

Visual Display of Tropical Cyclone Structure Zone Hazard Assessment Based on Almost Periodic Analysis

A.A. Paramonov^{1,A}, A.V. Kalach^{2,A,B}

^A MIREA - Russian Technological University, Moscow, Russia

^B Voronezh Institute of the Federal Penitentiary Service of Russia, Voronezh, Russia

¹ ORCID: 0000-0002-8504-2108, paramonov_a_a99@mail.ru

² ORCID: 0000-0002-8926-3151, a_kalach@mail.ru

Abstract

A visual hazard assessment of tropical cyclone structure zones based on almost periodic analysis is proposed. We consider a visualization toolkit that allows us to customize and display both tropical cyclone zones whose radii are multiples of the found characteristic near-periods and shading of the interzonal space taking into account the degree of hazard relative to the cyclone center.

As the main tools we used the visualization modules of the matplotlib library Circle and Wedge, which allow us to customize the identified structural zones according to their hazard degree. This development can be useful for emergency-rescue services as an operational diagnostic tool to support decision-making in emergencies caused by natural hazards.

Keywords: almost periodic analysis, data analysis, image processing, tropical cyclones, typhoons, technosphere safety, emergency situation, natural hazards, tropical cyclone classification, safety assessment, visualization.

1. Introduction

Visualization of research results plays an important role in the perception and interpretation of the obtained data. Nowadays, image analysis methods are quite popular. For example, in [1] the results of research on the effectiveness of algorithms for object detection on low quality images are presented. This issue is very important in the context of, for example, telemedicine, for object detection on MRI images.

In the field of technosphere safety, researchers are currently actively studying issues related to mathematical, numerical modeling and analysis of natural climatic phenomena, such as, for example, snow avalanches [2] or tornadoes [3].

Natural phenomena such as tropical cyclones pose a considerable danger, which can cause not only irreparable damage to infrastructure, but also lead to the death of the population. To study the kinetics of vortex flows, O.V. Opryshko in his work investigates the model of gas flow in the natural part of tornadoes and tropical cyclones [4].

The paper [5] considers the study of the interrelationship of earthquakes and tropical cyclones. As a result of studying the dynamics of earthquakes and tropical cyclones, characteristic time intervals were revealed, as a result of which the probability of a powerful seismic shock becomes maximum when cyclones become active again.

The relevance of the study of tropical cyclones for the territories of the Russian Federation is confirmed by the work of N.A. Ozerova. [6], during the study of the peculiarities of the evolution of tropical cyclones, which have their influence on the weather of the Far East of the Russian Federation. The system of tropical cyclone diagnostics based on satellite data, which is being developed within the framework of the “Priority 2030” program, can serve as another confirmation [7].

Prediction of vortex structures development in his work [8] is studied by Levina G.V. Specific configurations of vortex clouds, corresponding to the initial stage of cyclogenesis, found in the work, are proposed by the author to be used in operational meteorological diagnostics when analyzing satellite images of clouds.

For tracking and monitoring of tropical cyclones, a methodology for reconstructing the intensity of tropical cyclones from their satellite images has been developed [9].

All developments in the field of tropical cyclone research are accompanied by the implementation of software packages with visualization of processed data [10,11].

A review of models and methods for analyzing data represented as a spatio-temporal process is considered in the paper. The study formulates the problem of finding relationships between multi-parametric characteristics with time and space as an argument [12].

This paper presents the possibility of visual assessment, using the Python programming language software tools, of the results of almost periodic analysis of photo and video data of tropical cyclone dynamics.

Almost period – values closest to periods. In general terms, an almost periodic function $f(t)$ is a function that satisfies the condition: $|f(t+\tau)-f(t)|<\varepsilon$, where $\varepsilon>0$ is the offset, τ is the almost period of the function $f(t)$.

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 allows the identification of critical turning points in the trends of the data under study, regardless of a priori assumptions.

2. Almost periodic approach of tropical cyclone image analysis

Processing and subsequent analysis of images of tropical cyclone structures consists of several steps. First, the original image is converted to black-and-white format, to the default size of 500x500 pixels. The center of the tropical cyclone from which the image is further transformed into polar coordinates is determined. Slices of the obtained image along the polar angle values are processed by the generalized shift function (1).

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

where n is the total number of samples of the function $y(t)$; t - positive and negative integers, including zero; Δt - positive integer, argument shift; τ - positive integer, values of almost periods.

The local minima of the obtained function are analyzed at different environments of the argument Δt and the most significant and coinciding ones are selected, being almost periods for the vector of values under study. The results of processing the generalized shear functions for all slices of the image are summarized and the most occurring values of almost periods that characterize the studied state of the tropical cyclone structure in the image are selected. The identified near-periods are displayed in the image by multiple circles from the identified center of the tropical cyclone, highlighting the characteristic zones of the tropical cyclone structure in the image. This analysis and visualization approach has been demonstrated in [13-15].

The key feature of this study is to supplement the visualization of tropical cyclone boundary zones based on the identified near-periods by marking rings according to the type of hazard representation.

3. Assessment of tropical cyclone hazard zones and visualization tools used

When processing the photo and video sequences of the largest tropical cyclones for the last years, the following estimates of the hazardous zones of the tropical cyclone structure depending on their assumed categories on the Saffir-Simpson scale were obtained.

The stages of development of tropical cyclones of the first and second categories showed the presence of common features, due to which the structural division of the cyclone into the following ranges was obtained. Particularly dangerous zones of a tropical cyclone are located from the hurricane center to the marked circle with a tripled or quadrupled radius, which is based on the found characteristic almost period. Danger zones are located beyond the tripled or quadrupled radius circles to circles with radii that are multiples of the tripled or quadrupled near-period, and areas beyond these circles are considered high watch areas.

Tropical cyclones located at the stage of development of the fourth and fifth categories have similar visual signs. Here, especially dangerous zones of a tropical cyclone are located from the center of the hurricane to the marked circle with a radius of about 110 pixels. The danger zones are located up to circles of double or triple the radius equal to the identified near period. Areas beyond these circles are considered to be high watch areas.

Tropical cyclones of the third category of danger on the Saffir-Simpson hurricane scale can have similar structural features of development as cyclones of the second category and cyclones of the fourth category. Because of this, no clear assessment criterion was formulated for them, and when processing the frames of a cyclone that is at a given stage of development, the parameters are manually adjusted depending on the structure under study.

To solve the problem of displaying only the zones with radii that are multiples of the revealed almost periods, the plot module of the matplotlib library of the Python programming language worked perfectly. The image data in black-and-white format is a matrix of pixels that take values from 0 to 255, which allows you to display it using the contourf module, designed to display the contour representation of data.

An example of visualization is shown in Fig. 1. In the resulting visualization, we can see how circles are drawn from the marked center from the center of the “eye of the storm”, with radii that are multiples of the period of 81 pixels.

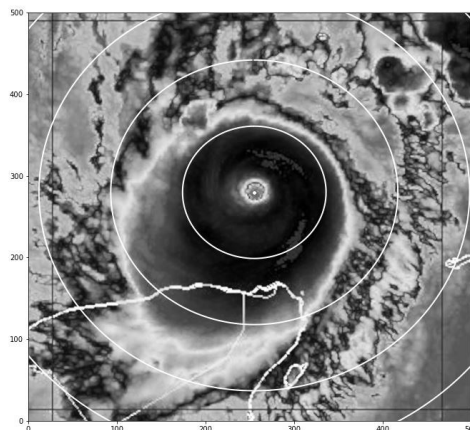


Fig.1. Tropical cyclone Milton, state as of 21:35 UTC 8.10.24, with labeled structural circles, multiples of almost period 81 pixels

In the course of the task of marking the formed rings by hazard zones, a problem arose about the possibility of hatching on the graphical plane with the capabilities of the used visualization tools. The solution to this problem was an additional visualization section of the matplotlib.patches library.

This section provides a set of visualization modules that allow you to define arbitrary two-dimensional regions on the graph. In this section, two program modules were used to solve

the task at hand. The first one is Circle, which displays on the plane a circle with specified coordinates of the center and radius values. This module was used to display and further hatch the area of the circle with radius equal to almost period.

The second module used was Wedge. It is often used to display wedge-shaped shapes with a given center and radius, covering the given boundaries at the corners of the mark. This module has a width parameter that allows you to draw a partial wedge from the inner to the outer specified radius.

4. Calculation results and their visualization

To build the necessary visualization, the Circle module was fed with the values of the tropical cyclone center point on the image, and the Wedge module was configured as follows. As input parameters, the module also accepted the coordinates of the tropical cyclone center, the radius, the size of which was equal to the corresponding value, a multiple of the detected near-period. The boundaries of the structure markup angles were set from 0 to 360 degrees to reflect the ring. And the value of the almost period was specified as the width parameter.

To fill the danger zones with hatching, an additional parameter hatch was supplied to the Circle and Wedge modules, which sets the type of hatching to be displayed. A slanted hatch ("/") was selected to indicate a high hazard zone, a dot or polka-dot hatch (".") was selected to indicate a hazard zone, and a grid hatch ("#") was selected to indicate a high-surveillance zone.

For an image of a tropical cyclone that is, for example, in the fifth stage of development and with a detected near-period of 81 pixels, the result of the visualization of the danger zones would be the image from Fig. 2

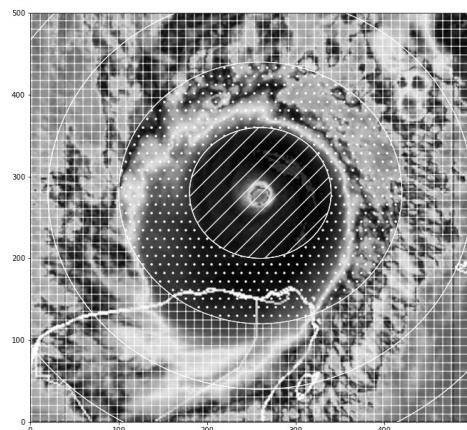


Fig.2. Structural tropical cyclone hazard zones for a near period of 81 pixels and tropical cyclone hazard category five on the Saffir-Simpson Hurricane Scale

Since in the developed classification of hazardous zones of tropical cyclone structure in the image depending on the detected near-periods the boundaries of hazardous zones can change depending on the tropical cyclone under study and the vagueness of determining its hazard level according to the Saffir-Simpson hurricane scale, the functionality of additional parameter customization is provided.

As an example, to cover the capabilities of the program, let us consider a case with a smaller period and if the third category of a tropical cyclone is set, which by its characteristics can belong both to the zone of assessments of the first and second categories and to the zone of assessments of the fourth and fifth categories (Fig. 3).

If we change the parameters in such a way that the lower boundaries of the danger zones are maximum and the upper boundary of the danger zone is minimum, then the obtained result is presented in Fig. 4.

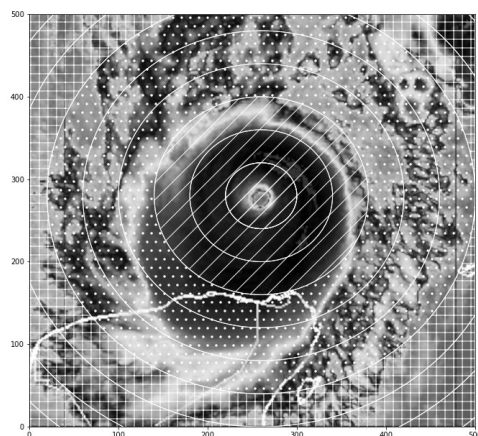


Fig.3. Structural tropical cyclone hazard zones for a near period of 40 pixels and tropical cyclone hazard category three on the Saffir-Simpson hurricane scale

It should be noted that varying the parameters may result in identical cases of zone marking.

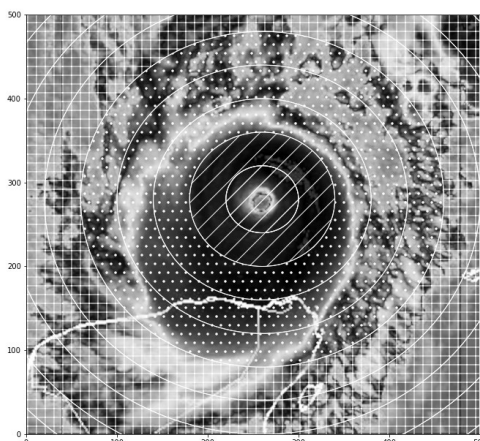


Fig. 4. Structural zones with modified settings along tropical cyclone zone boundaries

Thus, if we change the estimation of the third category and estimate the obtained parameters of the tropical cyclone as a tropical cyclone of level 4, the result coincides with the data from Fig. 4.

The general functionality of the image processing and analysis program is shown in Fig. 5.

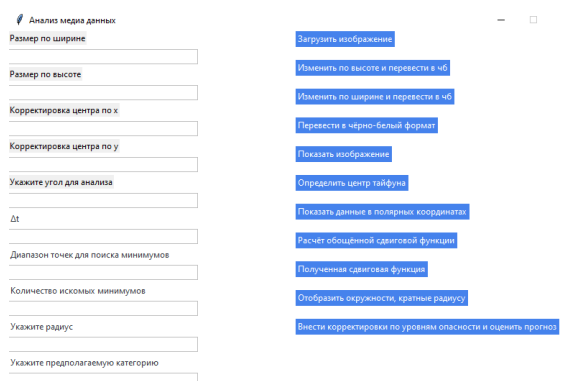


Fig. 5. Image processing tool window

The program's functionality allows you to load images for processing and analysis from your local computer environment and resize images as needed. For convenience of processing and further analysis, images can be converted to black and white format at the click of a but-

ton, and the results of all conversions performed by the program can be displayed on the screen for viewing.

The center of the cyclone is determined automatically; if necessary, manual adjustment is provided to correct the determined center.

To identify quasi-periodic structures, the image is converted to polar coordinates, and for each polar angle value, function (1) is calculated for the radius vector values. Analysis of the cross-sections reveals characteristic quasi-periodic values of the radius vectors.

After performing quasi-periodic analysis for images, multiple radii are constructed based on the found quasi-periodic values and marked according to the described hazard criteria.

To deploy and use the program, it is sufficient to have a computer with the Windows operating system and the Python 3.9 or higher programming language installed. The program has not been tested on other operating systems.

The following key software packages and libraries were used to develop the program with the corresponding capabilities. The Tkinter package for creating a graphical user interface, the pandas library for using mathematical tools necessary for data processing and analysis. The comprehensive Matplotlib library for graphical visualizations, as well as the multiprocessing package to speed up data processing using a process parallelization mechanism.

5. Conclusion

As a result of this study, a visual assessment of the danger of tropical cyclone structure zones based on almost periodic analysis is proposed.

The visualization toolkit is considered, which allows setting up and displaying both the tropical cyclone zones, the radii of which are multiples of the found characteristic almost periods, and the shading of the inter-zonal space taking into account the degree of danger relative to the cyclone center.

The developed software implementation of the proposed visualization method is planned to be submitted for state registration of programs.

This development can be useful for emergency services as an operational diagnostic tool to support decision-making in emergency situations caused by natural hazards.

References

1. Provorova A. A. Polyakova I. Yu. V. Comparison of the effectiveness of different approaches in the task of object detection on a low-quality image // Scientific Visualization. - 2024. - T. 16, № 3. - C. 1-13. - DOI 10.26583/sv.16.3.01.
2. Lentyaeva, T. V. Program realization of the three-dimensional model of the snow mass dynamics // Vestnik of the Voronezh Institute of FSIN of Russia. - 2023. - № 3. - C. 104-111.
3. Chirkunov, Yu. A. Pikmullina, E. O. Mathematical modeling of the snow mass dynamics. O. Mathematical modeling of gas particle motion inside a tornado // Vestnik of Voronezh State University. Series: Physics. Mathematics. - 2023. - № 3. - C. 18-31.
4. Opryshko, O. V. Numerical Simulation of Near-Bottom Parts Of A Tornado And A Tropical Cyclone In A Stationary Case // Journal of Computational and Engineering Mathematics. - 2023. - Vol. 10, No. 1. - P. 30-43. - DOI 10.14529/jcem230104.
5. Golovachev S. P., Dubrov M. N., Volkov V. A., Alexandrov D. V., Eremin I. S., Kalenov D. S. Investigation of Atmosphere-Ocean Interactions. S. S., Kalenov D. S. Investigation of the atmosphere-ocean-lithosphere interrelations on the example of interaction of intense tropical cyclones and the strongest earthquakes // Modern Problems of Remote Sensing of the Earth from Space. - 2024. - T. 21, № 4. - C. 99-111. - DOI 10.21046/2070-7401-2024-21-4-99-111.
6. Ozerova N. A. Study of the peculiarities of the evolution of tropical cyclones affecting the weather of the Russian Far East // European Journal of Natural History. - 2023. - № 1. - C. 29-34.

7. Priority 2030. System of diagnostics of tropical cyclones. [Electronic resource]. URL: <https://2030.dvfu.ru/sistema-diagnostiki-tropicheskikh-ciklonov/> (circulation date 26.01.2025).
8. Levina G. V. Application of the theory of turbulent vortex dynamo for early diagnostics of tropical cyclones nucleation // Fundamental and Applied Hydrophysics. - 2022. - T. 15, № 2. - C. 47-59. - DOI 10.48612/fpg/vaxg-xdmv-11pn
9. Yakusheva, A. N. Ermakov, D. M. Development of a New Automatic Methodology for Tropical Cyclone Intensity Recovery from Multispectral Satellite Earth Observations Data Using Artificial Neural Networks // Modern Problems of Earth Remote Sensing from Space. - 2024. - T. 21, № 2. - C. 336-349. - DOI 10.21046/2070-7401-2024-21-2-336-349.
10. Vareljyan G. G., Naryshkina Y. N., Dorfman K. V., Alekseev E. V. Automated information system "Web. V. Automated information system "WebGis Avia 1" // Certificate of state registration of computer program No. 2022617909 Russian Federation: № 2022616354.
11. Krivonosov M. I., Vershinina O. S., Pirova A. Yu., Kanakov O. I. Pro-software complex for construction of correlation climatic networks and assessment of the association of network metrics with the position of tropical cyclones // Certificate of state registration of the computer program No. 2022682718 Russian Federation.
12. Krynetsky, B. A. Analysis of models of periodic structures of space-time processes // Actual problems of applied mathematics, computer science and mechanics : proceedings of the International Scientific Conference, Voronezh, December 04-06, 2023. - Voronezh: Limited Liability Company "Valborn", Publishing House "Research Publications", 2024. - C. 497-501.
13. Paramonov A. A., Kalach A. V. On the Possibilities of Application of the Near-Periodic Analysis Method for Image Processing // Modeling of Systems and Processes. - 2024 - T. 17, № 3. - C. 44-52. DOI: <https://doi.org/10.12737/2219-0767-2024-42-50>.
14. Paramonov A. A. Detection of almost-periodic characteristics of satellite-images of typhoons in the aspect of solving problems of technosphere safety // Technosphere safety. - 2024. - T. 44, № 3. - C. 71-76.
15. Paramonov, A. A. A.; Kalach, A. V. Modeling of emergency situations using almost-periodic analysis of images of the structure of tai-funs // Bulletin of the South Ural State University. Series: Mathematics. Mechanics. Physics. - 2024. - T. 16, № 4. - C. 67-74. - DOI 10.14529/mmph240408.