Turbulent vortex dynamo in the Earth’s atmosphere and the emerging opportunity to affect tropical cyclogenesis

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Abstract. The interpretation of tropical cyclogenesis as an extreme threshold event in the helical atmospheric turbulence allows us to discuss the idea on affecting the birth of a hurricane. A hypothetical way is based on the crucial role of the intense vortical cloud convection, known as Vortical Hot Towers, in the excitation and maintenance of large-scale helical-vortex instability. Some quantitative estimates are given, for which results of idealized cloud-resolving numerical simulation have been applied. The modern numerical modeling of atmospheric processes makes it possible to investigate and evaluate the possibilities of managing the instability, for example, on the basis of “Hurricane Nature Run.”

1. Introduction
The theoretical hypothesis on the turbulent vortex dynamo is dating back to the early 1980s [1, 2]. Then, after the discovery of the alpha-effect in magnetohydrodynamics [3] and based on the formal similarity of equations, describing the magnetic field in a moving electrically-conducting medium and the vorticity in non-conducting fluids [4, 5], several research groups over the world were involved in the search for analogs to this phenomenon in general hydrodynamics of non-conducting fluid. To date, the most famous of the latter is the so-called anisotropic kinetic alpha (AKA)-effect found in [6] and became the first, which was simultaneously illustrated by full numerical simulation of the three-dimensional Navier-Stokes equations.

What are the fundamental features inherent in all the above-mentioned phenomena? The discovered effects demonstrated the possibility of self-organization in turbulence, namely, the emergence of large-scale and long-lived structures against the background of smaller and chaotic components of motion. In all cases, turbulence was characterized by the broken mirror symmetry. Turbulence with such a symmetry break is called helical. In helical turbulence, dissipation process can be attenuated due to a reduced turbulent viscosity [7, 8], what allows energy to be accumulated at its generation scales. Such energy accumulation can lead to the onset of large-scale instability under certain conditions. In the three discussed phenomena, each of discovered large-scale instabilities had the excitation threshold. As it is well known from the stability theory, threshold phenomena can be controlled.

The prospect of controlled generation of large-scale magnetic fields aroused wide interest among experimenters and the emergence of MHD dynamo projects in different countries of the world [9].

In the case of proven applicability of the vortex dynamo hypothesis to atmospheric processes, the idea of controlling the genesis of large-scale intense helical vortices in the atmosphere such as tropical cyclones looked no less exciting.
1.1. Research program on the turbulent vortex dynamo (TVD)

Finding ways to manage the expected large-scale vortex instability was included as a task in an extensive research program started in the middle 1980s and aimed at testing the hypothesis on the turbulent vortex dynamo. Theoretical, experimental, and numerical investigations were carried out by research groups in several scientific centers throughout the USSR. The program culminated in two field campaigns in the tropical Pacific – the expeditions “Typhoon–89” and “Typhoon–90.” In the expeditions, of 100 days each, one and four research ships participated in typhoons’ seasons of 1989 and 1990, respectively. More details about the program can be found in reviews [10, 11].

At this juncture, let us only note that following the theoretical analysis of the TVD mathematical model, a few ideas were advanced of how the formation of intense large-scale helical vortices might be affected. The suggestions were offered to test in the appropriately designed laboratory experiments on thermal convection in rotating fluids [10]. In the present work, it is worth to recall the one of them [12], which emphasizes the fact that the threshold of large-scale instability depends on the helicity value. The proposed way to manage the instability was based on introducing of external small-scale helicity into a rotating layer of non-uniformly heated fluid and was targeted at a generation or intensification of already existing large-scale spiral vortex. An alternative case was also examined on how to suppress the strengthening of existing large vortex or, at all, the actual process of such vortex formation.

1.2. Helicity of the velocity field and its diagnostic utility in tropical cyclone (TC) studies

For our further discussion, a short introduction is necessary for what helicity is. As the experience of the author, who is trying to apply the TVD theory to the study of tropical cyclones, shows, this topic is causing misunderstandings among hurricane specialists, since the very definition of the term “helicity” differs in general hydrodynamics and meteorology, see, e.g., [13].

The new knowledge about helicity in TC studies gained by our efforts is also worth to note. Helicity of the velocity field is defined as the scalar product of velocity $V(r,t)$ and vorticity $\omega(r,t) = \text{curl} V$ vectors [14]. The volume integral calculated in a specific space domain,

$$\mathbf{H} = \int V \cdot \omega \, d\mathbf{r},$$

(1)

gives the helicity of vortex system, where $\int V \cdot \omega$ is the helicity density of the flow

$$\mathbf{H} = \int \omega = \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) + \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) + \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right).$$

(2)

Both quantities are pseudoscalars, i.e., they change sign under change from a right-handed to a left-handed frame of reference.

Turbulence characterized by the non-zero mean helicity,

$$\langle \mathbf{H} \rangle \neq 0,$$

(3)

is called helical. A non-vanishing mean helicity determines according to its sign the predominance of the left-handed or the right-handed spiral motions in the examined flow. Expression (3) provides a necessary but not sufficient condition for the appearance of large-scale helical-vortex instability.

In TC studies, helicity analysis is a new tool that allowed us to reveal one more condition favorable for TC genesis, as well as to quantify the chaotic influences resulting from moist convection [11, 15, 16, 17]:

- if condition (3) is satisfied for the atmospheric turbulence in a region with a favorable environment for the formation of a tropical cyclone [18], this means the possible occurrence of large-scale vortex instability [11, 15, 16];
- the vertical contribution of helicity in formula (2) allows localizing the vortical moist convection in the atmospheric field of vertical helicity and quantifying the height and intensity.

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of rotating convective structures. As it was shown in [17], the emergence of the first convective vortical hot tower (VHT) of 13-14 km in height may signal the beginning of the secondary circulation formation and the subsequent onset of large-scale vortex instability within several hours.

The fundamental meaning of helicity in the diagnosis of TC genesis is connected with the fact that the onset of large-scale vortex instability requires a special topology of the vortex velocity field – the newly forming mesoscale vortex becomes energy-self-sustaining when a helical structure of the system-scale circulation organizes. Helicity is a quantitative measure of such organization – a topological invariant, which characterizes the structure of the velocity vector field and measures the degree of linkage of the vortex lines. To ensure the large-scale helical-vortex instability, the linkage of horizontal and vertical components of vorticity is the necessary condition. This is why, in our studies on TC genesis, the vertical contribution of helicity is of primary importance.

2. Interpretation of tropical cyclogenesis as a threshold extreme event in the three-dimensional helical moist convective atmospheric turbulence

Substantiation of the applicability of the TVD theory to the problem of tropical cyclogenesis became possible almost thirty years after the publication of works [1, 2]. This required new knowledge in tropical meteorology gained by the most modern research tool, which is a cloud-resolving numerical modeling of atmospheric processes. In the 2000s, intense rotating cumulonimbus clouds were first discovered in numerical simulation [19] and, a year later, they were confirmed by observation data got with use of airborne Doppler radar in the genesis phase of an Atlantic Hurricane Dolly (1996) [20]. These convective coherent structures were called “Vortical Hot Towers” – VHTs. Based on [19, 20], a new scenario of tropical cyclogenesis under realistic meteorological conditions was presented by using a numerical cloud model [21]. The scenario [21], realized in a favorable tropical environment, demonstrated self-organization of moist atmospheric convection from cloud scales of several kilometers horizontally up to a tropical depression vortex of hundreds of kilometers.

The TC genesis scenario [21] and the corresponding data of cloud-resolving numerical simulation became the basis for a series of collaborative Russian-American works aimed at introducing the TVD theory in TC studies. The summary of undertaken efforts, including a conclusion about the emerging opportunity to impact on TC genesis, was first presented and discussed in seminar at the National Center for Atmospheric Research (Boulder, CO, USA); both abstract and recorded presentation are available in [22]. The presentation was followed by a detailed review-research article [11].

3. Crucial role of VHTs in tropical cyclogenesis

In the context of the present work, let us briefly recall the main characteristics of VHTs and the key role of vortical cloud convection in providing the TVD in the tropical atmosphere. Based on this knowledge, a targeted way for controlling TC genesis can be proposed.

3.1. Vortical Hot Towers

The cloud hot towers in a developed tropical cyclone are shown in NASA visualization – figure 1(a), which is available in Wikipedia [23]. These intense cumulonimbus convection structures were first described in 1958 [24] while their vortical nature was identified nearly fifty years later, in [19, 20]. As seen in figure 1(a), the VHTs can penetrate throughout a troposphere height up to 16–18 km. Figure 1(b) is a fragment of visible satellite image borrowed from Fig. 3[19]. VHTs in Tropical Storm Gustav (2002) are shown: “…the region of deep convection is marked by the black line, …individual hot towers are marked by black dots.” For illustrative purposes, the main characteristics of VHTs are given as an inscription in figure 1.

In hurricane studies, helical features of VHTs were noted in [25], where they were described as “deep moist convective clouds that rotate as an entity and/or contain updrafts that rotate in helical fashion (as in rotating Rayleigh-Bénard convection) …. These locally buoyant vortical plume structures amplify pre-existing cyclonic vorticity by at least an order of magnitude larger than that of
the aggregate vortex.” In [26, 27], helicity was calculated but for developed, not at the genesis stage, tropical cyclones of 1998–2001 sampled during the NASA Convection and Moisture Experiment (CAMEX). Using tropospheric-deep dropsonde soundings carried out by reconnaissance aircrafts, the most extreme values of helicity, among the largest ever reported in the literature, were found in the vicinity of deep convective cells. In TC research, it has first been shown [26] that there exists an association of large helicity and intense convection. The authors [27] noted that VHTs are helical by definition because they contain coincident updrafts and vertical vorticity.

3.2. VHTs as the main “actors” in ensuring the large-scale instability and trying to control it
Scenario of “A vortical hot tower route to tropical cyclogenesis” [21] emphasized the role of vortical moist convection and provided a basis to substantiate the vortex dynamo [11]. This also prompts us what way might be to try managing the large-scale helical-vortex instability in the atmosphere.

3.2.1. A VHT formation
To this end, it is useful to recall a mechanism of VHT formation described in detail and illustrated in [21]. At the same time, this is also a process of the vertical vorticity and helicity generation on cloud scales. In review [11], in order to demonstrate both of them in the same image, Fig. 9(b) showing the VHT and Fig. 10 on vortex tilting were borrowed from [21] and combined. The resulting illustration is presented here as figure 2.

The VHT was formed [21] in realistic meteorological conditions of favorable for TC genesis environment [18], which included cyclonic low-level vorticity from a preexisting mesoscale cyclonic vortex (MCV). It is important to note, that the existence of initial large-scale vortex disturbance was also considered as a necessary condition for the TVD realization in the atmosphere by authors [1, 2].
In [21], the simulation was initialized with a weak MCV elevated above the sea surface, with a maximal mean tangential wind at \( z = 4 \text{ km} \). The vortex had a basic-state cyclonic tangential velocity field that increased in magnitude with height below \( z = 4 \text{ km} \) and decreasing above. This provided an environment rich in horizontal and vertical vorticity. Ignoring buoyant effects, we could consider the horizontal vorticity profile at the initial time as being due solely to the vertical shear of horizontal wind of the initial MCV. Such vertical shear profile will generate a radial vorticity profile that, when tilted upward by an updraft, generates negative (positive) relative vertical vorticity anomalies on the radially inward side of the updraft below (above) \( z = 4 \text{ km} \). Evolving convection tilts ambient horizontal vorticity into the vertical while at the same time stretching MCV-generated vertical vorticity. As some updraft intensifies to become a hot tower, both ambient and tilting generated vertical vorticity is stretched even more, leading to a strong convectively generated vertical vorticity anomaly.

![Formation of a VHT](image)

**Figure 2.** Formation of a VHT: (a)&(b) Schematic of vortex tilting within the initial MCV [21]. Purple lines represent vortex filaments. (a) Radial vorticity generated by vertical shear profile of initial MCV. (b) Updraft tilts radial vortex filament upward, generating a vertical vorticity dipole with negative relative vorticity radially inward (outward) at heights below (above) \( z = 4 \text{ km} \). (c) Vertical velocity \( w (\text{ms}^{-1}) \) and absolute vertical vorticity \( \eta (\times 10^{-4} \text{s}^{-1}) \) signatures associated with deep cumulus convection in experiment A1 at \( t = 40 \text{ min} \). Horizontal cross sections are 20 km × 20 km subdomains. The existence of a strong vorticity dipole collocated with the core of the hot tower and its orientation suggest tilting of ambient vorticity associated with the initial MCV.

Based on cloud-resolving numerical data [21], the thorough quantitative analysis of helicity generation during TC formation was carried out and described in detail in the INI Preprint (Cambridge, UK) [28]. In contrast to the widely used approach in meteorology [13, 26, 27], both the vertical and horizontal contributions of helicity were introduced into consideration. The numerical analysis [28] showed that the vertical contribution of helicity was two orders of magnitude less than the horizontal one in the atmospheric conditions of tropical cyclogenesis. Nevertheless, in addition to its fundamental role in creating a special topology of the velocity field, the former also proves useful for more familiar purposes: for identification (mean helicity values) and localization (helicity density field) of rotating vertical flows. Thus, the non-zero vertical helicity can serve as an indicator of the presence of vortical convection in the examined area [17, 28, 29]. Non-zero horizontal helicity can be considered as a sign of existing or emerging shear flow.

Important confirmation for the discussed mechanism of the vertical helicity generation was delivered from a laboratory experiment [30], which was performing simultaneously with numerical
simulation for the same statement of the problem. In [30], the non-zero vertical helicity was generated as a result of interaction of ascending convective plumes and shear flow in non-rotating fluid layer. The mean values of two other spatial contributions of helicity were also found non-zero. Experiment [30] became the first one, in which all three spatial contributions of helicity were examined, thereby getting the beginning of a new approach to the analysis of helical flows in subsequent studies.

In review [11], the mechanism shown in figure 2 (a, b) was interpreted as an effective way to generate helicity on cloud scales in the atmosphere and was illustrated by the results of the relevant quantitative analysis [28] of numerical simulation data [21].

3.2.2. How was generated the first intense VHT in numerical simulation [21]?

This matter is worth to be emphasized, especially, in the context of the present research. First of all, because the threshold of large-scale instability depends on the helicity value [1, 2, 10], while VHTs are the main sources of helicity generation on cloud scales in a forming TC [11]. Secondly, an intense VHT of 13-14 km in height gave start to the formation of the secondary circulation in all experiments [21] examined in our studies [11, 17, 28]. These were convincing reasons for the priority attention paid to both events in TC evolution in [17]: indeed, it was found that such intense VHT and the formation of secondary circulation soon, within several hours, were followed by large-scale instability. This is also important for practice, when performing operational meteorological diagnostics of the TC genesis. The intense VHTs can well be traced in satellite data, and they can serve as pronounced signals about the upcoming instability [17].

Interestingly, that the VHT, presented in figure 2(c), was the first and very intense updraft of 14 km in height (its upper part, exceeding 9 km, was not shown), developed in simulations [21] within the very first hour of experiment. However, this was not a result of natural convective instability in the atmosphere. The VHT was generated by a local heating at low levels, $z = 2 \text{ km}$ [21]. The heating was applied for the first 300 s in simulation in order to stimulate cumulus convection in the local environment of the MCV. In [11, 28], this allowed us to quantitatively examine how helicity could be generated by a single updraft in the absence of other developed convective flows and evaluate the effect of initial conditions on this process.

3.2.3. Helicity generation prior to the onset of instability

This process was analyzed in detail [11, 28] for four experiments from [21]: A2, B1, C3, and E1.

The experiments were simulated using the same horizontal grid increment equal to 3 km. All of them started with an initial MCV in the midtroposphere. A maximum tangential velocity was at height $z = 4 \text{ km}$ and equal to 6.6 $\text{m s}^{-1}$ in A2, B1, and E1, and 5.0 $\text{m s}^{-1}$ in C3. Sea surface temperature (SST) = 29°C in all cases. In B3, low-level moisture was decreased by 2 g/kg. In E1, the Coriolis parameter was set to zero.

Two values of mean helicity, $<H>$, are given in table 1. The first of them is the absolute maximum generated by the first VHT; the corresponding time moment shown at left of this value. The second was generated by a population of intense VHTs at the start of large-scale instability.

| Experiment | Initial VHT Time (h) | Initial VHT Helicity Max ($\text{m}^4 \text{s}^{-2}$) | Onset of Instability Time (h) | $<H>$ Helicity ($\text{m}^4 \text{s}^{-2}$) |
|------------|----------------------|----------------------------------------|-------------------------------|----------------------------------------|
| A2         | 1.5                  | $3.3 \times 10^{11}$                  | 12                            | $4.0 \times 10^{11}$                  |
| B3         | 1.0                  | $2.0 \times 10^{11}$                  | 40                            | $2.0 \times 10^{11}$                  |
| C3         | 1.5                  | $2.0 \times 10^{11}$                  | 18                            | $2.0 \times 10^{11}$                  |
| E1         | 1.5                  | $3.5 \times 10^{11}$                  | 10                            | $3.2 \times 10^{11}$                  |

The performed examination allows us to evaluate what maximal helicity values can be generated by each initial VHT and how much time this process takes. One can find the obtained results in table 1.
For example, in experiment A2, it took about 1.5 hours. The characteristics of the initial VHTs were also determined. Thus, the most intense VHT (exp. A2) was about 10 km horizontally and reached 14 km in height, its maximal vertical velocity and vorticity values were 33 ms\(^{-1}\) and \(20 \times 10^{-4}\) s\(^{-1}\) (about 20 times the planetary rotation), respectively.

As one can see in table 1, in all four cases there existed a pre-instability stage, which followed the initial maximum of helicity. At this stage, the first VHT was destroyed, but within several hours a few small, gradually increasing ascending rotating convective flows appeared. This time interval was also characterized by a start of process of merging of convective cells. The observed phenomenon was described in detail, analyzed quantitatively and interpreted in [21] as a manifestation of upscale organization of atmospheric rotating moist convection. The process of merging was accompanied by not only an emergence of larger and stronger convective structures but also an increase in the background vorticity and helicity in adjacent areas. As a result, the mean helicity, after some decrease, began to increase again.

Convective activity was progressing by an emergence of a whole population of updrafts of various sizes and intensity, which interacted with each other by merging, and resulted in more intense structures. The observed convective updrafts were growing gradually with time in height until the new intense VHT 13-14 km high appeared and gave start to the formation of the secondary circulation. At this stage of 1-2 hours long, several intense VHTs were formed and initiated the beginning of large-scale instability.

Duration of the whole pre-instability period depended on initial conditions in each experiment – table 1.

3.2.4. Managing the large-scale helical-vortex instability

From the point of view of affecting the large-scale instability, attention is drawn to the fact that the helicity level (table 1), corresponding to the onset of instability in each experiment, is very close to or coincides with the maximal initial value and, therefore, can be generated by the single VHT.

Recent results [17] highlight the pre-instability evolution of nascent vortex: the appearance of intense “critical” VHT 13-14 km high, resulting from natural convection development, is followed by the formation of secondary circulation within 1-2 hours and, nearly simultaneously with the latter, the onset of instability.

So we have a target for impact. This is the formation of secondary circulation. The method of impacting was proposed by the authors [21] themselves in their seminal work – this is the creation of intense VHT by local heating.

Obviously, the impact can be not only aimed at favoring the fast vortex formation, as was demonstrated in [21], but also the suppression of the TC genesis. Modern cloud-resolving numerical modeling allows simulating and analyzing both possibilities. Such a study can be carried out, for example, on the basis of “Hurricane Nature Run” [31], which represents a data set and depicts the entire life cycle of an Atlantic hurricane from initiation as an African easterly wave, to tropical cyclogenesis, to rapid intensification, and finally to recurvature over the North Atlantic.

4. Conclusions

In the present work, the special features of helical turbulence are emphasized. Under certain conditions, such turbulence, characterized by the broken mirror symmetry, is capable of amplifying and sustaining large-scale vortex disturbances by ensuring energy transfer from small scales to large ones. What is more, all discovered large-scale “helical” instabilities in magnetohydrodynamics and general fluid dynamics of non-conducting fluids have an excitation threshold. This opens a way for controlling the instabilities. Discovery of the helical nature of atmospheric turbulence during TC formation [15] allowed the interpretation of tropical cyclogenesis as large-scale helical-vortex instability in the atmosphere [11, 17, 32]. Development of these studies suggests further searching for the threshold of instability in the atmosphere. Modern atmospheric science offers a perfect tool for these purposes – the cloud-resolving numerical simulation.
Acknowledgments
The paper was prepared in the framework of the research project “Monitoring” no. 01200200164. The author is deeply grateful to the Workshop Organizers for their interest in this research. Post-processing for the discussed cloud-resolving simulation was supported in part by the U.S. National Science Foundation, Grant ATM-0733380.

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