A realization of the turbulent vortex dynamo in the atmosphere: based on the 21st century knowledge

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Abstract. A brief summary of the results of numerical modeling undertaken to substantiate the action of the turbulent vortex dynamo (TVD) in the atmosphere is presented. Two series of numerical experiments are discussed. The first of them was aimed at examining a mathematical model of TVD formulated as the mean-field equations, which describe the dynamo-effect in a non-uniformly heated medium. To simulate and demonstrate the main peculiarities of the new large-scale instability in turbulence, an ingenious statement of the problem for numerical analysis was produced, namely, within a simpler framework – the Rayleigh-Bénard problem on laminar thermal convection in an extended horizontal layer. Within the second series, our developed numerical approach, used and tested in the initial series as well as obtained results therein allowed applying the TVD theory to diagnosis of tropical cyclogenesis. To this purpose, the Russian-American collaboration was initiated and the most advanced to that date tools of atmospheric analysis were utilized. Tropical cyclone formation was examined through the analysis of the American data of near-cloud-resolving (2-3 km horizontal grid spacing) atmospheric numerical simulation.

1. Introduction
Modern astrophysical and geophysical researches show more and more examples of the emergence of organized structures in turbulence, the spatial and temporal scales of which can significantly exceed those of turbulent pulsations. Among them are the large-scale motions driven by non-uniform heating of the environment in the Sun and stars’ convective zones, planets’ atmospheres, and the Earth's atmosphere and oceans. Vivid illustrations for such phenomena are tropical cyclones, representing large-scale long-lived helical vortices of anomalous intensity, which arise in the atmosphere of the Earth dozens of times a year.

A way to understanding the phenomenon of tropical cyclone is our ability to find a reasonable explanation for the fact why such mode of flow organization becomes the most preferred in some specific states of the atmosphere. By other words, what are the conditions and physical mechanisms that initiate the process of self-organization of atmospheric turbulence and may provide the transformation of small-scale convective atmospheric cells, each with the horizontal dimension and lifetime typical for an ordinary cumulus cloud (several kilometers and several hours), to a rapidly rotating vortex with a special helical structure, of diameter of a few hundreds of kilometers and a lifetime of up to a number of days.

The problem of tropical cyclogenesis remains among the most complex and unresolved ones in meteorology. In order to puzzle out this phenomenon, one more idea may be tried, connected with searching for a solution based on the peculiarities of heat and mass transfer in pre-hurricane conditions.
of the tropical atmosphere. Indeed, it is well known, convective motions transporting latent and sensible heat from the underlying water surface are the main source of energy for these atmospheric vortices. A breakthrough hypothesis on this subject was put forward within the framework of the theory of turbulent vortex dynamo [1, 2, 3]. The authors [3] substantiated theoretically that the single large-scale vortex of a special spiral topology, characterized by the linkage of horizontal and vertical circulation on the vortex system scales, could be formed as a result of self-organization of small-scale helical convective turbulence. They hypothesized further that such new ordered large-scale flow configuration allows more efficient heat removing from the overheated ocean surface than numerous chaotic small convective cells. For instance, in tropical meteorology to evaluate a probability of cyclogenesis initiation, the following is applied for thermal conditions in most situations. Water temperatures of at least 26.5 °C are needed down to a depth of at least 50 m to provide the overlying atmosphere unstable enough for sustaining convection and thunderstorms [4].

However, as for any other theoretical findings, the final and reliable assessment can only be made on the basis of experimental evidence. In the case under discussion, numerical simulation was chosen as the primary tool to address the theory examination.

2. Numerical evidence of the turbulent vortex dynamo

We are going to briefly sum up results for two different series of numerical experiments. The first of them was undertaken to examine a mathematical model of the turbulent vortex dynamo (TVD) formulated as the mean-field equations, which describe the dynamo-effect in a non-uniformly heated medium. Within the second one, our developed numerical approach, used and tested in the initial series as well as obtained results therein allowed applying the TVD theory to diagnosis of tropical cyclogenesis. To this purpose, the Russian-American collaboration was initiated and the most advanced to that date tools of atmospheric analysis were utilized. Tropical cyclone formation was examined through the analysis of the American data of near-cloud-resolving (2-3 km horizontal grid spacing) atmospheric numerical simulation.

2.1. Helicity and helical turbulence: implication in self-organization and inverse energy cascade

According to the long-standing classical concept of turbulent flows, any large-scale formation, for instance a vortex of spontaneous or forced origin, should be destroyed by turbulence. It is quite another matter if the symmetry of turbulence is broken. The weakest of possible deviations of turbulence from completely disordered is a violation of reflection invariance (mirror-invariance breakdown). Turbulence showing this property is called helical. Apart from the mean energy it is also characterized by nonzero pseudoscalar $H = \int (V \cdot \text{curl} V) \, d\mathbf{r}$ representing a mean helicity. Helicity is one of the main characteristics of the vector velocity field $V (r, t)$ [5, 6, 7, 8]. This quantity is a topological invariant measuring the degree of linkage of the vortex lines of a flow. It is also a measure of the lack of mirror symmetry of the flow. Helicity is, like energy, an inviscid quadratic constant of motion in barotropic fluids. Existence of the second quadratic constant of motion (in addition to the energy) makes helical flows relatively more stable. Helical structures resist dissipation and survive longer [9]. However, unlike energy, helicity can be both positive and negative. Its sign determines the predominance of the left-handed or the right-handed spiral motions in the examined flow.

In nature, helical turbulence is generated by pseudovector physical fields, such as magnetic or Coriolis force field. In theoretical and numerical studies, to break the symmetry of turbulence an approach is often applied that employs a force of special kind called the forcing function or simply – the forcing.

Small-scale helical turbulence has a number of special features. Under certain conditions it can display a tendency towards self-organization and is capable of intensifying and sustaining large-scale vortex disturbances by means of energy transfer from small to large scales [6, 7, 8].

As an illustration for such process in the natural conditions of the Earth’s tropical atmosphere may become a new scenario of tropical cyclogenesis advanced by Montgomery et al. [10] and known as “A
vortical hot tower route to tropical cyclogenesis.” The work demonstrated how a mesoscale tropical depression vortex of hundred kilometers in diameter could develop from rotating cumulonimbus convection cores with characteristic diameter of ten kilometers as a result of system-scale convergence and upscale vorticity growth. Though in seminal work [10] the helical features of atmospheric moist convective turbulence were not explicitly introduced into consideration, a process of upscale vorticity organization examined by the authors reveals lot in common with TVD’s scenario [1, 2, 3].

Following this new atmospheric concept almost immediately, in the same 2006, collaborative Russian-American researches were started. They were based on near-cloud-resolving numerical data [10] and aimed at introducing the TVD theory into tropical cyclone investigations.

2.2. The turbulent vortex dynamo in a non-uniformly heated environment

The generating properties of small-scale helical turbulence leading to the large-scale structure formation were first discovered in magnetohydrodynamics (MHD) by Steenbeck et al. [11]. This phenomenon is known as the alpha-effect. The discovery of the alpha-effect paved the way towards a vigorous development of MHD-dynamo theory. The formal similarity of equations describing the magnetic field $\mathbf{B}$ in a moving electrically-conducting medium and vorticity $\mathbf{\Omega} = \text{curl} \mathbf{V}$ in non-conducting fluids [6, 7, 8]

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

$$\frac{\partial \mathbf{\Omega}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{\Omega})$$

gave an impetus to a search for analogs to this phenomenon in general hydrodynamics.

In non-MHD fluid dynamics, the first theoretical example of large-scale instability generated by specific properties of turbulence with a symmetry break was proposed by Moiseev et al. [1] for a compressible fluid in isothermal conditions. The finding gave the researchers a ground to hypothesize a mechanism for intensification of large-scale vortex disturbances in the atmosphere that was called the turbulent vortex dynamo [2].

A mathematical model of the vortex dynamo-mechanism operating in developed thermoconvective turbulence was advanced in [3] and was obtained by the same methods as the model in [1] without a temperature field, namely, by use of the mean-field theory [12].

Let us note that in both, MHD and non-MHD, cases the theory gives thresholds for the large-scale helical instability. Thus, theoretical ground [1] was applied in [2] to estimate the conditions in the Earth's atmosphere, which are corresponded to the formation of tropical cyclones. Later, the approach [1, 2] was extended by authors [13, 14] for the atmosphere of Jupiter to interpret the dimensions and lifetime of large-scale long-lived vortex disturbances caused by the fall of the fragments of comet Shoemaker-Levy 9 in 1994. Both applications to the atmospheres of planets, the Earth and Jupiter, were discussed in detail in review [15].

2.3. A generating term to provide the vortex dynamo in thermoconvective turbulence

By analogy with the model of the alpha effect in magnetohydrodynamics, the helical-vortex instability is ensured by a generating term obtained by averaging the equations for the turbulent velocity field. The term represents a force of some kind in the physical sense [16]

$$f = C \left\{ e \cdot (\text{curl} \mathbf{V})_z - \frac{\partial (e \times \mathbf{V})}{\partial z} \right\}, \quad e = \{0,0,1\}.$$

The force parameterizes the influence of small-scale helical turbulence formed in a rotating non-uniformly heated medium. As it has been substantiated theoretically [3, 17] and illustrated by numerical simulations [18, 19], term (3) creates a positive feedback loop between the poloidal and toroidal component of the vector velocity field. This feedback provides mutual intensification of both components [18, 19]. The key role in the feedback generation and maintenance is held by the vertical component of vorticity, which appears in the equation for the vertical velocity as it follows from
expression (3). In a more realistic sense, e.g. for tropical cyclones, such a hypothetical result would mean the formation of positive feedback between the tangential and transverse circulation in the atmospheric vortex through a rotating upward flow.

The dimensionless coefficient $C$ characterizes the small-scale turbulence and is related in a rather complicated manner to its characteristics such as the scale of the energy-containing eddies of the turbulence $\lambda$ and characteristic time $\tau$ of the turbulent velocity correlation [17, 18, 19], and is proportional to the angular velocity of a fluid layer rotation $\Omega$, and the power of internal heat sources $\Lambda$. Two independent studies [17, 20] demonstrated that the necessary condition for reaching the vortex dynamo effect is volume heat release in the investigated region. Indeed, it follows from (3): if coefficient $C$ turns to zero in the absence of volumetric heat release ($\Lambda=0$), then generating term $f$ also turns to zero, and the dynamo-effect is impossible. As applied to the atmosphere, this means that heating from below owing to solar radiation obtained by the underlying surface is insufficient for the initiation of large-scale instability.

It is important to note that atmospheric turbulence in pre-hurricane environment is formed precisely under these conditions [4, 10, 16].

However, in those years when the TVD was just discovered [1, 2, 3], in the last two decades of the 20th century, the immediate application of the new phenomenon for explaining the genesis of tropical cyclones caused serious difficulties. Indeed, unlike the magnetohydrodynamics, where the mean electromotive force acts as the generating term [6, 8, 11, 12] by linking the two different physical fields – the magnetic field and the velocity field – and ensuring the amplification and maintenance of large-scale magnetic field, the force described by formula (3) in the TVD theory could not get such transparent interpretation. In a non-conducting medium, the obtained hypothetical force should operate based on velocity field alone. Nothing similar to this was known to scientists at that time.

For further advancement in studying the new phenomenon, a numerical investigation of mathematical model [3] was undertaken.

2.4. Numerical simulation of helical-vortex effects in Rayleigh-Bénard convection [18, 19]

An ingenious statement of the problem for numerical analysis was chosen to simulate and demonstrate the main peculiarities of the helical-vortex instability by the simplest available way.

It is well known that the Rayleigh-Bénard convection produces a great number of similar convective cells. Authors [18, 19] suggested such cells in a stationary laminar convection regime to be considered as structures of an intermediate scale and used as an initial state for numerical modeling. Term (3) had to represent a forcing function included into equations of thermal convection to imitate the influence of small-scale helical turbulence generated in a rotating fluid with internal heat sources. Indeed, force (3) should pump energy into the system and being applied to the initial state, which includes a number of convective cells, may parameterize a transfer of the energy from turbulence to these relatively larger scale motions.

Thus, the strategy applied to numerical experiments included the study of Rayleigh-Bénard convection in an extended horizontal layer of incompressible fluid heated from below [18, 19]. The Boussinesq system with term (3) added as the forcing function to the momentum equation was used for this purpose. An essential difference of such approach from the conventional ones was in a way that the forcing acts. It does not generate the turbulence of prescribed properties but is applied to a developed natural convection flow and influences it relatively “softly”: the forcing generates only a helical structure of flow and initiates a positive feedback between the poloidal and toroidal components of vector velocity field.

Further, within this framework, the researchers tried and implemented an intriguing idea: is it possible to simulate some signs of large-scale instability in these relatively simple conditions?

2.4.1. Numerical implementation. For numerical simulation the above problem was formulated for four physical variables (stream function, vorticity, azimuthal velocity and temperature) and was investigated by the finite differences method. One of the simplest numerical realizations, allowed
transforming the three-dimensional problem to two dimensions but saving all three components of the velocity, was applied for a cylindrical computational domain with axial symmetry. Throughout the calculations, the cylinder had a radius much larger than its height – $R:h = 10:1$. All boundaries were considered as impenetrable solid surfaces. Thermal conditions included constant but different temperatures on the upper and lower surfaces what corresponded to heating from below, and the thermally insulated lateral surface.

The statement of the problem included four dimensionless parameters: Rayleigh, Prandtl and Taylor numbers – $Ra$, $Pr$, $Ta$, which are common to characterize the thermal convection in rotating fluids, and parameter $S$ describing the intensity of the forcing [18].

2.4.2. The most striking manifestations of new large-scale instability. In numerical experiments, a statement of the problem with application of the forcing function was implemented. This allowed imitating the large-scale helical-vortex instability on the basis of laminar helical convection and demonstrating a number of qualitatively new effects in flow structure and energetics predicted within the theoretical model [3, 15].

It is necessary to briefly remind the main findings [18, 19] in order to emphasize those of them, which may have the most immediate relevance to recently highlighted processes in the Earth’s tropical atmosphere [16, 21, 22, 23, 24, 25]:

- it has been shown how the nonzero mean-helicity of the velocity field $H \neq 0$ is generated that implies the broken mirror symmetry;
- aimed at searching for large-scale instability and its expected excitation threshold, several modes of helical-vortex flow have been modeled at various combinations of dimensionless parameters;
- the excitation and action of positive helical feedback between the horizontal and vertical circulation, leading to a rapid increase in the kinetic energy of vortex system, has been investigated;
- how this feedback could be identified by examining integral kinetic energies of the horizontal and vertical circulation has been demonstrated;
- new effects in flow structure and energetics attributed to the large-scale helical-vortex instability have been found and examined;
- numerical experiments vividly illustrated a probable scenario for development of the new instability by merging of helical convective cells and consequent intensification of newly forming larger-scale helical vortices through the helical feedback linking the horizontal and vertical circulation.

The discovered effect of cell merging was observed in a wide range of governing parameters. Depending on the ratio between the intensity of convection, rotation and intensity of the helical forcing, several steady-state modes of mixed and forced convection with a different number of helical vortex cells were obtained and described in detail [18, 19]. As the most impressive illustration we present a formation of the stationary forced mode included the single helical vortex. The corresponding set of isoline maps for the stream function demonstrates a flow evolution under the action of forcing – figure 1. In cylindrical geometry using the axial symmetry condition (the axis of symmetry coincides with the left boundary of the domain in the figures), convective motions are realized as axially symmetrical annular rolls. Projected onto the computational domain lying in the $(r,z)$ plane, these movements look like a system of cells with the direction of vertical circulation alternating from structure to structure.

To produce the presented flow evolution, the stationary convective regime at $Ra=3000$, $Pr=1$, $Ta=100$, $S=0$ was chosen as the initial state – figure 1(a). The number of cells that fit along the radius turns out to be nine, and their horizontal scale, as one would expect from classical knowledge on thermal convection, is comparable to the height of the cylindrical layer. The
forcing of intensity $S=6.4$ was applied to this initial distribution, and the Rayleigh number was set $Ra=1100$, which is much lower than the critical number $Ra^* \approx 1724$ found for free convection in the applied conditions of these numerical experiments.

Under the action of forcing, the convective motions become spiral and the process of their merging starts – see, figure 1(b)-(e). As a result, one helical vortex structure with a horizontal scale of the order of the radius of computational domain is formed – figure 1(f).

![Figure 1. Merging of helical convective cells: (a) t=0; (b) 0.3; (c) 0.4; (d) 0.5; (e) 1.0; (f) 30.0.](image)

The process of merging occurs quickly enough, covering only a span of approximately two units of dimensionless time (introduced as usually in Rayleigh-Bénard problem through relation of the layer height $h$ and the coefficient of kinematic viscosity $\nu - h^2/\nu$ [18]). At first, the intensity of observed flow decreases as compared with the initial mode, since there is a significant reduction in the heat flux due to the Rayleigh number change to its subcritical value for free convection equal to $Ra=1100$. According to [19], the evolution of helical instability in this time interval does not noticeably affect the intensity of movements, but manifests itself primarily in a qualitative change in the flow pattern, destroying the typical structure of the convective mode and forming instead one
vortex cell by the time moment $t \approx 2$ (not shown). Yet the intensity of the formed large-scale flow is still very low. From this moment until the realization of the fully established regime at $t = 30$, shown in figure 1(f), fundamental changes in the flow structure are no longer observed, but a sharp increase in the kinetic energy of the vortex occurs. As a result, the kinetic energy of large-scale spiral vortex $E_r = 4335$ greatly exceeds the energy of the initial convective mode $E_a = 236$.

The flow mode that has been formed under the progressing helical-vortex instability is fundamentally different in its structure and energetics from the initial free convection regime. Under the action of helical forcing, initiating an intense tangential flow, the process of cells merging occurs and the dissipative losses associated with the existence of ascending and descending motions, which form the convective circulation within each cell, decrease. In such conditions, the nature of heat transfer in the layer changes radically. Heat transfer is carried out by forced convection due to intense helical-vortex motion in the large-scale cell. Consequently, the emerged toroidal field of tangential circulation on the one hand suppresses natural convective motions, and on the other hand, itself organizes a vortex cell.

Thus, the resulting large-scale motion represents a spiral vortex, in which the high-intensity horizontal circulation is linked with a weaker vertical circulation.

A number of mixed convection regimes leading up to different amount of helical vortex cells in established steady states were examined thoroughly in [19]. The undertaken numerical analysis of the mathematical model for TVD in a convective system culminated in three important conclusions:

- the existence of an excitation threshold for the helical-vortex instability has been confirmed;
- it has been shown that the increasing intensity of forcing, $S$, results in the threshold decrease and increase of horizontal dimensions of convective structures, and consequently, smaller number of cells in stationary states;
- increasing effectiveness of heat transfer (evaluated by the Nusselt number) within a helical and larger vortex flow configuration has been emphasized.

Thus, the presented results clearly show that the energy of additional helical source can be converted into the energy of intense large-scale vortex flows. A tendency was found to merging of convective cells that leads to the increase in the horizontal scale of vortex motions as well as to considerable intensification of fluid motion and heat transfer. The discovered new effects may have the immediate relevance to the large-scale instability in turbulent states.

These findings gave the authors of [18, 19] an impetus to search for possible application to tropical cyclone investigations.

3. Numerical analysis of self-organization of cloud convection in the tropical atmosphere

Bridging the turbulent vortex dynamo theory and tropical cyclone investigations was not possible, based on the knowledge of the 20th century, and it was awaiting "its time." Only recently it became possible to address the TVD theory examination by use of direct numerical simulation of atmospheric phenomena what implies a very high spatial resolution of 3-1 km and less horizontal grid spacing. This required the breakthrough of American scientists in tropical meteorology and cloud-resolving numerical modeling of atmospheric processes that happened in the 2000s.

A decisive opportunity for bringing both matters together became the discovery of rotating cloud convection in the tropics in 2004 [26], now known as vortical hot towers - VHTs. The new finding immediately got the observational evidence based on direct measurements in the tropical atmosphere in 2005 [27]. A new scenario of tropical cyclogenesis based on self-organization of rotating moist atmospheric convection followed that in 2006 [10].

3.1. Rotating moist convection – vortical hot towers (VHTs) are helical by definition.

By now, the VHTs and their role in tropical cyclone formation have become a subject of significant amount of studies and reliably confirmed in observations performed by researchers over the world, see
e.g. [28, 29, 30], and references therein. These rotating convective structures were closely investigated in several field experiments in the Atlantic and Pacific oceans.

The cloud hot towers in the tropical atmosphere of the Earth were first described in 1958 [31] as horizontally small (~10-30 km wide) but intense cumulonimbus convection cores that reached the tropopause, that in the tropics typically lies at least 15 km above sea level. The term ‘hot’ comes not from the temperature of the air but because of the intense latent heat release due to phase transitions of moisture (vapor – water – ice) along the tower height.

The vortical tropical convection – VHTs – was first found nearly a half of the century later [26, 27]. Typically, VHTs exhibit convective lifetimes on the order of one hour. For example, a thorough observational evidence of VHTs [32] showed that the specific updraft was 10 km wide and had vertical velocities reaching 10-25 m/s above 6 km. The convective cell was extending up to a height of 17 km. The peak vertical velocity within this updraft exceeded 30 m/s. Maximum values of vertical relative vorticity reached up to 6-18·10^{-3} 1/s, what by the one-two order of magnitude exceeds the planetary rotation.

The authors [33, 34] paid the closest attention to the helical features of convective towers. In [33], helicity was calculated in Hurricane Bonnie (1998) using tropospheric-deep dropsonde soundings carried out by reconnaissance aircrafts during the NASA Convection and Moisture Experiment (CAMEX) and the most extreme values of helicity, among the largest ever reported in the literature, were found in the vicinity of deep convective cells. These cells reached as high as 17.5 km. As it was noted in [34], in which helicity calculations were performed for eight tropical cyclones of 1998-2001 sampled during the CAMEX, VHTs are helical by definition because they contain coincident updrafts and vertical vorticity.

3.2. Self-organization of atmospheric moist convection in the tropics.

Near-cloud-resolving idealized simulations [10] showed how a mesoscale tropical depression vortex could develop from rotating deep cumulonimbus convection as a result of upscale vorticity growth. The simulations first generated a number of VHTs, each of 10-30 km horizontal scale, which eventually resulted in an intense mesoscale helical vortex. The enlargement of flow scales occurred by multiple mergers of small-scale convective structures. Such atmospheric scenario of self-organization had much in common with that observed in simulations of the helical-vortex Rayleigh-Bénard convection [18, 19]. This did become evident when both scenarios were brought together and discussed in seminars of Montgomery Research Group at Colorado State University in Fort Collins.

On the background of these findings, the ideas of vortex dynamo acquired a completely new meaning. It became evident that the vortical hot tower route to tropical cyclogenesis [10] represents the most appropriate basis to take into account helical features of convective atmospheric turbulence. This gave a start to collaborative Russian-American studies aimed at applying the TVD theory to examination of tropical cyclogenesis.

3.3. “Helical” post-processing of atmospheric simulation data.

To analyze the process of self-organization of moist atmospheric convection observed under conditions of tropical cyclogenesis as posed in [10], a set of helical characteristics was computed, as well as some other integral characteristics of the velocity field which were applied in [19].

The velocity fields used for post-processing in our studies [21, 22, 23, 24, 25] originated from [10] (in which a more detailed information can be found) and were obtained by use of three-dimensional non-hydrostatic Regional Atmospheric Modeling System (RAMS) comprising time-dependent equations for all three components of velocity, pressure, potential temperature, total water mixing ratio, and cloud microphysics and utilizing an interactive multiple nested grid scheme. For all numerical experiments [10] three nested grids were used. Our post-processing of the model data was carried out on the finest computational grid for subsequent times with a time increment of 10 minutes during 72 hours of numerical experiment. Characteristics were calculated in the computational domain of 276×276×20 km in Cartesian coordinates by use of uniform finite-difference grid. Throughout the
post analysis the vertical increment was equal to 500 m; the horizontal increments were 2 and 3 km. We also applied an analysis of system-scale dynamics from a traditional vortex-centric perspective when the Cartesian model data were transformed into a local cylindrical coordinate system.

It is important to point out that no external assumptions were imposed on the fluid motions investigated and described in [21, 22, 23, 24, 25], i.e., no external forcing terms were imposed to mimic a “helical alpha effect”. In other words, the presented results are the outcome of a direct numerical simulation subject to the usual caveats of a sub-grid scale closure that is used to remove small scale motions at the horizontal grid scales of the model (~3 km).

3.4. Helical tropical cyclogenesis.

For purposes of quantitative diagnosis, we have analyzed the evolution of energetics and structure of the forming vortex. The integral kinetic energy of primary tangential and secondary transverse circulation was applied to diagnose the onset of large-scale vortex instability. A pseudoscalar – helicity of the velocity field (helicity density, integral helicity as well as its horizontal and vertical contribution) was applied to quantitatively analyze the topology.

The first discovery of the undertaken collaborative Russian-American efforts [21] was the break of the mirror symmetry of atmospheric turbulence – non-zero mean helicity generation – during tropical cyclone formation that gave us the impetus to further search for the large-scale vortex instability.

The process of helicity generation was examined with a special focus on how this is realized by a single VHT generated by a local heating at low levels [16]. It can be summarized that the VHTs appear as a result of interaction between cloud moist convection and vertical wind shear. Each convective updraft generates the vertical vorticity by tilting of horizontal vortex filaments and amplifies it by stretching. This process provides a linkage of horizontal and vertical vortex lines and results in helicity generation on a local cloud scale whilst an evolving population of VHTs of different sizes and intensity during tropical cyclone evolution ensures the linkage of circulations on mesoscales.

For the first time in tropical cyclone research, a role of special topology of forming vortex provided by interaction of motions of different scales was emphasized [16]. It has been found that the newly forming mesoscale vortex becomes energy-self-sustaining when a helical structure of the system-scale circulation organizes. Such helical mesoscale organization is only possible due to the linkage of primary tangential and secondary transverse circulation, which is realized through rotating convective structures of cloud scales – VHTs. Helicity dynamics allows tracing such upscale flow organization.

The foregoing results allowed suggesting a key role of VHTs as a necessary element to provide the dynamo effect. Based on the mathematical model for the turbulent vortex dynamo, an analogy was traced [16] between the role of interaction 'moist convection – vertical wind shear' (see, hypothetical forcing (3)) in creating the vortex dynamo in the atmosphere and the role of the mean electromotive force providing the MHD dynamo in electrically conducting medium.

4. Diagnosis of tropical cyclogenesis

By adapting and using for analysis of atmospheric data our developed approach [18, 19], which was tested in the search for a large-scale vortex instability in the helical-vortex Rayleigh-Bénard convection, we have discovered similar instability in conditions of tropical cyclogenesis [23, 24, 25]. The onset of instability was identified as the start of mutual intensification of the primary and secondary circulation making a nascent hurricane vortex energy-self-sustaining. It must be stressed that the observed new instability begins several hours earlier than the vortex of tropical depression is formed. At present, it is the latter that is usually declared in meteorological observations as the formation of a tropical cyclone. If the discovered instability is reliably confirmed for tropical cyclones observed in real atmospheric conditions, it may be suggested to consider the emergence of this instability as the commencement of tropical cyclogenesis.

Evidently, our most important finding, contributing to both the fundamental science and practical issues of the earlier warning of the population about the hurricane danger, is connected to the fact that the onset of cyclogenesis is now getting the precise interpretation - it coincides with the beginning of
new found instability. Moreover, our results show that this instability starts earlier (from a few hours up to a few tens of hours) than the formation of a tropical depression vortex takes place – the event, for which the regional storm tracking services usually declare a tropical cyclone emergency.

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