

1 Conference Proceedings Paper

# 2 How Does Cyclogenesis Commence Given a Favorable 3 Tropical Environment?

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8 **Abstract:** In a series of collaborative Russian-American works (Levina and Montgomery, 2009–2015), we applied the funda-  
9 mental ideas on self-organization in turbulence with the broken mirror symmetry, the so-called "helical" turbulence. In this  
10 context, tropical cyclogenesis is considered as a threshold extreme event in the three-dimensional helical moist convective  
11 atmospheric turbulence of a vorticity-rich environment of a pre-depression zone. This allowed us to discover a large-scale  
12 vortex instability and answer a question "When will cyclogenesis commence given a favorable tropical environment?" The  
13 new instability emerges against the background of seemingly disorganized convection, without a well-defined center of  
14 near-surface circulation and noticeably precedes the formation of a tropical depression. This can give the fundamental  
15 ground and quantitative substantiation for the term "Potential Tropical Cyclone" as a beginning of TC genesis. In the present  
16 work, we explore in detail the crucial role of special convective coherent structures of cloud scales – Vortical Hot Towers  
17 (VHTs) – in the formation and maintenance of the secondary circulation and, therefore, of the whole mesoscale vortex sys-  
18 tem. Based on it, we propose how the onset of large-scale instability, i.e. the beginning of TC genesis, can be diagnosed ex-  
19 actly and distantly with VHTs patterns in the field of temperature (satellite data) and vertical helicity (cloud-resolving nu-  
20 merical analysis). The present research is intended to contribute to a recently initiated development [17,18] of operational  
21 diagnosis of the beginning of TC genesis based on GOES Imagery and supported by cloud-resolving numerical modeling.

22 **Keywords:** tropical cyclogenesis; cloud-resolving numerical analysis; GOES imagery

## 24 1. Introduction

25 The lack of a universally accepted definition of tropical cyclogenesis and the related problem of accurate  
26 diagnosis of the birth of hurricane vortices remain among the major challenges of modern tropical meteorology.  
27 First of all, because the forecast of the developing vortex and the entire system of warning the population about  
28 the possible emergency situation depend fundamentally on this.

29 Despite such uncertainty, it was necessary to develop specific approaches for diagnosis and forecasting.  
30 Therefore, in meteorological practice it has been proposed to consider the formation of a surface-concentrated  
31 warm core vortex, characterized by a reduced pressure and a well-defined center of closed wind circulation, as  
32 the occurrence of a tropical cyclone (TC). If the maximum tangential surface wind speed in a vortex does not  
33 exceed  $17 \text{ m s}^{-1}$ , then the vortex is called a tropical depression (TD), which is considered as the lowest classifica-  
34 tion of the TC intensity. The greatest difficulty is the diagnosis of such an event, since the TCs emerge above the  
35 water surface and very often far from ground tracking centers with the necessary measuring facilities.

36 Modern approaches using satellite data and numerical models of the atmosphere of high spatial resolution  
37 have made it possible to achieve significant progress. Nevertheless, so far the most accurate diagnosis of the  
38 formation of TC is obtained by direct measurements from aircraft in the area of an incipient vortex. As far as we  
39 are aware, such approach has been consistently applied only in the United States. What is more, since the 2017  
40 hurricane season, the U.S. National Weather Service (NWS) has introduced a term "Potential Tropical Cyclone –  
41 TCP" in order to prevent a significant risk of life-threatening situations. In the glossary on the website of the U.S.  
42 NOAA/NWS National Hurricane Center (NHC) [1], the new term describes "... a disturbance that is not yet a  
43 tropical cyclone, but which poses the threat of bringing tropical storm or hurricane conditions to land areas  
44 within 48 hours." Meanwhile, above mentioned in situ measurements and additional NWS' efforts of 2017 are

insufficient in order to diagnose the exact timing of TC genesis. The genesis event can be accurately diagnosed only based on an atmospheric process, or a series of such processes, that can provide a quantitative threshold criterion.

To this purpose, in our collaborative Russian-American works [2–4], we applied a theoretical hypothesis on the turbulent vortex dynamo [5,6]. The hypothesis offers a way for intensification of large-scale vortex disturbances in the atmosphere due to energy transfer from small-scale helical turbulence. Similarly to two other well-known large-scales instabilities in helical turbulence, the alpha-effect in magnetohydrodynamics [7] and the anisotropic kinetic alpha (AKA)-effect in non-conducting fluid [8], the vortex dynamo theory gives an excitation threshold of the instability [5,6,9] and quantitative estimations for the corresponding atmospheric parameters [6].

## 2. Cloud-Resolving Numerical Analysis for the Accurate Diagnosis of TC Genesis

Author’s experience gained in numerical examination of the mathematical model of the turbulent vortex dynamo in a convectively unstable rotating fluid [10–12] was used to elaborate a procedure for the exact diagnosis of TC genesis.

A numerical approach was developed in order to trace and analyze processes of self-organization in the tropical atmosphere, spanning convective clouds with horizontal dimensions of 3–30 km to mesoscale vortices of hundreds of kilometers [2–4]. The approach was applied for post-processing of data from idealized near-cloud-resolving numerical simulations of tropical cyclogenesis [13], where the authors proposed a new scenario of tropical cyclone formation based on the upscale organization of convective processes – “a vortical hot tower (VHT) route to tropical cyclogenesis.”

To analyze the self-organization process of convective atmospheric turbulence [13], we calculated a number of special integral hydro- and thermodynamic characteristics and used for this purpose the output of the Regional Atmospheric Modeling System (RAMS) numerical simulations performed within a series of experiments [13]. For all numerical experiments [13], three nested grids were used. In our study, we operated with RAMS output for physical fields in Cartesian coordinates ( $x, y, z$ ) calculated for the two horizontal resolutions. In the control experiment, the horizontal grid increment was equal to 2 km on the finest grid whilst it was 3 km in all other numerical experiments. The vertical grid increment was 400 m at the surface and gradually stretched with height to the top of the domain at 22 km. In our post-processing, the same horizontal grid increments were applied while along the height the RAMS data were interpolated to 40 vertical levels uniformly distributed from the lower level at  $z = 500$  m up to the upper one at  $z = 20$  km with the vertical increment equal to 500 m. Tropical cyclone formation during 72 hours was traced with time increment 10 minutes.

### 2.1. Is the Atmospheric Turbulence in the Area of TC Formation Helical?

In the post-processing, the first and fundamental stage was about examination of the helical features of moist convective atmospheric turbulence during TC formation. At this stage, the necessary environment for the existence of the vortex dynamo-effect has been tested. As the theory [5,6,10,14] gives, the large-scale instability of such kind appears in 3D helical turbulence characterized by the non-zero mean helicity of the velocity field. By the time our research started in 2009, there had been no attempt to verify whether this condition was being met in the real atmosphere.

#### 2.1.1. Helicity of the velocity field

Helicity of the velocity field is defined as the scalar product of velocity  $\mathbf{v}(\mathbf{r}, t)$  and vorticity  $\boldsymbol{\omega}(\mathbf{r}, t) = \text{curl} \mathbf{v}$  vectors [15]. The volume integral calculated in a specific space domain,

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

gives the helicity of vortex system, where  $\mathbf{v} \cdot \boldsymbol{\omega}$  is the helicity density of the flow. Both quantities are pseudo-scalars, 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,  $\langle H \rangle \neq 0$ , is called helical. Helicity is one of the main characteristics of the velocity vector field. The mean helicity, like energy, is an inviscid constant of motion. This pseudoscalar quantity falling into the category of topological invariants characterizes the structure of the velocity vector field and measures the degree of linkage of the vortex lines. A non-vanishing mean helicity, implying the symmetry break with respect to coordinate system reflections, determines according to its sign the predominance of the left-handed or the right-handed spiral motions in the examined flow.

1 2.1.2. The non-zero mean helicity generation during TC formation

2 The non-zero and persistently increasing with time mean helicity of atmospheric turbulence within an area  
 3 of a developing TC was found in [2]. This has become the first example of such phenomenon in a natural system  
 4 – the tropical atmosphere of the Earth. However, the non-zero helicity does not necessarily imply that the  
 5 large-scale vortex instability is underway. In fact, this only means that we have a case of the helical turbulence  
 6 and the existing departure of the mirror symmetry in turbulence of such kind produces an environment condu-  
 7 cive to the onset of large-scale instability.

8 Indeed, this was an important signal and impetus to search for the instability. To diagnose the very insta-  
 9 bility, we need the analysis of the system-scale energetics.

10 2.2. *When Will a Nascent TC Become Energy-Self-Sustaining and Intensifying?*

11 "In terms of the macro variables, the tropical cyclone consists of a horizontal quasi-axisymmetric  
 12 circulation on which is superposed a thermally-direct transverse (overturning) circulation. These are sometimes  
 13 referred to as the 'primary' and 'secondary' circulations, respectively. The former refers to the tangential or  
 14 swirling flow rotating about the central axis, and the latter to the transverse or 'in-up-and-out circulation' (low-  
 15 and middle-level inflow, upper-level outflow, respectively). When these two components are combined, a  
 16 picture emerges in which air parcels spiral inwards, upwards and outwards [16] (p.39)."

17 The authors of the vortex dynamo theory [5,6] proceeded from the same concept that a developed TC is an  
 18 intense mesoscale atmospheric vortex, in which the main component of velocity lies in a horizontal plane. The  
 19 powerful tangential circulation is superimposed on a weaker transverse circulation formed by the radial and  
 20 vertical velocity components (in the cylindrical coordinates). Following [5,6], the vortex dynamo-effect should  
 21 generate a linkage of air streamlines on mesoscales, i.e., the helical structure of the TC system and produce the  
 22 positive feedback linking the circulations and providing their mutual intensification.

23 The numerical examination of the vortex dynamo model confirmed [10–12] that the first sign of the hy-  
 24 pothesized large-scale helical-vortex instability should be generation of the linkage of tangential and transverse  
 25 circulation on the system scale, and resulting of it, a positive feedback that makes the forming large-scale vortex  
 26 energy-self-sustaining. Such feedback was expected to reveal itself in mutual intensification of both circulations.

27 For diagnosis of the large-scale helical-vortex instability during TC formation [3,4,14], this means that we  
 28 should analyze the evolution of kinetic energy divided into two parts: of primary, EP, and secondary, ES, circu-  
 29 lation, similarly to that was performed in [10–12]

$$30 \quad E = EP + ES. \quad (2)$$

31 To quantitatively diagnose an emerging feedback loop between the primary and secondary circulation, we  
 32 examined the kinetic energy. An only innovation was introduced that the energy of the primary and secondary  
 33 circulation should be calculated separately. The energy was calculated through the squares of the  
 34 corresponding components of velocity in the cylindrical coordinates, was integrated over the whole  
 35 computational domain and normalized by the number of grid points. Then, the energy evolution – EP(t) and  
 36 ES(t) – was plotted in the same figure in order to determine whether the mutual amplification of circulations  
 37 starts and when [3,4,14]. The time moment, when the mutual intensification of both circulations starts, marks  
 38 the onset of large-scale vortex instability.

39 2.3. *Accurate Diagnosis of the TC Genesis Stage*

40 Cloud-resolving numerical analysis of the evolution of the kinetic energy of the primary circulation, EP, and  
 41 the secondary circulation, ES, in a forming tropical cyclone makes it possible to determine the time moment G,  
 42 when their mutual amplification begins and the forming vortex becomes energy-self-sustaining and intensifying  
 43 [3,4,14,17]. Time G can be interpreted as the beginning of TC genesis and it matches perfectly to designate the  
 44 "Potential Tropical Cyclone [1]." The subsequent formation of a tropical depression (TD) after a few hours can be  
 45 interpreted as the completion of the TC genesis stage.

46 **3. Results**

47 Our interpretation of tropical cyclogenesis as the pre-depression large-scale helical-vortex instability allows  
 48 providing the exact time when cyclogenesis commences and quantifying the chaotic influence resulting from  
 49 moist convection. We propose the fundamental ground and quantitative substantiation for the term "Potential

1 Tropical Cyclone" as a beginning of TC genesis. Based on the VHTs role in the formation and maintenance of the  
2 secondary circulation and, therefore, of the whole mesoscale vortex system, we propose how the onset of  
3 large-scale instability can be diagnosed with VHTs patterns in the field of temperature (satellite data) and ver-  
4 tical helicity (cloud-resolving numerical analysis). The present research is intended to contribute to a recently  
5 initiated development [17,18] of early and exact operational diagnosis of the beginning of TC genesis based on  
6 GOES Imagery and supported by cloud-resolving numerical analysis.

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