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APPLICATION OF THE TURBULENT VORTEX DYNAMO THEORY FOR EARLY DIAGNOSTICS OF THE TROPICAL CYCLONE GENESIS

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Abstract

The climate change is becoming more and more obvious, which leads to an increase in the number of intense atmospheric vortices (tropical and quasi-tropical cyclones, polar hurricanes, tornadoes) and an expansion of the geographical and seasonal limits of their occurrence. A recent example was the quasi-tropical cyclone in the Black Sea on August 11–16, 2021. Under these conditions, the accurate diagnosis of cyclogenesis is extremely important and, based on it, the forecast of further evolution and the trajectory of the forming vortex. The main source of energy for tropical, quasi-tropical and polar hurricanes is thermal convection caused by significant temperature differences between the atmospheric layer and the underlying water surface. This allows us to propose a unified approach for the diagnosis of cyclogenesis in all three cases.

For the first time, an original approach is proposed for determining the exact time of the onset of tropical cyclogenesis. This approach includes a combined analysis of satellite images of cloudiness and the corresponding data of cloud-resolving numerical modeling for the region of developing vortex disturbance. The theoretical basis is the fundamental hypothesis of a turbulent vortex dynamo. The theory provides quantitative criteria that determine the excitation of large-scale vortex instability in the atmosphere. Atmospheric numerical modeling makes it possible to accurately determine the moment of time at which the necessary conditions for the onset of instability are realized. This moment is interpreted as the beginning of cyclogenesis. The specific configurations of vortical cloud convection found in the work, which correspond to the initial stage of cyclogenesis, can be used in operational meteorological diagnostics when analyzing satellite images of cloudiness. The approach is illustrated by the example of diagnostics of tropical cyclogenesis.

Keywords: tropical cyclogenesis, diagnosis, turbulent vortex dynamo, vortical cloud convection, satellite imagery, cloud-resolving numerical modeling

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ПРИМЕНЕНИЕ ТЕОРИИ ТУРБУЛЕНТНОГО ВИХРЕВОГО ДИНАМО ДЛЯ РАННЕЙ ДИАГНОСТИКИ ЗАРОЖДЕНИЯ ТРОПИЧЕСКИХ ЦИКЛОНОВ

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Аннотация

Все более очевидным становится изменение климата, которое приводит к увеличению числа интенсивных атмосферных вихрей (тропических и квазитропических циклонов, полярных ураганов, облачных смерчей-торнадо) и расширению географических и сезонных пределов их появления. Недавним примером стал черноморский квазитропический циклон 11–16 августа 2021 г. В этих условиях чрезвычайно важна точная диагностика циклогенеза и основанный на ней прогноз дальнейшей эволюции и траектории формирующегося вихря. Главным источником энергии для тропических, квазитропических и полярных ураганов является тепловая конвекция, вызванная значительной разностью температур между атмосферным слоем и подстилающей водной поверхностью. Это позволяет предложить единый подход для диагностики циклогенеза во всех трех случаях.

Впервые предложен оригинальный подход для определения точного времени начала тропического циклогенеза. Такой подход включает комбинированный анализ спутниковых изображений облачности и соответствующих

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данных облачно-разрешающего численного моделирования для области развивающегося вихревого возмущения. Теоретическим базисом является фундаментальная гипотеза о турбулентном вихревом динамо. Теория дает количественные критерии, определяющие возбуждение крупномасштабной вихревой неустойчивости в атмосфере. Атмосферное численное моделирование позволяет точно определить момент времени, в который реализуются необходимые условия для возникновения неустойчивости. Этот момент интерпретируется как начало циклогенеза. Найденные в работе специфические конфигурации вихревой облачной конвекции, соответствующие начальной стадии циклогенеза, могут быть использованы в оперативной метеодиагностике при анализе спутниковых изображений облачности. Иллюстрация подхода дана на примере диагностики тропического циклогенеза.

Ключевые слова: тропический циклогенез, диагностика, турбулентное вихревое динамо, вихревая облачная конвекция, спутниковые данные, облачно-разрешающее численное моделирование

1. Introduction

Recently, it has been suggested that climate change leads to an increase in the number of emerging intense atmospheric vortices: tropical and quasi-tropical cyclones, polar hurricanes, and tornadoes. Moreover, intense vortices penetrate more frequently beyond the geographic regions and seasonal intervals of their previous observation, for example, to higher latitudes and earlier/late months of the year. Some tropical cyclones (TCs) have reached unusually high intensity at the end of the usual hurricane season. Recent cases include Atlantic Hurricane Sandy (October 22–November 2, 2012). It reached the northeastern states and became the fourth in US history in terms of cost of damage. Hurricane Pablo (October 25–28, 2019) became the easternmost of the Atlantic TCs, with the vortex reaching hurricane intensity at 18.8°W while centered at 42°N. [1]. This TC was the second most northern event to an unnamed hurricane of 1971 at 46°N. Quasi-tropical cyclones in the Mediterranean Sea, also known as ‘*medicanes*’, manifest increase in frequency [2].

Such whirlwinds do not bypass the territory of Russia. Quasi-tropical cyclones (quasi-TCs) are often called subtropical cyclones/mesocyclones/storms in the Russian scientific literature and media. The first satellite images of the Black Sea mesoscale cyclonic vortices, which registered an ‘*eye of a storm*’ feature, date back to 2002 and can be found in the archives of the Met Office of Great Britain [3, 4]. However, these vortices had a very short lifetime and have not been studied. The very first quasi-TC studied in detail reached a maximum surface wind speed of 25 m/s with a pressure drop in the center to 992 hPa, formed over the Black Sea on September 25–29, 2005 [5, 6] (Fig. 1, *a*). Another intense persistent Black Sea quasi-TC should be investigated (Fig. 1, *b*). It appeared recently, on August 11–16, 2021. The previous 2005 eddy formed far from densely populated areas, and the current season cyclone was close to the coast of the Caucasus, Kras-

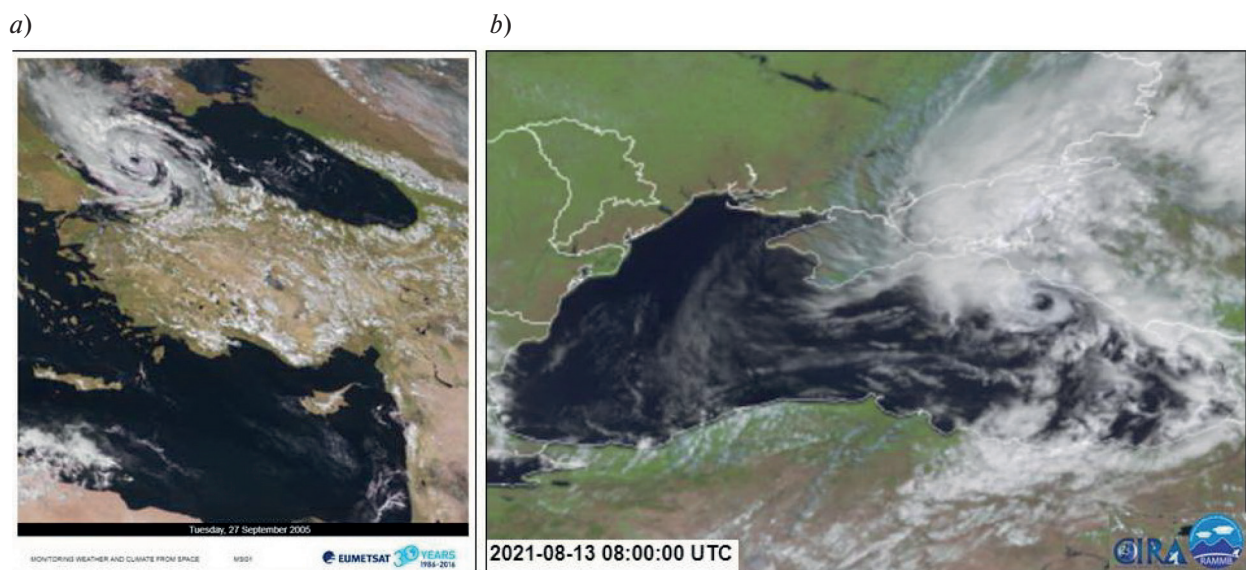


Fig. 1. Quasi-tropical cyclones over the Black Sea

nodar Territory, and Crimea for several days. It moved from the Black Sea to the Sea of Azov. This Black Sea cyclone caused record-breaking precipitation: on August 13–15, the three-day totals of precipitation in Temryuk amounted to 516 mm (which is equal to about half a ton of water per 1 m² and is comparable to the annual precipitation rate), Anapa — 219 mm, Novorossiysk — 178 mm [7]. Tropical cyclones, although they do not originate near the territory of Russia, regularly come to the Far East Russian regions. Another type of hurricane cyclonic vortices recorded over our country was discovered in the analysis of satellite images of cloud cover relatively recently, in the 1960s, namely — the polar hurricanes. Previously, these cyclones originated mainly in the Barents and Okhotsk Seas. Due to the Arctic warming, the vortices started to form over the Laptev, the East Siberian, and Kara Seas.

Tropical, quasi-tropical, and polar hurricanes are intense atmospheric vortices characterized by winds of enormous destructive force and massive clouds. They cause heavy precipitation and storm surges, and floods in coastal areas. These phenomena pose a significant threat to life and economic activity. Therefore, the diagnostics of the origin of such vortices and the prediction of their further evolution are not only among the fundamental problems of the atmosphere and ocean physics but also have an apparent practical focus.

When diagnosing the birth of tropical, quasi-tropical and polar hurricanes in different climatic zones of the planet, the fundamental and unifying consideration may be the fact that the same physical mechanism, namely, thermal convection, plays an important role in their formation. The interpretation of tropical cyclogenesis as a large-scale instability in helical atmospheric turbulence proposed in joint Russian-American studies in 2009–2015 [8] allows for its extension to hurricane-like mesocyclones in mid- and high latitudes.

The development of numerical diagnostics of the TC formation was started by authors [9–11] and tested for several idealized scenarios of tropical cyclogenesis.

2. Materials and methods of research

2.1. The problem of diagnostics of the tropical cyclone (TC) genesis

The problem of tropical cyclogenesis is one of the most important and still unsolved fundamental problems of tropical meteorology and atmospheric physics. Even today, there is no generally accepted definition of tropical cyclogenesis, which should serve as a fundamental basis for accurate quantitative diagnostics of the TC initiation event. The consequent forecast of the formed vortex dynamics and the entire system of warning the population about a possible emergency situation critically depends on the solution to this problem.

However, despite the current uncertainty, the urgent need for diagnosing and predicting such extreme weather events motivated the development of a specific system of indicators that would allow us to determine a TC formation event. Based on this system, in meteorological practice, the formation of a TC is considered to be the formation of a warm core surface-concentrated vortex, in which the tangential wind speed reaches the highest values at lower levels; with reduced pressure in the center of the surface closed wind circulation. When the maximum surface wind speed in the formed vortex does not exceed 17 m/s, it is called a tropical depression (TD). TD is considered the initial stage on the TC intensity scale. In this case, the greatest difficulty is the diagnosis of the event because the formation of TC occurs above the water surface and is often far from ground-based tracking centers equipped with the necessary measuring instruments. Modern means of space monitoring and numerical models of the atmosphere assimilate satellite data. They have greatly improved the situation. Nevertheless, at this time, the most reliable confirmation of the TC formation is direct measurements from an aircraft in the emerging vortex zone. As far as we know, this approach is used on a permanent basis only in the USA [2, 12]. But even in these cases, it is almost impossible to determine the exact time of TC genesis.

TC genesis can only be accurately diagnosed based on an atmospheric process or a set of processes, in which there are quantitative threshold criteria for this phenomenon.

Tropical cyclogenesis is a threshold large-scale vortex instability in helical atmospheric turbulence

Joint Russian-American studies [8–11] put forward and substantiated the interpretation of tropical cyclogenesis as a self-organization process of moist-convective helical atmospheric turbulence. Under

atmospheric conditions favorable for cyclogenesis [2], such a process can initiate large-scale vortex instability. The papers [13, 14] discuss how the proposed interpretation makes it possible to quantitatively and accurately diagnose the fact of a hurricane vortex emergence, using the onset of large-scale vortex instability as an indicator.

For diagnostic purposes, the authors of [8–11] applied the theoretical hypothesis of a turbulent vortex dynamo [15, 16], which suggests a mechanism to amplify large-scale vortex disturbances in the atmosphere by transferring energy from small-scale turbulence. This process is known as the inverse energy cascade, the existence of which was substantiated in three-dimensional helical turbulence characterized by the break of mirror symmetry [17]. Similar to two other well-known large-scale instabilities in helical turbulent media, the alpha effect in magnetohydrodynamics [18] and the anisotropic kinetic alpha (AKA) effect in a non-conducting fluid [19], the vortex dynamo theory gives a threshold for excitation of a large-scale instability [15, 16, 20] and quantitative estimates for the corresponding atmospheric parameters [16].

2.2. Diagnosis of tropical cyclogenesis using cloud-resolving numerical modeling and satellite data

It was shown [13] how the results of studying tropical cyclogenesis by means of idealized numerical modeling [8–11] can be applied in meteorological practice for real atmospheric vortices. The proposed method offers accurate and, what is fundamentally important, remote diagnostics of the time moment when the TC genesis begins. Operational, i. e. real-time, meteorological diagnostics requires a joint analysis of data from cloud-resolving numerical modeling of the emerging vortex and the corresponding cloud-iness imagery in the infrared range obtained from a geostationary satellite. It was found [13] that specific configurations of deep rotating cloud convection emerge at the moments of pivotal events during TC initiation (formation of secondary transversal circulation, onset of large-scale vortex instability, and emergence of a TD vortex). It is important to emphasize that such typical configurations are identified clearly in two different physical fields and by two independent methods of analysis, in the vertical helicity field (numerical simulation) and the temperature field (satellite data). Thus, the proposed diagnostics focuses on the crucial role played in tropical cyclogenesis by intense rotating cloud structures known as vortical hot towers (VHTs) [21–23].

2.3. Vortical Hot Towers (VHTs)

NASA visualization made for tropical Hurricane Bonnie (1998) and posted on Wikipedia [24] is a good illustration of vortical hot towers. These intense cumulonimbus convective structures were first described in 1958 [25], while their vortical nature was determined almost fifty years later [21, 22]. In [25], hot towers were defined as small in horizontal dimensions, about 10–30 km, but intense cumulonimbus convective clouds. They reach the tropopause, which in the tropics usually is at altitudes of 16–18 km. Indeed, in visualization [24], the height of the most intense tower is close to 18 km. It is important to note that the definition of “hot” is not associated with the temperature of these cloud structures but with the fact that over the entire height of the tower, there is an intense release of energy due to the sequence of phase transitions of water: vapor–water–ice.

The discovery of the vortical nature of tropical convection was not only an important scientific discovery [21] but also a spectacular demonstration of a completely new means of atmospheric research capability. Vortical hot towers (VHTs) were discovered using numerical simulations of ultra-high spatial resolution for those times (the early 2000s) — cloud-resolving, 2–3 km in horizontal directions.. A year later, the existence of the VHTs was confirmed [22] with field observations. These measurements were taken earlier by an aircraft in the zone of a nascent hurricane. Later, during a research flight the authors of [26] were lucky to observe a single intense VHT for about 40 min, measure and document the typical characteristics of this rotating cloud structure. Thus, it was confirmed that the characteristic lifetime of convective towers is roughly one hour. The tower was about 10 km across and about 17 km high. Vertical velocities reached 10–25 m/s in the middle troposphere and exceeded 30 m/s at the upper levels. In this case, the maximum values of the relative vertical vorticity were $6\text{--}18\cdot 10^{-3}$ 1/s, which exceeds the planetary rotation by 1–2 orders of magnitude.

The helical properties of VHTs were reported in [27], where these structures were described as deep moist convective clouds. They rotate as an entity and/or contain helical rotating updrafts similar to those

observed in Rayleigh-Benard convection in a rotating fluid. It was further emphasized that such locally emerging vortical structures amplify the pre-existing background cyclonic vorticity by at least an order of magnitude. The authors of [28] found record values of helicity near convective towers in Hurricane Bonnie (1998) while processing measurement data in the NASA CAMEX field experiment (Convection and Moisture Experiment, 1998–2001). VHTs were called helical by definition, since they simultaneously contain updrafts and vertical vorticity.

A significant amount of studies has been carried out in different countries of the world on VHTs and their role in the genesis and development of TCs. The review [29] presents generalized information on this issue. Special attention was also devoted to vortex tropical convection in several field experiments in the Atlantic and Pacific oceans [30].

Before proceeding to the discussion of TC genesis diagnostics, it is practical to illustrate how VHTs appear in typical datasets used for the proposed analysis — on satellite data of the observed TC, routinely used by meteorological services, and in an idealized cloud-resolving numerical simulation [8, 13].

2.4. VHTs on satellite images of cloudiness

Figure 2 shows satellite images of the Tropical Storm *Grace* on August 14, 2021, obtained from the GOES-16 geostationary satellite. It is also designated as GOES-East and is designed to monitor the region of North and South America. At the time of the presented scenes, the vortex was approaching the Windward Islands from the Atlantic Ocean, with the center coordinates at 15.9°N and 60.7°W. The maximum force of the surface wind was about 18 m/s. The area shown in the figures is approximately 2000×2000 km. The atmospheric vortex scene is presented in two ranges. The “GEOCOLOR” range in Fig. 2, *a* provides the closest approximation to the daytime image. The infrared channel *Band 13*, with a resolution of 2 km, is intended for cloud analysis (Fig. 2, *b*); in particular, for determining the upper boundary of clouds. Dark red and black colors correspond to very intense convective systems that reach the tropopause (15–16 km) and penetrate the lower stratosphere. In English-language literature, there is a specific term for such structures — Overshooting Cloud Tops (OCTs). The corresponding regions with intense convection in Fig. 2, *a* are circled in black.

Similar intense convective dynamics, including cloud towers, are also noticeable in the Black Sea quasi-TC (2021). In Fig. 1, *b*, these patterns are visible near the Black Sea coast to the northwest of the vortex’s “eye” and in cloudiness over the Sea of Azov.

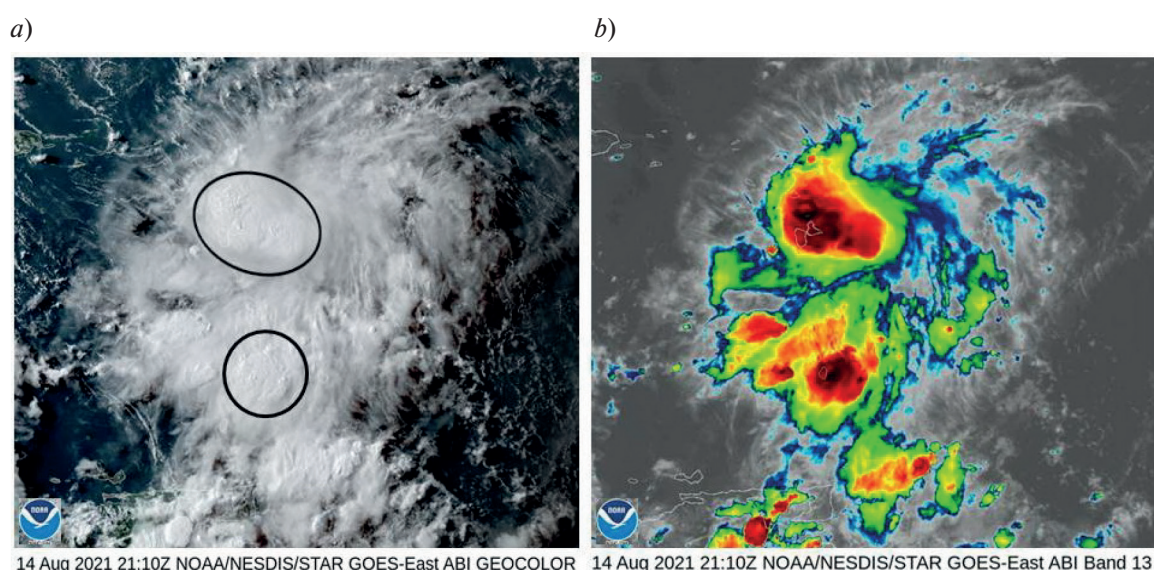


Fig. 2. Vortical hot towers in Tropical Storm Grace 14 August 2021

2.5. VHTs in idealized numerical simulation

A way for VHTs localization in numerical simulation was first proposed and applied in [8, 10, 13] with the author's participation. The method is based on the helical nature of vortex convection. Indeed, rotating vertical cells can be perfectly identified using the vertical helicity field, which is the product of vertical velocity and vertical vorticity.

For this purpose, in the post-processing of cloud-resolving atmospheric numerical simulation data, the helicity density field h was calculated, i. e. helicity values were determined at each point of the computational domain. In particular, the vertical helicity contribution h_z was used to localize the vortex convection

$$h = \mathbf{V} \cdot \boldsymbol{\omega} = u \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) + v \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) + w \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right). \quad (1)$$

The helicity density (Eq. 1) is a pseudoscalar quantity [29, 30]; therefore, it can be either positive or negative. In a right-hand Cartesian or orthogonal curvilinear coordinate system, positive helicity density is generated in a moist atmosphere by cyclonic updrafts and/or anticyclonic downdrafts. Similarly, negative helicity is produced in the case of anticyclonic updrafts and/or cyclonic downdrafts. The information on the vertical helicity field in combination with analysis of the vertical velocity or vertical vorticity field is used to distinguish upward and downward rotating flows. The layout of positive and negative values of the vertical helicity density shows a complete picture of rotating vertical flows in the study region.

As an illustration, Fig. 3 shows the vortical moist convection localized in the vertical helicity field for the numerical experiment A2 described in [23]. In this experiment, the genesis and development of TCs were studied using the regional atmospheric model RAMS (Regional Atmospheric Modeling System) with a horizontal spatial resolution of 3 km. The system of rotating convective flows of different sizes and intensities, shown in Fig. 3, presents a moment when the model TC reached the stage of a Category 2 hurricane with a maximum tangential velocity of 43 m/s near the surface.

Summarizing the discussion on the VHTs, we emphasize that vortical cloud convection is present throughout the entire life cycle of TCs: from the genesis stage to the vortex of the highest hurricane intensity. Rapid rotation did not suppress cloud convection in Hurricane Bonnie, which on August 22, 1998 [24] was at the Rapid Intensification (RI) stage of maximum surface wind from 35 m/s to 50 m/s [28]; in Tropical Storm Grace (Fig. 2) [33], in the model hurricane of the 2nd category of intensity (Fig. 3), and Black Sea quasi-TC of storm intensity (Fig. 1, b).

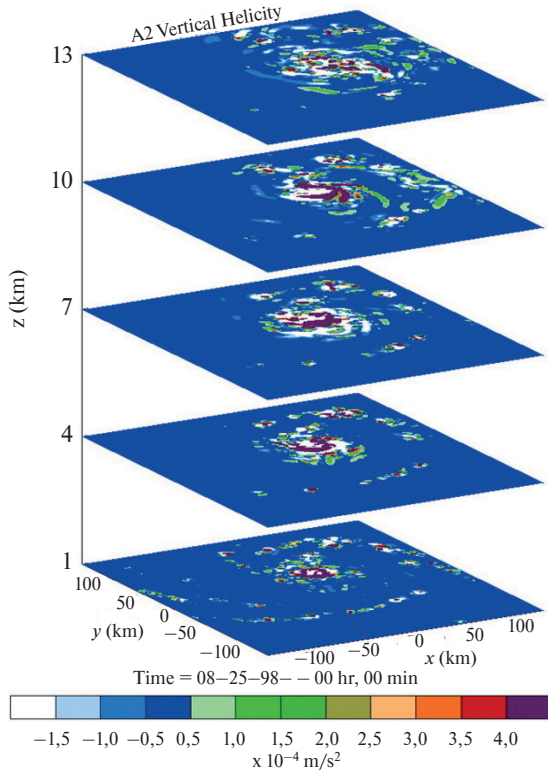


Fig. 3. Vortical moist convection. The field of the vertical helicity density ($\times 10^{-4} \text{ m/s}^2$) in five horizontal levels of $276 \times 276 \text{ km}$ at $z = 1, 4, 7, 10, 13 \text{ km}$

3. Results

3.1. Accurate diagnosis of TC genesis

The review paper [8] presents all the stages of research that lead to the theory of turbulent vortex dynamo application for TC genesis diagnosing using cloud-resolving numerical simulation. Below, we will discuss only the main milestones.

A necessary condition for a vortex dynamo's existence in a tropical atmosphere is the violation of the mirror symmetry of atmospheric turbulence during the emergence of a TC [15, 16]. This requirement predetermined the goal of the first study [9] from a series of joint Russian-American studies between 2009–2015 [8–11]. All works in this series are based on American numerical simulation data with a horizontal spatial resolution of 2–3 km [23]. The very title of the work [23], *A vortical hot tower route to tropical cyclogenesis*, for the first time in tropical meteorology, emphasized the role of vortical cloud convection, specifically, VHTs in the origin of TCs.

Calculations and analysis of the helical characteristics of the velocity field took place for the first time in [9] in the process of initial vortex disturbance amplification and a TD vortex formation with its subsequent intensification to the stage of a mature hurricane. Later, the review [8] presented a detailed discussion of helicity generation at cloud scales (VHTs) and mesoscales of the vortex system. In this case, the study was focused on the mechanism of generation and intensification of vertical vorticity during the interaction of convection and vertical shear of the horizontal velocity [23, 34], which simultaneously provides an intense generation of helicity.

The study [9] showed that during the initiation and further development of TCs, the generation of an essentially nonzero and increasing integral helicity of the vortex system occurs. A nonzero integral helicity is a sign of turbulence symmetry breaking in the zone of TC formation and signifies the emergence of a specific flow topology characterized by a linkage of vortex lines [31, 32]. Thus, the authors of [9] obtained the first example of the nonzero integral helicity generation in a natural system — the Earth's tropical atmosphere. It was shown for the first time that atmospheric turbulence in the mesoscale region of TC formation $276 \times 276 \times 20$ km [23] is helical during the entire lifetime of a hurricane vortex. As is known from the theory of turbulence [17], in a spiral turbulent medium, the energy flux to the dissipation scales can be suppressed, and there are favorable conditions for the generation of large-scale vortex instability. The results of [9] became a powerful motivation for continuing research and searching for a vortex dynamo in the tropical atmosphere.

However, non-zero integral helicity does not necessarily mean the fact of a turbulent vortex dynamo existence. As follows from the theoretical model of the dynamo effect [15, 16] and was shown using the numerical study [35, 36] of the equations of this model, the occurrence of large-scale instability must be diagnosed by analyzing the energy of the vortex system.

3.2. Diagnostics of TC genesis using cloud-resolving numerical simulation

The procedure for instability diagnosing is based on the features of the structure and dynamics of TCs (Fig. 4).

The basis for Fig. 4, *a*, served the image of transection of a tropical cyclone presented in [37], Fig. 3. In Fig. 4, *a*, the base image (Fig. 3 [37]) schematically shows the primary tangential and secondary transversal circulations. A visualization [24] is superimposed on the right side of the TC section to demonstrate the presence of vortical cloud convection (VHTs). As a result, such a composite image of the TC schematically illustrates both the large-scale motions and motions on the scale of cumulus clouds, which play a fundamental role in the excitation of a turbulent vortex dynamo.

The formed TC is an intense atmospheric vortex where the main velocity component lies in the horizontal plane [38]. A powerful tangential (primary) circulation is superimposed on a weaker transversal (secondary) circulation formed by the radial and vertical velocity components (in cylindrical coordinates) Fig. 4, *a*.

The vortex dynamo theory [15, 16] was based on the same concept about the TC structure. Following [15, 16], the dynamo effect should create a linkage [31] of the primary and secondary circulations at mesoscales, i.e. the spiral structure of the TC system as a whole. According to the concept of a vortex dynamo, such linkage signifies the creation of positive feedback between the circulations, which provides their mutual reinforcement. Moreover, unlike all known concepts of tropical cyclogenesis [2], this feedback, here we call it *helical*, is implemented and maintained within the framework of only one physical field — the velocity field. When the helical feedback appears, the nascent vortex becomes energetically self-sustaining and intensifying, which corresponds to the instability emergence. The emerging instability can be diagnosed with innovative method [8, 10, 11, 13], based on the features of the helical feedback.

For this purpose, the kinetic energy of primary and secondary circulation is calculated separately. Then, in the same figure, graphs of both energy characteristics' evolution are plotted to determine the moment when their mutual intensification begins. As shown in Fig. 4, *b*, this occurs approximately at $t = 12$ h. The further development of the instability depends on the conditions in the tropical atmosphere that favor the TCs' formation [2]. These conditions were simulated in the numerical experiments [23], which are the base for the present research.

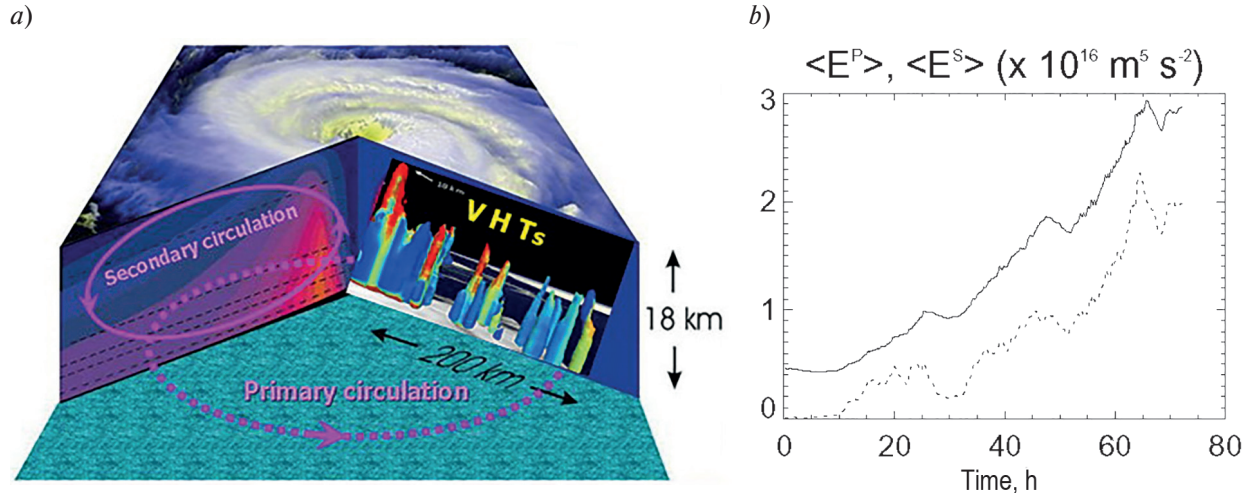


Fig. 4. Diagnostics of TC genesis: *a* — schematic of the linkage of primary and secondary circulation through VHTs population; *b* — evolution of the kinetic energy of primary (solid line) and secondary (dotted line) circulation

4. Discussion

4.1. The key role of the VHTs in creating a vortex dynamo in the atmosphere

As noted above, a turbulent vortex dynamo in the atmosphere should be created by a helical positive feedback that acts between the components of the same physical velocity field — between the primary tangential and secondary transversal circulations [15, 16]. The first feedback link connecting the secondary circulation with the primary one was apparent at the time of the vortex dynamo hypothesis formulation in 1983; it is the effect of the Coriolis force on the horizontal velocity. Feedback loop closure mechanism, which connects the tangential circulation with the transversal, became available only after the discovery of vortical cloud convection in 2004.

Closing of the positive feedback loop between the primary and secondary circulation in the emerging hurricane is achieved by the VHTs.

The studies [8, 13] present a detailed discussion on how the closing feedback link between circulations is created. This process is directly related to the genesis and sustainment of a separate VHT. The formation of a single VHT was first presented and substantiated by the authors of [23] in terms of rotation and stretching of vortex filaments (*vortex tilting and stretching*).

VHTs result from the interaction of moist cloud convection and vertical shear of the horizontal wind. Each ascending convective flow generates vertical vorticity due to the inclination of horizontal vortex filaments and enhances it due to stretching, thereby linking the primary and secondary circulation. Such a process creates a linkage between horizontal and vertical vortex filaments and is quantitatively characterized by the generation of helicity on the local scale of cumulus clouds. During the formation of TCs, a whole family of VHTs of various sizes and intensities develops (Fig. 2–3; Fig. 4, *a*). These VHTs can be represented as numerous dynamic “staples” that ensure the linkage of circulations at mesoscales and thereby create and maintain the integrity of the vortex system throughout the lifetime of the TC.

A special TC topology with a linkage of vortex filaments on cloud scales and linked circulations on mesoscales can be traced by analyzing the local and integral helical characteristics of the velocity field.

Thus, the results in [8] show that the emerging TC becomes energetically self-sustaining and intensifying when the spiral structure of the system-scale circulation is formed. Helical organization at mesoscales results from the linkage of tangential and transversal circulation, which is produced by rotating cloud-scale convective formations — VHTs.

Given the above, the natural “markers” of the genesis and development of TCs are VHTs. Research [13] determined typical configurations of the VHTs in the vertical helicity field, which made it possible to diag-

nose the appearance of large-scale vortex instability, i. e., the birth of the TC based on cloud-resolving numerical simulation [23]. Figure 5 shows the patterns of the vertical helicity field at the level $z = 13$ km, which correspond to the onset of a large-scale vortex instability at the time $t = 12$ h and the formation of a TD vortex at $t = 16$ h in the numerical experiment A2 [23]. Orange, red, and dark red mark the VHTs.

4.2. On practical application for diagnosing the real TCs genesis

To test the diagnostics proposed by [13], it is necessary to perform a cloud-resolving numerical simulation of a real observed TC for which detailed meteorological data are available in the period preceding the declaration of a TD or tropical storm. This should be followed by a coordinated analysis for diagnosing the TC genesis using two sets of data: numerical and satellite. For example, the Atlantic Hurricane Isaias (2020) could be an appropriate candidate for research. The meteorological data that will be required to diagnose this TC is available from the archive of the National Hurricane Center [39]. This case is of particular interest, because joint efforts of stationary meteorological services and research aircraft failed to confirm the TD formation for several days, despite observations of stronger winds in the disturbance zone, corresponding to the next stage of TC intensity — a tropical storm. According to the analysis of the VHT configurations based on satellite data, undertaken by the author and presented in [13], the TC genesis was possible to diagnose 15–18 h earlier than it was actually done.

5. Conclusion

In this work, devoted to tropical cyclogenesis, we applied fundamental concepts of self-organization in turbulence with broken mirror symmetry, the so-called “helical” turbulence. In helical turbulence, an inverse energy cascade is possible from small-scale motions to large vortices [17], which ensures the existence of large-scale long-lived structures. These ideas are the foundation of the turbulent vortex dynamo theory. A number of theoretical works [15, 16, 20] affirmed the threshold existence for the excitation of large-scale vortex instability. In application to the genesis of tropical cyclones, the method of cloud-resolving atmospheric numerical modeling, allows accurate diagnosing of a new large-scale vortex instability emergence timing and answers the question: “*When does cyclogenesis begin?*”

As shown by the atmospheric numerical experiments’ analysis performed to simulate the TCs formation [8–11, 13, 14], the new instability significantly precedes the TD vortex emergence (from several hours to tens of hours). Particular cloud-scale convective coherent structures, vortical hot towers (VHTs), play a crucial role in the instability excitation. The study [13] revealed typical configurations of the VHTs in the vertical helicity field and the temperature field corresponding to the secondary transversal circulation formation, the emergence of large-scale vortex instability, and the formation of a TD vortex.

The presented results affirm remote and accurate diagnostics of TC genesis in real-time by analyzing and comparing data from two independent sources: cloud-resolving atmospheric numerical modeling (vertical helicity field) and cloud satellite images (temperature field).

In the future, the possibilities of the proposed method should be studied for the diagnostics of genesis of the quasi-TCs and polar hurricanes, i. e., in cases where vortical cloud convection can appear. The first results on the detection of VHTs in the Black Sea quasi-tropical cyclone of 2005 were obtained using numerical simulation in [40].

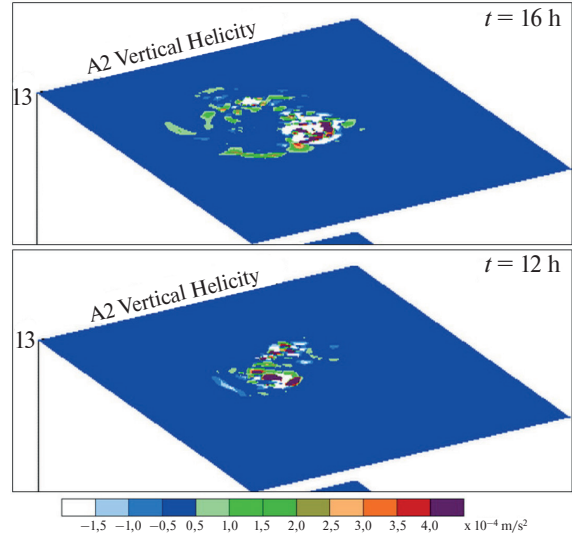


Fig. 5. Typical VHTs patterns in the vertical helicity field at an altitude of 13 km: $t = 12$ h — the onset of instability; $t = 16$ h — the formation of tropical depression. The horizontal plane with a size of 276×276 km of the computational domain is shown

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