Birth of a hurricane: early detection of large-scale vortex instability

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Abstract. A way is substantiated for detecting new large-scale vortex instability in the tropical atmosphere. The instability may occur several hours or even several dozens of hours before the formation of a tropical depression or tropical storm. The diagnosis of instability was developed on the basis of data from idealized cloud-resolving atmospheric simulation for tropical cyclogenesis. It is suggested how the evolving instability may be traced by combining high-resolution numerical modeling and GOES Imagery. As an illustration, it is speculated and discussed that the instability may have emerged in future Hurricane Isaias (2020) when it had a status of Potential Tropical Cyclone for 36 hours before it was diagnosed as Tropical Storm.

1. Introduction
A hurricane in the Americas or a typhoon in Southeast Asia and the Russian Far East are local names for a natural phenomenon defined in meteorology by the term tropical cyclone (TC). In the glossary on the website of the National Hurricane Center (NHC USA) [1], a tropical cyclone is described as “a warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center.” The position of the center is usually defined by the location of minimum wind or minimum pressure. Tropical cyclones are known by violent winds, torrential rain, high waves and, in some cases, very destructive storm surges and coastal flooding. Therefore, TCs are one of the biggest threats to human life and property, even at the initial phases of their evolution. One distinguishes several stages in the tropical cyclone intensity [1]: tropical depression (TD) for vortices with maximum sustained tangential near-surface winds up to 17 ms⁻¹, tropical storm (TS) – 18-32 ms⁻¹ winds, hurricane (H) – with winds 33 ms⁻¹ and higher, can attain a category of intensity from 1 to 5 (since 70 ms⁻¹).

1.1. Motivation
Despite the significant efforts of modern science, the phenomenon of the birth of a tropical cyclone, referred to in professional literature as "tropical cyclogenesis", remains one of the most sophisticated problems in meteorology. What is more, any clear consensus of opinion has not yet emerged concerning processes and physical mechanisms contributing to tropical cyclogenesis (TC genesis). Though up to date, a universally accepted definition of TC genesis does not exist, most researchers believe that is a fact of the formation of the tropical depression [2].

At this juncture, it is important to refer back to the NHC glossary [1] and emphasize that behind the given velocity estimation, one does not imply any specific process, leading to the genesis and holding this value as a characteristic of wind threshold.
Such situation, on the one hand, provides operational forecasters with a certain quantitative criterion, and on the other hand, it can cause subjective assessments. One knows enough cases when the TD stage was missed and a forming vortex was identified too late, already on the TS stage and dangerously close to densely populated regions.

Meanwhile, for example in the USA, under longstanding policy of the National Weather Service (NWS), it has not been permitted to issue any warning until after a TC, i.e., TD or TS had formed. In order to avoid a significant risk of life-threatening situations, since the 2017 hurricane season, NWS has introduced a term “Potential Tropical Cyclone – TCP.” In NWS advisory products, 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 hours [1].”

Till August 1, the unusually early 2020 Atlantic hurricane season already brought tropical cyclones, which were identified at the TS stage, i.e., missing the TD stage. One was the future Hurricane Isaias, which had been in the intermediate status of TCP for 36 hours, approaching the Leeward Islands and Puerto Rico from the Atlantic Ocean, and was declared as TS right next to them.

Indeed, it is difficult to diagnose such an event, as the formation of TCs occurs above the water surface and very often away from ground-based regional specialized meteorological centers with the necessary instrumentation. State-of-the-art remote monitoring from space and modern cloud-resolving atmospheric modeling systems, which allow for data assimilation technique, have significantly improved the situation. However, so far the most reliable confirmation of TC formation is provided by direct measurements within a forming vortex. In order to collect data on emerging TCs, especially near the USA territory, one usually sends reconnaissance aircraft into the zone of potential cyclogenesis. Such flights committed to satisfy both operational and research requirements allow confidently confirming the fact of birth of a hurricane. But even in these cases, it is practically impossible to determine the exact time of TC genesis due to an absence of appropriate criterion for this event.

1.2. A way for determining the precise time of birth of a tropical cyclone

A solution to the problem has been proposed in our recent works. We have developed an approach, which allows us to determine the precise time of the start of TC genesis. This has been implemented by a cloud-resolving numerical analysis of the kinetic energy of the nascent vortex and demonstrated for several idealized RAMS (Regional Atmospheric Modeling System) simulations [3, 4, 5, 6, 7].

As a theoretical ground we applied a hypothesized (to date) interpretation of TC genesis as a large-scale instability caused by the mechanism of the turbulent vortex dynamo in the atmosphere [7, 8, 9]. In this context, tropical cyclogenesis is considered as a threshold extreme event in the helical atmospheric turbulence of a vorticity-rich environment of a pre-depression cyclonic recirculation zone. In order to trace and analyze processes of self-organization in the tropical atmosphere, which span scales from convective clouds with horizontal dimensions of 1-5 km to mesoscale vortices of hundreds of kilometers, we used data of cloud-resolving numerical simulations [10].

Summarizing the studies, we noted [7] that much remains to be done. A statistical analysis of moist convective atmospheric turbulence under conditions of TC genesis is necessary to conclusively justify the possibility of dynamo-process in the atmosphere and to determine the threshold for the beginning of large-scale instability. However, these labor-consuming researches can be carried out in parallel with the introduction of our proposed method for diagnosing the onset of TC genesis into the practice.

Based on the investigations carried out for idealized RAMS experiments [6, 7, 8], the key outcome to use in the practical forecast of observed vortices can be formulated as follows: the cyclogenesis commences when a forming vortex becomes energy-self-sustaining and intensifying. This event is marked by the start of mutual intensification of the tangential and transverse circulation and can perfectly be traced in the kinetic energy evolution. Our above formulation has somewhat in common with the definition of TC genesis given in [11]: “… tropical cyclogenesis has occurred when the tropical storm has become self-sustaining and can continue to intensify without help from its environment (external forcing).” However, there is an essential difference between the two. While in [11], TC genesis is diagnosed for a developed vortex of TS intensity, we detect the onset of large-scale
vortex instability much earlier, at the pre-depression stage, i.e., on the background of seemingly disorganized convection without a pronounced center of circulation and pressure fall in the examined area. This means that everything following, including TD and TS formation, and their further possible intensification occurs on the background of the progressing new instability and may even be its result.

2. Putting forward interpretation: cloud-resolving modeling of TC genesis (Montgomery et al., 2006) as a numerical examination of new pre-depression large-scale vortex instability

In 2004, near-cloud-resolving numerical simulation [1 2] brought an important discovery about the vortical nature of atmospheric moist convection in the tropical zone and identified rotating cumulonimbus clouds, which were called “Vortical Hot Towers” – VHTs. A year later, the VHTs were first confirmed by observation data got with use of airborne Doppler radar in the genesis phase of Hurricane Dolly (1996) [13]. This gave the authors [10] a reason to advance a new scenario of TC formation based on self-organization of convective processes in a favorable tropical environment.

2.1. Cloud-resolving RAMS modeling of tropical cyclogenesis (Montgomery et al., 2006)

A statement of the problem for numerical simulation in [10] was motivated by observed cases of TC genesis and included realistic meteorological conditions. The authors examined how a midtropospheric mesoscale cyclonic vortex, which often appears over warm tropical waters, might be transformed into a surface-concentrated tropical depression. The focus was on the role of VHTs in the formation of TD vortex. Numerical experiments were carried out using a nonhydrostatic version of RAMS with 2-3 km horizontal grid spacing on the finest mesh from three nested grids of the model. Initial conditions included a kinematic and thermodynamic environment favorable for TC genesis, namely, zero ambient mean flow and conditionally unstable troposphere overlying warm water with sea surface temperature (SST) ≥ 26°C [14].

In the context of our discussion, one more feature of numerical experiments [10] is worth to be noted. This is an initial local heating in order to create a warm bubble thereby stimulating cumulus convection. The local heating was applied for the first 300 s at low level \( z = 2 \) km, 50 km to the east of the center of initial mesoscale vortex and resulted in the warm bubble with temperature surplus 2 K.

Nineteen sensitivity experiments were carried out in [10] to thoroughly study the new scenario of TC genesis. The set included five categories to examine the impact of: (A) horizontal resolution; (B) convective and thermodynamic processes; (C) perturbations in initial mesoscale convective vortex (MCV) structure; (D) absence of latent/sensible heat fluxes or momentum fluxes at ocean surface; and (E) absence of Coriolis parameter.

In all the experiments, except experiment C1, in which the initial MCV vortex was absent, a tropical depression was formed. Moreover, in experiments A1 and A2 (differing from each other only in horizontal resolution, 2 km and 3 km, correspondingly), it was possible to observe further evolution with the successive formation of a tropical storm and a hurricane of the second intensity category. At the same time, the characteristics of the vortices formed at the TD stage, as well as the duration of TD development, distinctly depended on the initial conditions.

Thus, in the article [10] entitled “A vortical hot tower route to tropical cyclogenesis”, the authors presented an “upscale growth mechanism appears capable of generating a tropical depression vortex.” This scenario punctuated an enlargement of vorticity patterns from strongly three-dimensional convective structures of 10–30 km horizontally (VHTs and convective downdrafts) to the mesoscale ones of hundreds of kilometers (TD).

A comprehensive analysis, carried out in [10] for the new scenario of TC genesis, is essentially similar to the classical approach usually applied to studying diverse instabilities in fluid mechanics. The key point: what is this instability, leading to the TD formation in the tropical atmosphere?

2.2. A hypothesis on the turbulent vortex dynamo in the tropical atmosphere

Indeed, there exists an appropriate theoretical hypothesis on a large-scale vortex instability in the atmosphere – the so called “turbulent vortex dynamo” proposed in [15]. The hypothesis is based on
ideas about the self-organization of turbulence, which is characterized by the broken mirror symmetry and therefore, permits an inverse energy cascade in three-dimensional cases. A turbulent fluid medium with such break of symmetry is called helical and described mathematically by a quantity, which is well-known in fluid dynamics as helicity of the velocity field [16, 17]. Helicity is the scalar product of velocity and vorticity vectors. This quantity is a topological invariant, which measures the degree of linkage of the vortex lines and characterizes the departure from the mirror symmetry of turbulence. The sources of helical turbulence are known to be the force fields of a pseudovector nature, such as the Coriolis force field.

From the outset, the hypothesis in [15] was intended as a possibility to explain the generation of large-scale intense vortex structures in the atmosphere due to the inverse energy transfer from smaller scale motions. For example, in a case of TC formation in the Earth's atmosphere, cumulus cloud convection was considered as a main source of energy. A probable physical scenario for an excitation of large-scale helical-vortex instability [15, 18] emphasized an initial break of the mirror symmetry of turbulence, for example, due to a weak large-scale vortex disturbance. That is well consistent with the problem formulation in [10], which included an initial MCV, although the authors of the numerical study did not imply any connection with the concept of turbulent vortex dynamo. Moreover, as it was found in later analysis [9, 19] of numerical data, the initial local heating [10] was another factor breaking the mirror symmetry of atmospheric turbulence by intense helicity generation on cloud scales from the very first beginning.

A series of studies [3, 4, 5, 6, 7, 8, 9] followed aimed at bridging the turbulent vortex dynamo theory and problem of tropical cyclogenesis. The first discovery of the undertaken Russian-American collaboration [3], based on cloud-resolving atmospheric modeling [10], was the break of the mirror symmetry of atmospheric turbulence – non-zero helicity generation – during tropical cyclone formation. This gave us the impetus to further search for the large-scale helical-vortex instability.

Special attention was paid to the helicity generation on cloud scales. For this purpose, a kind of "filter" was applied allowing us to accurately localize the rotating convective flows. That was an analysis of the atmospheric field of vertical helicity, which is defined as the product of the vertical velocity and the vertical vorticity. As a result, the existence of a whole spectrum of cyclonically rotating deep convection-VHTs of different horizontal and vertical sizes and intensity was found. VHTs were regarded as vortical coherent structures that spanned more than half of the depth of the troposphere (see, figure 1(a)), which reaches 15-16 km in height in the tropics. Some of these helical structures were extremely strong and extended through the bulk of the troposphere. Their ascending vertical velocities sometimes exceeded 30 m/s. The key role of VHTs in TC formation was highlighted. They supply the energy from the warm ocean and operate as dynamical “staples”, which connect the primary and secondary circulation and provide the mutual intensification of them both.

The above efforts culminated in the summing review research article [7]. Based on “helical” post-processing of RAMS simulation data [10], the beginning of TC genesis has been interpreted as an onset of large-scale vortex instability, which distinctly precedes the TD formation. A numerical approach to diagnose an exact time of commencement of TC genesis has been proposed.

3. Detection of the pre-depression large-scale vortex instability

Further in the article, we are going to detail the procedure for detecting the pre-depression instability: first, on the basis of idealized modeling [10]. It is then important to illustrate a suitable place for this method in diagnosing observed TCs, for example, by choosing a recent one of the 2020 Atlantic season – Hurricane Isaias.

3.1. Cloud-resolving numerical diagnosis of the instability

Starting the post-processing of atmospheric simulation data [10], we already had extensive experience in the theoretical and numerical study of the vortex dynamo model [15, 18]. Moreover, having applied a special forcing we managed to imitate the new instability in the laminar Rayleigh-Bénard convection in an extended horizontal layer of rotating fluid and to develop a technique for the detection of
instability [20, 21]. A real success came when this carefully tested approach [18, 20, 21] proved to be fully workable for the analysis of atmospheric experiments [10].

The authors of the vortex dynamo [15] proceeded from the assumption that a developed TC is an intense mesoscale atmospheric vortex, in which the main component of velocity lies in a horizontal plane – figure 1(a); for the presented schematic two illustrations were borrowed and combined: Fig. 3 [22] and NASA visualization [23]. The powerful tangential (primary) circulation is superimposed on a weaker transverse (secondary) circulation formed by the radial and vertical velocity components (in the cylindrical coordinates). Meanwhile, the transverse circulation is of crucial importance for the existence of such vortical system as a whole and ensures an energy supply from the ocean. Following the proposed hypothesis, the effect of the vortex dynamo should generate a linkage of air streamlines, i.e., the helical structure of the large-scale flow and produce the positive feedback providing the mutual intensification of both circulations. In the rotating Earth’s atmosphere, a link is evident between the transverse and tangential circulation: it is provided by the action of the Coriolis force on the horizontal velocity. However, at the time the hypothesis appeared in 1983, it was completely unclear how the second link might be formed between the tangential and transverse circulation that is needed to close the feedback loop for the vortex dynamo effect.

Figure 1. Numerical diagnosis of pre-depression large-scale vortex instability: (a) schematic of the linkage of primary and secondary circulation through VHTs population; (b) evolution of the kinetic energy and vertical helicity.

Scenario of tropical cyclogenesis [10] emphasized the role of vortical convection and provided a basis to substantiate the vortex dynamo. This has been done and shown how the interaction of moist convection with vertical wind shear, occurring in natural atmospheric conditions, can be interpreted in terms of the mathematical model of the turbulent vortex dynamo in a convective system [6, 7, 8]. A process of generation of the linkage of horizontal and vertical vortex lines, observed during such interaction on cloud scales, was examined as well as the formation of the linkage of circulations on the vortex system-scale. The process was quantified by the helicity of the velocity field, which is a measure of the degree of linkage [16].

To detect the onset of large-scale vortex instability, the evolution of kinetic energy and helicity was examined [4, 5, 6, 7, 9] – figure 1(b). The only innovation introduced was that the energy of the primary and secondary circulation, \( E^P \) and \( E^S \), should be calculated separately. The analysis of the energetics made it possible to determine the time point \( G \) (genesis), when the mutual intensification of circulations started and the nascent TC became energy-self-sustaining.

There exists a necessary condition for intensification [4, 5, 6, 7, 9]: the mesoscale vortex system should become helical through the linkage of the primary and secondary circulation, which is accomplished by convective cloud-scale structures – VHTs. The helicity of the velocity field is a quantitative measure of the linkage (upper panel). At time \( G \), the integral (over the computational
domain) vertical helicity – the product of the vertical velocity and vertical vorticity – becomes sharply increasing. This can be interpreted as a linkage of circulations on mesoscale, giving birth to a global helical vortex system. The further evolution of the vortex leads to the formation of a tropical depression (TD) over the next few hours. Throughout the whole TC lifetime, VHTs act as dynamical “staples”, providing the linkage of circulations. Thus, the positive feedback loop linking the tangential and transverse circulation is realized through population of VHTs.

Further discussion is aimed at using the diagnostic approach [4, 5, 6, 7, 9], which originated from analysis of idealized simulation, to directly detect the pre-depression instability in observed tropical cyclones. Therefore, let us focus on several specific aspects needed for meteorological diagnosis.

3.2. Formation of the secondary circulation
As it has been discovered and emphasized [4, 5, 6, 7, 9], the large-scale helical-vortex instability emerges against the background of the developing secondary circulation and nearly simultaneously with it. This means that the new instability appears against the background of disorganized convection, still in the absence of such helpful cyclone identity signs as a pronounced pressure fall and a well-defined center of developing circulation. Therefore, this is a challenging task for diagnosis based on the analysis tools commonly used by meteorologists to track the development of hurricanes. Given the experience gained in numerical modeling, a new and fairly easily implemented technique can be recommended.

To illustrate our recommendation, let us note some significant points that can also serve as a basis for atmospheric diagnosis of the pre-depression instability.

Foremost, this concerns the formation of the secondary circulation (SC). This process was analyzed in detail [4, 5, 6, 9] for four experiments from [10]: A2, B1, C3, and E1 – table 1.

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

In all experiments, a transformation of the midtropospheric vortex into a surface-concentrated tropical depression was observed. The evolution of the cyclone from a tropical depression (TD) through a tropical storm (TS) and up to a hurricane (H) occurred during 72 hours of the computational time only in A2. In experiments B3, C3, and E1, any further intensification of the formed TDs did not happen during the same time.

Table 1. Pre-depression large-scale vortex instability.

| Experiment | Time (h) | Max Vertical Helicity (ms$^{-2}$) | Genesis Instability Start Time (h) | Tropical Depression Time (h) | $V$ (ms$^{-1}$) |
|------------|----------|----------------------------------|-----------------------------------|----------------------------|----------------|
| A2         | 10       | $1.3 \times 10^{3}$              | 12                                | 16                         | 9.4            |
| B3         | 38       | $6.1 \times 10^{3}$              | 40                                | 48                         | 8.8            |
| C3         | 18       | $1.4 \times 10^{3}$              | 18                                | 26                         | 7.5            |
| E1         | 8        | $5.2 \times 10^{3}$              | 10                                | 20                         | 8.2            |

Until recently [7], the author did not pay special attention to one common feature that was observed in all the above numerical experiments. Meanwhile, it now appears to be of crucial importance for the early detection of instability. An additional impetus was given by tracking the formation of Hurricane Isaias (2020) since the emergence of the disturbance in the tropical Atlantic Ocean. Presumably, this feature can also be detected using GOES (Geostationary Operational Environmental Satellite) Image Viewer (https://www.star.nesdis.noaa.gov/GOES/). Let us start with discussion of the numerical detection.
3.2.1. Vertical helicity field as a tool to localize vortical convection. In our numerical analysis [4, 5, 6, 9], a new method was developed and applied, which allows localizing rotating convective flows. To this purpose, we used the helicity density (not an integral unlike [24]), i.e., helicity values calculated in each point of the finite-difference grid – \( h \), specifically, its vertical spatial contribution \( h_z \).

\[
h = \mathbf{V} \cdot \mathbf{\omega} = u \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) + v \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) + w \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right).
\]

Helicity density is a pseudoscalar quantity [16, 17], i.e., it can be both positive and negative. In a right-handed Cartesian or orthogonal curvilinear frame, positive helicity density will be generated in the moist atmosphere by cyclonic updrafts and/or anticyclonic downdraft motions. Similarly, negative helicity will be generated in the case of anticyclonic updrafts and/or cyclonic downdraft flows. By combining this with vertical velocity analysis, upward and downward rotating flows can be easily distinguished.

The values of vertical helicity for VHTs, presented in table 1, were calculated in Cartesian coordinates. They found to be the maximal ones over the computational domain, the lower 13 km of which are shown in figure 2(a).

![Figure 2. Vertical helicity field (1) in experiment A2 [10]: (a) \( t = 8 \, \text{h}, \, z = 1, 4, 7, 10, 13 \, \text{km}; \) (b) the upper level of computational domain 276 km × 276 km at \( z = 13 \, \text{km} \) is shown at \( t = 8, 12, 16 \, \text{h}. \)](image)

The vertical helicity field can serve as a kind of filter for recognizing rotating convective cells. To adjust the resolution of such a filter, the values in table 1 can be taken as a useful guide. For example, this method has been successfully applied in numerical modeling of a quasi-tropical cyclone over the Black Sea (September, 2005) and allowed the detection of multiple vortical convective cores [25].

3.2.2. A VHT \( \geq 13 \, \text{km} \) in height gives start to the formation of the secondary circulation (SC). Our analysis revealed that in all four experiments, the SC formation started with emergence of an intense VHT about 13-14 km in height. Such notable feature can be identified not only in idealized numerical simulation but also in satellite monitoring – figure 3.
Analysis of both the SC development and emergence of large-scale instability was carried out with a time increment of 10 minutes in A2, B3, C3, and E1. Characteristics were calculated in the computational domain of 276 km × 276 km × 20 km – figure 2 (the upper 7 km are not shown). Throughout the post analysis the vertical increment was equal to 500 m. For diagnostics, we applied calculations in Cartesian coordinates as well as an examination of the system-scale dynamics from a traditional vortex-centric perspective when the Cartesian model data were transformed into a local cylindrical coordinate system. We used the “Diagnostic Package” developed and described in [10].

At the pre-depression stage analyzed in this study, the center of computational domain was utilized as the system-scale center. A set of diagnostic fields (not presented in this paper) to study the SC and TD formation included azimuthal averages of radial wind, tangential wind, vertical velocity, diabatic heating rate, vertical vorticity, and vertical helicity. The first five of them were similar to those ones shown in figures 4 and 5 [10] for experiment A1. Multiple views of diagnostic fields for experiment A2, including azimuthal averages of helicity field, can be found in [9]. Detailed discussion of the diagnostic procedure for TD formation is presented for experiment A1 in [10], and for A2 in [9].

In this paper, let us focus on the SC formation and try to adjust it to atmospheric observations. This is aimed at catching early signs, favoring the emergence of new instability, on the basis of meteorological tracking data. To this purpose, the 3D field of vertical helicity with localized VHTs is shown in figure 2.

Figure 2(a) presents a “critical for SC formation” VHT found in experiment A2. The growing of this vortical cell started from height of 4 km near \( t = 5 \) h of experimental time. The tower reached 7 km in height at \( t = 6 \) h and 10 km at \( t = 7 \) h. However, only till \( t = 8 \) h, shown in figure 2(a) and figure 2(b) (upper panel), the VHT became strong enough to initiate a weak radial inflow at low levels up to 3 km. This gave a start to the SC development.

Over the next four hours, a stable system-scale SC was formed of hundreds of kilometers horizontally and spanning the entire troposphere up to 13-14 km in height. The circulation included a radial inflow near the surface and in the middle troposphere, rising flow in the center and radial outflow in the upper levels. At \( t = 12 \) h, the SC was sustained by the strong VHT and a few of horizontally smaller and less intense rotating convective cores, reaching also up to 13 km in height – figure 2(b). This population of VHTs provided the linkage of the primary and secondary circulation on the system scale what gave the start to the large-scale instability.

A similar scenario of SC formation was observed in three other experiments – B3, C3, and E1, for which the corresponding times of key events are given in table 1.

3.2.3. Several VHTs \( \geq 13 \) km in height may signal the possible start of large-scale instability. The onset of instability in all four experiments was characterized by very much alike pattern of the vertical helicity at \( z = 13 \) km, which is presented for experiment A2 at \( t = 12 \) h in figure 2(b).

The similarity of the helicity patterns was also noted during the TD formation in all experiments under discussion. The corresponding helicity field in A2 is shown at \( t = 16 \) h in figure 2(b).

The presented localization of the VHTs in the vertical helicity field (figure 2) hinted us an idea to compare the above discussed data with the meteorological fields obtained using the GOES Imagery. This was tried for the Hurricane Isaias (2020).

3.3. A simple way to recognize the tropical environment conducive to the large-scale vortex instability

The GOES Imagery is a useful tool in retrievals of cloud top height. It allows estimating cloud height based on the temperature of its top. Thus, while our numerical simulation provides VHTs detection in the vertical helicity field, GOES Imagery can help localize them in the temperature field. Bearing this in mind when tracking a tropical disturbance, one can analyze satellite data with a special focus on cloud tops about 13 km and higher – the so called “overshooting cloud tops.”

This was tried at the end of July 2020 to observe the arising tropical disturbances in the Atlantic basin. To this purpose, the NHC website [1] and the references therein were very helpful.

Hurricanes often originate from developing tropical waves that represent areas of disturbed weather
over the open ocean [2]. Such vigorous easterly wave off the coast of Africa, which was first identified by NHC on July 23, later gave birth to TS Isaias [1]. When traveling over warm tropical waters, the wave developed a broad area of low pressure and intensifying convection, and became more organized. This is well consistent with scenario of TC genesis in easterly waves [2]. Meanwhile, on July 28, satellite data showed that the system, approaching the Leeward Islands, did not have a well-defined center. This resulted in greater than average uncertainty regarding both the short-term and longer-term track, and intensity forecast. At the same time, surface observations suggested gale-force winds about 15-18 ms$^{-1}$. Therefore, a threat of TC genesis prompted to designate Potential Tropical Cyclone Nine at 15:00 UTC on July 28. However, the situation continued to remain very uncertain, since the Air Force Reserve reconnaissance aircraft, several hours later, also failed to detect a well-defined center of circulation.

With its acquired potential status, the cyclone still remained near U.S. Virgin Islands and Puerto Rico on July 29 – figure 3; winds $\approx 20$ ms$^{-1}$. As a formed tropical cyclone it was identified only at 03:00 UTC on July 30 and at the stage of tropical storm with winds approximately 23 ms$^{-1}$. The vortex named TS Isaias was located to the South of Puerto Rico – 250 km, and Dominica – 430 km.

Figure 3. Infrared satellite images on 29 July 2020: (a) 0900 UTC; (b) 1200 UTC. The color bar represents brightness temperature (°C). Dark red and black color is a manifestation of very strong updrafts, which reach the tropopause and can penetrate into the lower stratosphere.

Based on the author’s observations, the first overshooting cloud tops appeared (correspondingly, with both possible, formation of the secondary circulation and following large-scale vortex instability), when the disturbance was approaching the Leeward Islands on July 28. Highly likely, that the pre-depression instability was under way in the forming vortex passing near Puerto Rico – figure 3. In this case, TS Isaias could have been designated 15-18 hours earlier.

Hurricane Isaias is likely to be studied using high-resolution numerical models. In such studies, a combination of our approach with the paradigm of tropical cyclogenesis in an easterly wave critical layer (see [2] and references therein) can be recommended. This allows locating an area, where the highest space resolution should be applied for the diagnosis of the large-scale helical-vortex instability.

4. Conclusions

Giving our interpretation for tropical cyclogenesis as a large-scale instability based on the vortex dynamo effect, we propose to detect its emergence by combining high-resolution cloud-resolving
numerical atmospheric modeling and GOES Imagery. The developed numerical approach allows identifying the precise time when the cyclogenesis commences, marked by the start of mutual intensification of the tangential and transverse circulation in a forming vortex. Numerical examination of the processes on cloud scales has revealed what the environment should be, conducive to the onset of instability, and identified several milestones in the evolution of instability. In the present work, a preliminary trial is intended to show how the found milestones can help in the search for instability using satellite data. It is believed that after thorough investigation, collecting statistics on a large number of tropical cyclones, and summing all the results, it will be possible to confidently identify the instability only on the basis of satellite imagery.

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