of spatiotemporal remote sensing data enables tracking the dynamics of natural phenomena, especially tropical cyclones [17–19].

The present study is devoted to modified analysis and forecasting of tropical cyclone dynamics based on satellite images using the almost periodic data analysis method. The described modified almost periodic analysis method aims to improve existing data analysis tools with an ordered argument.

RESEARCH METHODOLOGY

Almost periodic analysis is the analysis of data with an ordered argument to identify dependencies that are close to periodic. The use of almost periodic analysis enables the identification of critical turning points in the trends of the data under study, regardless of *a priori* assumptions. During such an analysis, the almost period information parameter is determined by obtaining values closest to the periods. In general, an almost periodic function $f(t)$ is a function that satisfies the condition: $|f(t+\tau)-f(t)|<\varepsilon$, where $\varepsilon > 0$ is the shift, τ is the almost period of this function [20].

Currently, most studies using almost periodic analysis of discrete data with an ordered argument are based on formulas whose values are determined by sequential iterative algorithms.

The algorithm for almost periodic analysis of a discrete data set conceptually consists of two stages:

1) exclusion of the trend from the vector of processed data;
2) processing of the obtained oscillations with a generalized shear function to identify almost periods.

At the first stage, the trend component must be excluded from the processed data in order to further analyze the almost periodic components of the series fluctuations. Since there is no information about the trend equation at the initial stage of data processing, an approach based on a transformation based on the theory of proportions is used to remove it from the data. This approach to removing the trend from the data is independent of any *a priori* assumptions about the behavior of the trend in the data.

Trend exclusion based on the theory of proportions is based on the assumption that trend characteristics are encoded through reference points. As an example of implementation, consider the simplest dependence of the values of a discrete data set of three points y_t, $y_{t-\Delta t}$, $y_{t+\Delta t}$, which encode the entire series under study [21]. If we take the ratio of, for example, a geometric progression as a basis, then the transformations for excluding the trend and obtaining fluctuations relative to the ordered argument t for the data y will look as follows:

$$\ln\left(\frac{y_{t-\Delta t}y_{t+\Delta t}}{y_t^2}\right)\sim t, \tag{1}$$

[1] Ministry of the Russian Federation for Civil Defense, Emergencies, and Disaster Relief. https://mchs.gov.ru/ (in Russ.). Accessed August 10, 2025.

where y_t is the current value of the series y with the ordered argument t; $y_{t-\Delta t}$ is the previous value of the original series at a distance Δt based on the argument from the current value y_t; $y_{t+\Delta t}$ is the next value of the original series at a distance Δt based on the argument from the current value y_t.

As a result of such transformations, we obtain a series of oscillations corresponding to the shift parameter Δt. For a comprehensive analysis of all types of oscillations in the original data, it is necessary to obtain oscillations for each shift parameter by argument Δt. The range of Δt values is from 1 to $N/2$, where N is the length of the original data series.

The second step in the almost periodic analysis of a discrete data series with an ordered argument involves processing the obtained sets of oscillation vectors in order to exclude the trend using a shift function of the form:

$$a(\tau)=\frac{1}{n-\tau}\sum_{t=1}^{n-\tau}\left|\hat{y}_{\Delta t}(t+\tau)-\hat{y}_{\Delta t}(t)\right|, \quad (2)$$

where n is the total number of oscillation readings $\hat{y}_{\Delta t}(t)$, obtained during the shift by argument Δt.

Each oscillation vector is processed by function (2). As a result of the calculations, we obtain a vector of shear function values corresponding to a series of oscillations of the initial data when shifted by the argument Δt.

To obtain almost period values τ, the result of the shift function is examined for the presence of pronounced minima. The closer the minimum is to zero, the more significant and closer to the pure period the identified almost period value turns out to be.

The result of processing all sets of vibration vectors obtained by excluding the trend using transformation type (1) with the shift function (2) will be a matrix of shift function vectors. For sequential calculation and accounting for the dependence of the shift function on the value of Δt, a generalized shift function is determined. An example of its implementation, taking into account the geometric exclusion of the trend, is presented by the following formula[2]:

$$a(\tau,\Delta t)=\frac{1}{n-\tau-2\Delta t}\times \sum_{t=1}^{n-\tau-2\Delta t}\left|\ln\left(\frac{y_{t-\Delta t+\tau}y_{t+\Delta t-\tau}}{y_{t+\tau}^2}\right)-\ln\left(\frac{y_{t-\Delta t}y_{t+\Delta t}}{y_t^2}\right)\right|. \quad (3)$$

[2] Kuzmin V.I., Gadzaov A.F. *Methods for building models based on empirical data*: tutorial. Moscow: Moscow State Institute of Radio Engineering, Electronics and Automation (Technical University), 2012. 94 p. (in Russ.).

The applicability of these formulas in almost periodic analysis has been discussed in the literature [21]. However, the approach of sequential iterative calculation of discrete series values with an ordered argument is difficult to implement for large data volumes, including image processing [22].

In order to process and analyze large discrete series and matrices with ordered arguments, the authors implemented a modification of the mathematical apparatus of almost periodic analysis.

The first proposed modification comprised an algorithm for excluding trends from the data. By calculating the entire vector of fluctuations for a fixed shift value Δt, it became possible to perform trend exclusion operations:

$$\vec{P}_{\Delta t}=\ln\left(\frac{\vec{y}_{t-\Delta t}\cdot\vec{y}_{t+\Delta t}}{\vec{y}_t^{\,2}}\right), \quad (4)$$

where $\vec{P}_{\Delta t}$ is the vector of oscillation values obtained by excluding the trend based on the theory of proportions, with dimension $N-2\Delta t$; $\vec{y}_t^{\,2}$ is the vector of the square of the values y_t; $\vec{y}_{t-\Delta t}$ is the vector of the values $y_{t-\Delta t}$; $\vec{y}_{t+\Delta t}$ is the vector of the values $y_{t+\Delta t}$.

Then, the calculation of the shear function (2) for a fixed value of Δt can also be represented in vector form (5).

$$\vec{a}(\tau)_{\Delta t}=\frac{1}{N-\tau-2\Delta t}\left|\vec{P}_{\Delta t+\tau}-\vec{P}_{\Delta t}\right|, \quad (5)$$

where $\vec{a}(\tau)_{\Delta t}$ is the shift function vector for the vibration vector with a shift in the argument Δt; $\vec{P}_{\Delta t+\tau}$ is the excluded trend vector at the value Δt, shifted by τ; $\vec{P}_{\Delta t}$ is the excluded trend vector at the value Δt.

In (5), the modulus operation is overloaded, i.e., the result of the modulus of the difference between vectors $\vec{P}_{\Delta t+\tau}$ and $\vec{P}_{\Delta t}$ is a vector of absolute values.

As a result of such transformations, the set of vectors $\vec{a}(\tau)_{\Delta t}$ when calculating all shift values by the argument Δt becomes the result of the generalized shift function (3). The presented algorithms were implemented as a program for determining almost periods in empirical data with an ordered argument, capable of working with large volumes of data using parallel computing [23].

For the task of monitoring and forecasting the dynamics of the development of emergency situations caused by tropical cyclones, methods developed based on the almost periodic analysis of satellite images have been used to analyze tropical cyclone frames to form predictive estimates of the dynamics of the development of the structure of tropical cyclones.

Thus, for example, the method of processing and analyzing satellite images of tropical cyclones to identify almost periodic characteristics includes the following stages. At the first stage, the video sequence under study is cropped if the original data is presented in this format. The next step consists in processing and conversion of the frame to black and white format. The resulting images are a matrix of pixels that take values from 0 to 255. The size of the converted image is 500 × 500 pixels.

The next step involves determining the center of the tropical cyclone in the image and further converting the frame into polar coordinates. This transformation is chosen as a first approximation of the centric structure of tropical cyclones to enable the application of the almost periodic analysis to the obtained values of radius vector modules at fixed polar angles to identify the critical radii of cyclone structure zones.

Subsequent sequential processing of value vectors at fixed polar angles yields a set of matrices of generalized shear function results for each image slice. The almost period values of each image slice in polar coordinates obtained by analyzing the obtained minima of each generalized shear function are compared and the coinciding values are as characteristic almost periods of the entire structure of the studied tropical cyclone.

The method for forecasting the dynamics of tropical cyclones based on almost periodic analysis of satellite images enables for a predictive assessment of the dynamics of tropical cyclone structure based on identified almost periods and classified hazard zones in the early stages of tropical cyclone development.

On the basis of the almost periods identified as a result of the analysis, the original image is marked with circles having radii that are multiples of the identified almost periods. The central zone of the tropical cyclone frame, which usually occupies the areas of the first and second zonal circles, is classified as a particularly dangerous zone. Depending on the value of the almost period on which they are based, the zones of the next two or three circles occupy most of the frame of the tropical cyclone structure are classified as dangerous zones. The remaining zones in the frame of the tropical cyclone structure are zones of increased observation.

We will illustrate the described processing and analysis methods with the results of forecasts for the development of a tropical cyclone structure using the example of Hurricane Milton, which occurred from October 5 to 10, 2024. The data used for analysis consisted of photographs and video footage of the tropical cyclone taken from an open Internet source: the official website of the United States National Oceanic and Atmospheric Administration.[3]

[3] National Oceanic and Atmospheric Administration. U.S. Department of Commerce. https://www.noaa.gov/. Accessed February 08, 2025.

RESULTS AND DISCUSSION

Figure 1 shows a frame of a tropical cyclone in the infrared range converted to black and white format in Cartesian coordinates with the center of the cyclone marked, relative to which the cyclone structure is projected into polar coordinates (Fig. 2).

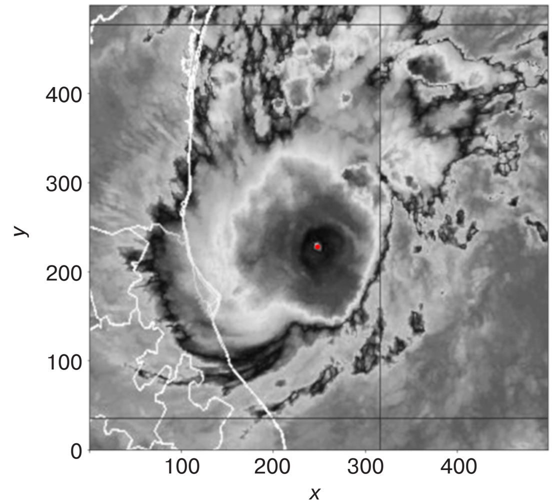

Fig. 1. Snapshot of the early development of tropical cyclone Milton at 15:00 UTC[4] on October 5, 2024, with the cyclone center marked at a size of 500 × 500 pixels

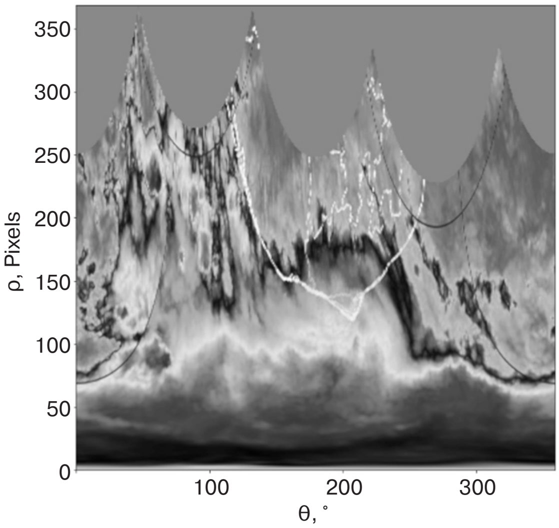

Fig. 2. Snapshot converted to polar coordinates showing the beginning of the development of tropical cyclone Milton, with a resolution of 360 × 360 pixels, where ρ are the values of the radius vectors, and θ are the values of the polar angles

Vertical sections of the obtained image (Fig. 2) at polar angles were processed using functions (4) and (5), resulting in a set of generalized shear function values for radius vector modules. Figure 3 shows an example of a slice of the generalized shear function with values

[4] Coordinated Universal Time.

similar to almost periods for a transformed cyclone frame at an angle of 50°.

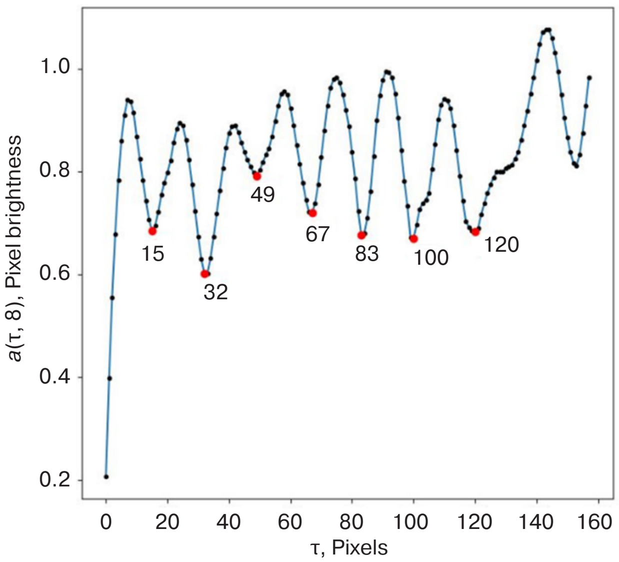

Fig. 3. Example of a generalized shear function at $\Delta t = 8$ for a vector of values at a fixed angle of 50°

The obtained results of almost periodic radius vectors (Fig. 3) are displayed on the original data. The results are presented as the snapshots of a video sequence in the form of circles with radii that are multiples of the detected almost period. The centers of the multiple circles are located in the detected center of the tropical cyclone structure (Fig. 1) with the detected almost periodic values serving as the reference radius of the first circle from the center.

Figure 4 depicts an example of determining centric zones that are multiples of the detected almost period of 83 pixels. The application of this marking will make it possible to determine the characteristic almost periodic components of the structure of the tropical cyclone under study, which will enable the application of a method for forecasting the dynamics of tropical cyclones based on almost periodic analysis of satellite images. The shading of the highlighted areas in Figure 4 should be noted. Diagonal shading indicates particularly dangerous areas affected by the tropical cyclone, while dotted shading indicates dangerous areas affected by the tropical cyclone, and grid shading indicates areas of increased observation.

As a result of studies [24–26], it was established that the almost periodic values of the structure of tropical cyclones obtained in images of the early stages of their development are manifested in the later stages of hurricane development with an error of no more than 12%, which is acceptable in the tasks of forecasting dynamic systems of technical analysis [27].

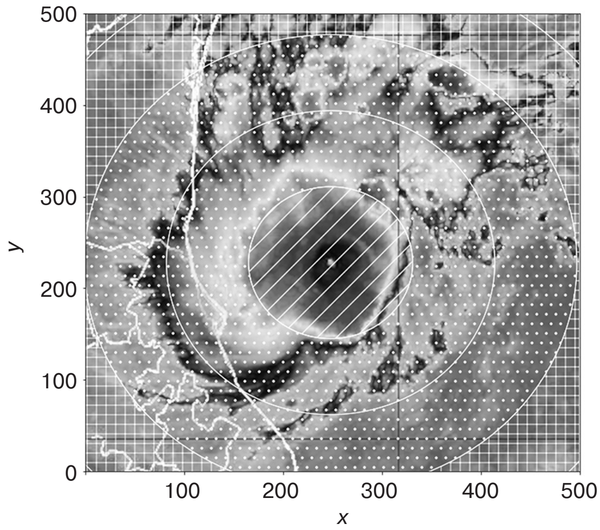

Fig. 4. Snapshot of the early development of tropical cyclone Milton at 15:00 UTC on October 5, 2024, with marked danger zones

To verify the forecast estimates based on the identified almost period of 83 pixels, a frame of tropical cyclone Milton was taken at the moment it reached its peak dynamic state at 21:35 on October 8, 2024, and zones multiple of the almost period of 83 pixels were marked (Fig. 5). It is important to note that the obtained results describe the structure of the tropical cyclone with a sufficient level of accuracy.

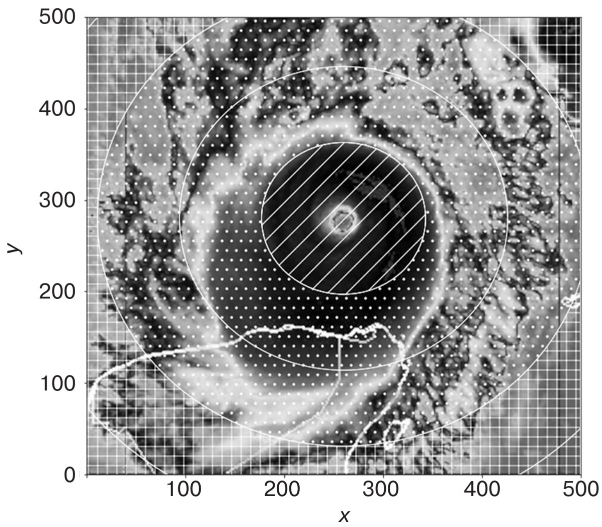

Fig. 5. Snapshot of tropical cyclone Milton at its peak on October 8, 2024, at 21:35 UTC, with danger zones marked

To obtain numerical estimates, a method is applied for processing and analyzing satellite images of tropical cyclones to identify almost periodic characteristics for the data (Fig. 5). The results of the generalized shift function cross-sections yield almost periods close to the values obtained at an early stage (Fig. 6).

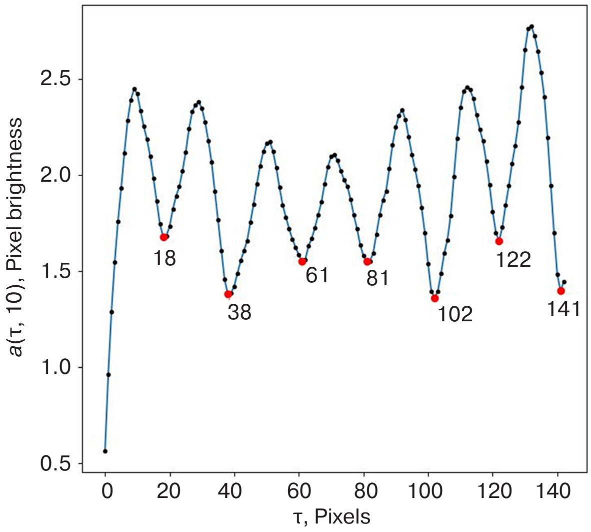

Fig. 6. Generalized shift function at $\Delta t = 10$ for a vector of values at a fixed angle of 45° for the image in Fig. 5

The accuracy of the forecast values obtained for almost periods can be estimated using the formula:

$$\sigma = \frac{\left|\tau_{\text{forecast}} - \tau_{\text{actual}}\right|}{\tau_{\text{actual}}}, \qquad (6)$$

Where τ_{forecast} is the value of the forecast almost period, τ_{actual} is the value of the calculated actual almost period.

Thus, the forecast estimates with the revealed actual values of almost periods for the tropical cyclone structure in Fig. 6 have an error not exceeding 5%. This confirms the previously obtained results on the estimates of the forecasting dynamics of the tropical cyclone structure based on almost periodic analysis. The obtained results of the errors of the obtained forecast values are comparable with complex models that take into account the relationships of the physical quantities of cyclones [28].

CONCLUSIONS

The article presents a modified method of almost periodic data analysis with an ordered argument to analyze both one-dimensional data of large dimensions and data arrays on the example of tropical cyclone frames.

The method for processing and analyzing the satellite images of tropical cyclones for identifying the almost periodic characteristics was used to establish the characteristic almost periods of the tropical cyclone structure at the initial stage of formation on the example of cyclone Milton. Unlike existing approaches used in constructing forecasts, in which physical parameters of tropical cyclones are used, the proposed approach provides a simultaneous opportunity to monitor and forecast the dynamics of the development of the structure of tropical cyclones based on satellite images using the identification of the almost period, a parameter that is independent of physical quantities. Using one of the characteristic almost periods as an example, the marking of dangerous zones of the tropical cyclone structure was implemented based on circles with radii multiples of the identified almost period of 83 pixels.

The developed methodology based on the modified almost periodic analysis method was tested on the example of forecasting the dynamics of tropical cyclones development. The accuracy of the forecast estimates obtained during the study was about 95%.

The developed approach was used to identify characteristic structural changes in tropical cyclone images and predict the dynamics of a tropical cyclone with sufficient accuracy using Hurricane Milton as an example. The obtained results are of practical importance for risk assessment and the development of emergency management strategies caused by tropical cyclones.

Authors' contributions

A.A. Paramonov—processing the initial data, calculating parameters, and analysis of results.

A.V. Kalach—problem formulation, analysis of results.

T.E. Saratova—designing the research stages, analysis of results.

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