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Helical Cyclogenesis in the Earth's Atmosphere and Beyond †

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Abstract: In the present publication, we highlight how a breakthrough discovery of vortical cloud convection by high resolution atmospheric simulations paved the way for the helical scenario of cyclogenesis. We briefly discuss the hydrodynamical helicity required to study the self-organization in turbulence with the broken mirror symmetry; it differs from that one used in meteorological applications. We give practical recommendations for "helical" post-processing to diagnose the large-scale vortex instability. We also discuss the first findings in our attempts to extend the developed approach to studies beyond the tropics, to mid-latitudes quasi-tropical cyclones, namely, that one observed over the Black Sea in September 2005.

Keywords: planet atmospheres; helical moist convective turbulence; upscale energy transfer; cyclogenesis

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1. Introduction

Back in the 1980s, the first theoretical works [1–4] appeared, in which the existence of intense large-scale atmospheric vortices was interpreted on the basis of fundamental concept about the processes of self-organization in turbulence. Self-organization here refers to the formation of larger and longer-lived ("coherent" [5]) vortex structures against the background of smaller and chaotic components of motion. An essential feature of self-organization processes is their non-equilibrium, meaning that a constant influx of energy from outside is needed to sustain the resulting large-scale structures in a stable state. In this context, the inverse energy cascade in turbulence, realized under some special conditions and allowing the transfer of energy from small to large scales [6], becomes of particular importance. As such a case with special conditions, the authors [1–4] considered the three-dimensional helical turbulence in an electrically non-conducting environment. Helical turbulence is characterized by the break of mirror symmetry and is generated in physical fields with pseudovector properties, such as magnetic or Coriolis force fields [7,8]. Turbulence of such kind is observed in geo- and astrophysical systems. Amongst the familiar natural systems, the rotating atmospheres of planets can be emphasized, where the spiral properties of the velocity field are attributed to the action of the Coriolis force.

Therefore, naturally, the main focus of the authors [1–4] was on the Earth's atmosphere.

At that time, two independent research groups of theorists from different countries were actively involved in the development of this problem. By the first of them, as a possible application of their turbulent vortex dynamo theory [1,2], the accent was made on the hurricanes/typhoons formation in the tropical atmosphere. Unlike the MHD-dynamo in magnetohydrodynamics [7,8], the turbulent vortex dynamo implies a large-scale helical-vortex instability in electrically non-conducting medium. The authors [3,4] put forward a universal concept of helical cyclogenesis, which was suitable for various climatic zones including tropical, mid, and polar latitudes. However, in both cases, the very basis was unclear – how is the process of helicity generation implemented in real atmospheric turbulence? In the 1980s, there were neither technical possibilities for measuring helicity in the atmospheric flows, nor numerical atmospheric modeling systems with the necessary spatial resolution. Moreover, at that time the very notion of helicity was just beginning to be introduced into the study of atmospheric phenomena.

Nevertheless, an attempt was undertaken to test the hypothesis on the turbulent vortex dynamo by direct atmospheric measurements during the ship expeditions "Typhoon–89" and "Typhoon–90" in the tropical Pacific in 1989 and 1990, respectively [9–11]. A special mathematical model was developed to describe large-scale motions in the atmosphere during these field campaigns [12]. The basic advantage of the model was that it could be easily applied to the processing of field experiment data (vertical profiles of wind velocity, temperature, humidity, etc.), enabling the researchers to estimate the dynamic parameters of the atmosphere such as helicity, kinetic energy and helicity fluxes from small-scale turbulence to large-scale structures. Spectra of atmospheric turbulence were obtained and examined for various synoptic conditions. The analysis discovered a non-zero helicity of the atmospheric turbulence (i.e. the break of the mirror symmetry!) and brought an implication that inverse energy transfer might exist from the small scales to large ones in conditions of tropical cyclone formation. Unfortunately, these very promising atmosphere-oriented investigations were not continued in Russia after 1991 unlike related theoretical and numerical works, and laboratory experiments on thermal turbulent convection in rotating fluid, whose results obtained up to 2000 were summarized in [9].

With the advent of the new millennium, new opportunities have emerged through the development of numerical modeling of atmospheric processes with high spatial resolution – cloud-resolving one.

In the present publication, we highlight how a breakthrough discovery of vortical cloud convection by high resolution atmospheric simulations [13–15] paved the way for the analysis of a real helical scenario of cyclogenesis. We introduce and briefly discuss the hydrodynamical helicity [16] required to study the self-organization in turbulence with the broken mirror symmetry; it differs from that one used in meteorological applications. Based on the data [15], the corresponding analysis of the helical features of atmospheric moist convective turbulence for tropical cyclone formation was first undertaken in collaborative Russian–American studies, which were summarized in review [10]. Being progressed, this resulted in a procedure for the accurate operational diagnosis of the onset of large-scale helical-vortex instability, i.e. the birth of a hurricane [17–19]. Further, we discuss the first findings in our attempts to extend the developed approach to studies beyond the tropics, to mid-latitudes quasi-tropical cyclones, namely, that one observed over the Black Sea in September 2005.

2. Methods. New Era of Cloud-Resolving Atmospheric Modeling

In the 2000s, near-cloud-resolving simulations of tropical cyclogenesis allowed the researchers [13] to discover a vortical nature of atmospheric moist convection. Rotating cloud structures were identified numerically and called vortical hot towers (VHTs) in [13], and a year later, they were first documented based on observations data obtained by airborne Doppler radar [14]. These publications were followed by "A vortical hot tower route to tropical cyclogenesis" [15], in which an "upscale growth mechanism appears capable of generating a tropical depression vortex" was presented. Such a scenario emphasized an upscale vorticity cascade from strongly three-dimensional convective structures (VHTs) of 10–30 km horizontally to the tropical depression (TD) scale of hundreds of kilometers.

Atmospheric data obtained in numerical investigations [15] with horizontal space resolution 2 km and 3 km were chosen for collaborative Russian-American studies aimed at testing the theoretical hypothesis on the turbulent vortex dynamo; the detailed discussion can be found in review [10]. In the context of the present paper, it is worth sharing a few key points of our "helical" post-processing, which are applicable to the analysis of the self-organization processes in moist convective turbulence, regardless of latitude, in the atmosphere of the Earth and other planets.

2.1. Helicity of the Velocity Field and Its Diagnostic Utility in Tropical Cyclone (TC) Studies [11]

For the current discussion, a short introduction is necessary about what helicity is. As the experience of the author, who is working to apply the turbulent vortex dynamo theory to the study of tropical cyclones, shows, this topic is causing misunderstandings among meteorologists and hurricane specialists, since the very definition of the term "helicity" differs in general hydrodynamics and meteorology, see, e,g., [16].

The new knowledge about helicity in TC studies [10] gained from our efforts is also worth noting.

Helicity of the velocity field is defined as the scalar product of velocity $\boldsymbol{V}(\boldsymbol{r},t)$ and vorticity $\boldsymbol{\omega}(\boldsymbol{r},t) = \mathrm{curl}\,\boldsymbol{V}$ vectors [20]. The volume integral calculated in a specific space domain,

$$H = \int \boldsymbol{V} \cdot \boldsymbol{\omega}\, d\boldsymbol{r}\,, \tag{1}$$

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

$$h = \boldsymbol{V} \cdot \boldsymbol{\omega} = \mathrm{u}\left(\frac{\partial \mathrm{w}}{\partial y} - \frac{\partial \mathrm{v}}{\partial z}\right) + \mathrm{v}\left(\frac{\partial \mathrm{u}}{\partial z} - \frac{\partial \mathrm{w}}{\partial x}\right) + \mathrm{w}\left(\frac{\partial \mathrm{v}}{\partial x} - \frac{\partial \mathrm{u}}{\partial y}\right). \tag{2}$$

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,

$$\langle H \rangle \neq 0, \tag{3}$$

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.

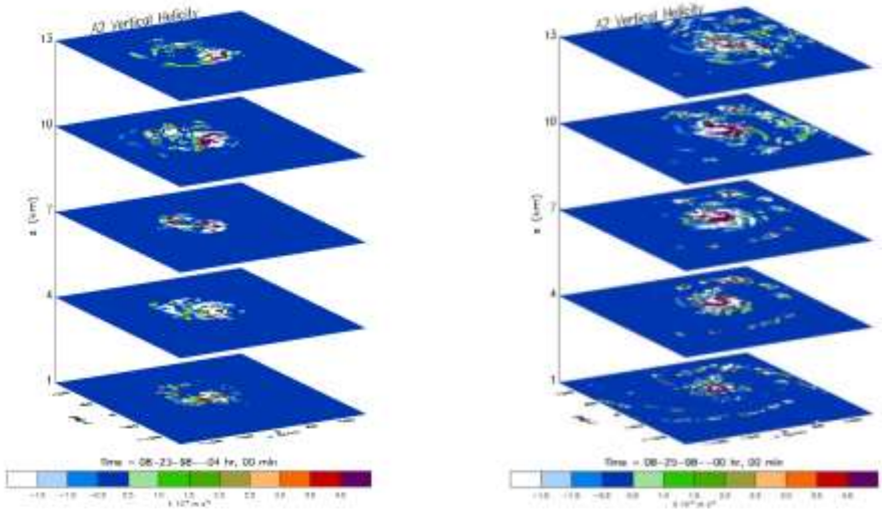
2.2. Practical Recommendations for "Helical" Post-Processing to Diagnose the Large-Scale Instability

- It would be recommended to start the post-processing by checking the fulfillment of condition (3) in the examined area of the specific cyclone formation, as was done in [21]. This stage does not require significant time and computational resources. A positive result would mean that there is an environment conducive to the vortex dynamo effect, thereby encouraging scientists to continue their research.
- As a next step, the general procedure for the diagnosis of instability can be applied; Section 3 [18] gives the detailed explanation. Bearing in mind that VHTs can be considered as the main "actors" in ensuring the large-scale helical-vortex instability in the tropical atmosphere [10,11] and taking into account that they are helical structures, it was proposed to introduce the vertical helicity field for their identification [10,11,18,19].

2.2.1. Vertical Helicity Field as a Tool to Localize Vortical Convection

To this end, we used the helicity density (not its integral value unlike [22]), i.e., helicity values calculated in each point of the finite-difference grid – h, specifically, its vertical spatial contribution, h_z, in formula (2). This allows localizing the vortical cloud convection in the atmospheric field of vertical helicity and quantifying the height and intensity of rotating convective structures.

In Figure 1, rotating cloud convection is shown in the vertical helicity field for the experiment A2 from [15] at two stages in the model TC evolution. In this experiment, the TC genesis and further vortex intensification up to hurricane strength were simulated using the model RAMS (Regional Atmospheric Modeling System) with a horizontal space resolution of 3 km.



(**a**) (**b**)

Figure 1. Vortical moist convection. The field of the vertical helicity density (×10^{-2} m/s^2) in five horizontal levels of 276 × 276 km at z =1; 4; 7; 10; 13 km: (**a**) The tropical depression with sustained winds near 9 m/s at t = 16 h; (**b**) The hurricane vortex of Category 2 with sustained winds reaching 43 m/s at t = 60 h.

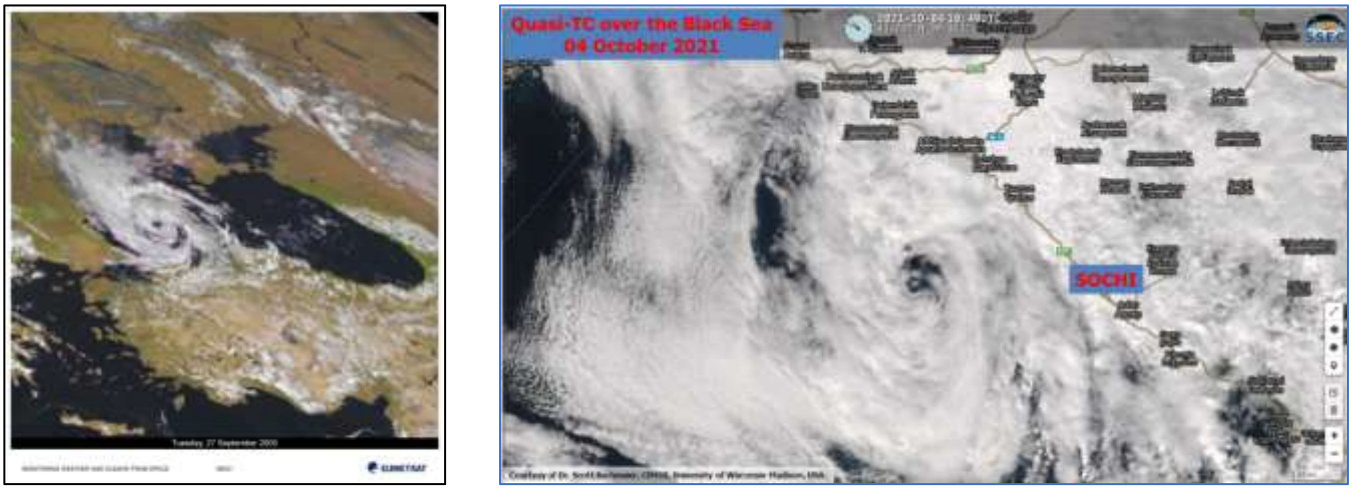
Figure 1 presents a whole spectrum of rotating convective flows of different horizontal and vertical size, intensity, and rotational signature within a forming TC vortex. Orange, red and dark red regions correspond to strong positive helicity. In our post-processing, the vertical velocity and vertical vorticity were also analyzed. This allowed both an identification of the formation of rotating convective structures, updrafts and downdrafts, and determination of their rotational signature, i.e., cyclonic or anticyclonic.

2.3. Operational Diagnosis of Tropical Cyclogenesis

The performed cloud-resolving numerical analysis of tropical cyclogenesis allowed us to apply the fundamental physical theory of the turbulent vortex dynamo [1,2] and develop an approach for operational real time diagnostics of the birth of a hurricane [17–19]. This resulted from collaborative Russian-American efforts of 2009–2015, which had as a basis bringing together pioneering works [9,15] from both sides. Recent discussions at the prestigious international meetings in 2021 (the 34th American Meteorological Society Conference on Hurricanes and Tropical Meteorology, the General Assembly of the European Geophysical Union, and the 4th Electronic Conference on Atmospheric Sciences – ECAS2021) have shown that the proposed diagnostics can help forecasters in identifying these dangerous storms earlier than is possible now. The diagnostic approach should now be tested using cases of tropical cyclogenesis, which have previously been observed and well documented, and then – be put into meteorological practice.

3. Quasi-Tropical Cyclones over the Black Sea

A few years ago, leading world experts predicted an increased occurrence of hurricane-like extratropical cyclones in the western Mediterranean and Black Sea [23]. In the Russian meteorological community, due attention was not paid to this. Although a cyclone of this type already appeared in the southwestern part of the Black Sea in September 2005 (Figure 2a) and was the subject of study in several publications of those years [24,25], many considered that cyclone as an exotic case that has a negligible chance of repeating itself. The situation changed dramatically in the summer of 2021, when several hurricane-like cyclones appeared near the densely populated areas of the coast of the Black and Azov Seas during August–October. The most impressive of them with an "eye" of the storm close to Sochi is shown in Figure 2b.



(**a**) (**b**)

Figure 2. Quasi-tropical cyclones over the Black Sea: (**a**) 27 September 2005 – EUMETSAT MONITORING WEATHER AND CLIMATE FROM SPACE, https://pics.eumetsat.int/viewer/index.html; (**b**) 04 October 2021– Courtesy of Dr. S. Bachmeier, CIMSS, University of Wisconsin-Madison, USA.

3.1. An Uncompleted Attempt to Diagnose the Large-Scale Helical-Vortex Instability

In 2018–2019, Russian scientists initiated cloud-resolving modeling of the cyclone observed over the Black Sea in 2005 in order to search for the large-scale helical-vortex instability [26, 27].

The studies were carried out using a non-hydrostatic version of the WRF (Weather Research and Forecasting) atmospheric model. Horizontal space resolutions of 1 km and 2 km were chosen. According to the above recommendations (see, Section 2.2), at the first stage, the integral characteristics were calculated. The integral helicity of the developing vortex system, which was significantly different from zero, was found 12–18 hours after the beginning of the simulation, and during the further evolution of the cyclone, it increased approximately 4 times after 60 hours. This gave grounds to start a complete procedure for diagnosing large-scale vortex instability and to start searching for and analyzing rotating cloud convection. The method of localization of such structures is presented above in Section 2.2.1. Contrary to the expectations of numerous skeptics, vortex convective structures of various size and intensity have been discovered. Some of them reached 10 km in height, and their relative rotation significantly exceeded the planetary one. The obtained results were presented at two conferences in Moscow in 2018 and 2019 [26,27], but the studies were not continued due to their recognition as irrelevant to Russia and the refusal in funding that followed.

4. Conclusions

The publication of this work has two goals: fundamental and applied. In the light of recent new developments [28.29], it is necessary to pay close attention to the concept of helical cyclogenesis [1–4]. The authors [28] theoretically substantiated the large-scale helical-vortex instability based on the inverse energy cascade in a rotating stratified moist atmosphere, taking into account the tilt of the rotation axis. It was found in [29] that small-scale moist convection provides an upscale energy transfer to large cyclones at Jupiter's high latitudes. Given what is described in this paper for the Earth's atmosphere, all the results support the universality of the concept of helical cyclogenesis. It is probably only a matter of time before this concept is confirmed at different latitudes of the Earth's atmosphere and on other planets. As to the practical applications, the author would like to take advantage of the present publication to encourage colleagues to test the proposed diagnostics for real atmospheric vortices as soon as possible.

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