

Proceeding Paper

How Does Cyclogenesis Commence Given a Favorable Tropical Environment? [†]

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[†] Presented at the 4th International Electronic Conference on Atmospheric Sciences, 16–31 July 2021;

Available online: <https://ecas2021.sciforum.net>.

Abstract: In a series of collaborative Russian–American works (Levina and Montgomery, 2009–2015), we applied the fundamental ideas of self-organization in turbulence with broken mirror symmetry, the so-called “helical” turbulence. In this context, tropical cyclogenesis is considered as a threshold extreme event in the three-dimensional helical moist convective atmospheric turbulence of a vorticity-rich environment of a pre-depression zone. This allowed us to discover a large-scale vortex instability and answer the question “When will cyclogenesis commence given a favorable tropical environment?”. The new instability emerges against the background of seemingly disorganized convection, without a well-defined center of near-surface circulation and noticeably precedes the formation of a tropical depression. This can give the fundamental ground and quantitative substantiation for the term “Potential Tropical Cyclone” as a beginning of TC genesis. In the present work, we explore in detail the crucial role of special convective coherent structures of cloud scales—vortical hot towers (VHTs)—in the formation and maintenance of the secondary circulation and, therefore, of the whole mesoscale vortex system. On this basis, we propose how the onset of large-scale instability, i.e., the beginning of TC genesis, can be diagnosed exactly and distantly with VHTs patterns in the field of temperature (satellite data) and vertical helicity (cloud-resolving numerical analysis). The present research is intended to contribute to a recently initiated development of operational diagnosis of the beginning of TC genesis based on GOES Imagery and supported by cloud-resolving numerical modeling.

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



Citation: Levina, G. How Does Cyclogenesis Commence Given a Favorable Tropical Environment? *Environ. Sci. Proc.* **2021**, *8*, 20. <https://doi.org/10.3390/ecas2021-10320>

Academic Editor: Anthony R. Lupo

Published: 22 June 2021

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1. Introduction

The lack of a universally accepted definition of tropical cyclogenesis and the related problem of accurate diagnosis of the birth of hurricane vortices remain among the major challenges of modern tropical meteorology. The forecast of a developing vortex and the entire population warning system of possible emergencies fundamentally depends on this.

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

Modern approaches using satellite data and numerical models of the atmosphere of high spatial resolution have made it possible to achieve significant progress. Nevertheless, the most accurate diagnosis of the formation of TC is currently obtained by direct measurements from aircraft in the area of an incipient vortex. To our knowledge, such approach has

been consistently applied only in the United States. What's more, since the 2017 hurricane season, the U.S. National Weather Service (NWS) has introduced a term "Potential Tropical Cyclone—TCP" in order to prevent a significant risk of life-threatening situation. In the glossary on the website of the U.S. NOAA/NWS National Hurricane Center (NHC) [1], the new term describes "... a disturbance that is not yet a tropical cyclone, but which poses the threat of bringing tropical storm or hurricane conditions to land areas within 48 h." Meanwhile, the aforementioned 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. Similar to two other well-known large-scale 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

The 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 on 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 h was traced with a time increment of 10 min.

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] states, 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,

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

gives the helicity of vortex system, where $\mathbf{v} \cdot \boldsymbol{\omega}$ is the helicity density of the flow. 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, $\langle H \rangle \neq 0$, 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 the predominance of the left-handed or the right-handed spiral motions in the examined flow according to its sign.

2.1.2. The Non-Zero Mean Helicity Generation during TC Formation

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

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

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

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

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

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

For diagnosis of the large-scale helical-vortex instability during TC formation [3,4,14], we should analyze the evolution of kinetic energy divided into two parts: the energy of primary, EP , and secondary, ES , circulation, similar to that which was performed in [10–12]

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

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

2.3. Accurate Diagnosis of the TC Genesis Stage

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

3. Results

Our interpretation of tropical cyclogenesis as the pre-depression large-scale helical-vortex instability allows for providing the exact time when cyclogenesis commences and quantifying the chaotic influence resulting from moist convection. We propose the fundamental ground and quantitative substantiation for the term “Potential Tropical Cyclone” as a beginning of TC genesis. Based on the VHTs’ role in the formation and maintenance of the secondary circulation and, therefore, of the whole mesoscale vortex system, we propose how the onset of large-scale instability can be diagnosed with VHTs’ patterns in the field of temperature (satellite data) and vertical helicity (cloud-resolving numerical analysis). The present research is intended to contribute to a recently initiated development [17,18] of early and exact operational diagnosis of the beginning of TC genesis based on GOES Imagery and supported by cloud-resolving numerical analysis.

Funding: This research was supported by the Ministry of Science and Higher Education of the Russian Federation within the program “Monitoring”, state registration No. 01.20.0.2.00164. Post-processing for the discussed cloud-resolving simulation was supported in part by the U.S. National Science Foundation, Grant ATM-0733380.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

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