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Tropical cyclogenesis: a numerical diagnosis based on helical flow organization

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Abstract. A numerical diagnosis for tropical cyclogenesis is proposed based on near-cloud-resolving atmospheric simulation. Calculation and analyses of helical and energetic characteristics together with hydro- and thermodynamic flow fields allow the diagnosis of tropical cyclogenesis as an event when the primary and secondary circulations become linked on system scales thereby making the nascent large-scale vortex helical. A key process of vertical vorticity generation from horizontal components and its amplification by special convective coherent structures - Vortical Hot Towers (VHTs) - is highlighted. The process is found to be a pathway for generation of a velocity field with linked vortex lines of horizontal and vertical vorticity on local and system scales. The role of VHTs as connectors of the primary and secondary circulation is emphasized.

1. Introduction
In our works of 2009–2012, a numerical approach was developed and applied for analysis of helical features of the vortex velocity field generated during tropical cyclone (TC) formation. The main energy supply for tropical cyclones is provided from the ocean via latent and sensible heat fluxes (primarily latent fluxes). The supply is realized as cumulus convection. Recently, a long-standing idea on self-organization of convective processes in the tropical atmosphere under kinematically and thermodynamically favorable environmental conditions found a confirmation in a new scenario of tropical cyclogenesis proposed by Montgomery et al. (2006) and illustrated by high resolution (2-3 km horizontal grid spacing) direct numerical simulation by use of the Regional Atmospheric Modeling System (RAMS). The work demonstrated how a mesoscale tropical depression vortex could develop from cumulonimbus convection as a result of system-scale convergence and upscale vorticity growth. The first investigation of TC formation from the perspective of helical features of atmospheric flows of different scales, which contributed to the organization of the cyclone (helical self-organization) was conducted by Levina & Montgomery (2010). Using the data of near-cloud-resolving numerical simulation (Montgomery et al., 2006), helical characteristics of the velocity field were calculated and analyzed. It has been discovered that the process of hurricane formation is accompanied by the generation of nonzero and increasing helicity in moist convective atmospheric turbulence that implies a new topology of the flow when it is characterized by...
linked vortex lines (Moffatt, 1969). This means a break of the mirror symmetry of atmospheric turbulence when, following the theory of turbulence (Frisch, 1995), a large-scale vortex instability is possible.

Analysis of processes of vorticity and helicity generation on cloud convection and system scales was carried out in Levina & Montgomery (2011); Levina (2013) and revealed a new role of deep cumulonimbus rotating cores (Vortical Hot Towers – VHTs). While the work of Montgomery et al. (2006) showed that the convection could amplify pre-existing cyclonic vorticity and induce concentrations of vorticity much larger than that of the aggregative vortex, it was found by the foregoing studies that from the very first hours of TC formation, VHTs provided intense helicity generation on their local scales by linking horizontal and vertical components of vorticity. Further, a developing population of VHTs of different size and intensity (e.g., illustrated by Figure 1) created the secondary overturning circulation and sustained it during subsequent TC evolution. Moreover, VHTs linked the primary tangential and secondary overturning circulation on system scales (Figure 2) thereby providing the spiral structure and integrity of the evolving large-scale vortex. As soon as such linkage occurred, the nascent large vortex underwent a self-sustaining amplification process.

Figure 1. Hot Towers in Hurricane Bonnie 1998. Altitude of clouds is exaggerated. (Wikipedia, 2013).

Figure 2. Scheme of the linkage of primary and secondary circulation. A composite TC is borrowed from (Emanuel, 2003).

In the present paper, we demonstrate how the VHTs work to form the secondary circulation, generate helicity and provide the linkage of the tangential and overturning circulation. By means of quantitative analysis, we substantiate that such linkage provides a positive energy feedback between these two circulations. The results are suggested to support the hypothesized model of a large-scale, helical-vortex instability that operates over the ocean in which sufficient moisture fluxes maintain convective instability. Based on this perspective we offer a numerical diagnosis for tropical cyclogenesis.

2. Helicity of the velocity field: a hypothesis on the turbulent vortex dynamo

Helicity of the velocity field is a pseudoscalar quantity defined as the scalar product of velocity \( \mathbf{V}(\mathbf{r}, t) \) and vorticity \( \text{curl}\mathbf{V}(\mathbf{r}, t) \) vectors (Moffatt, 1969). More knowledge on helicity and helical turbulence can be gained in (Moffatt & Tsinober, 1992; Levina et al., 2000; Levina, 2013) and references therein. The volume integral calculated in a specific space domain,

\[
H = \int \mathbf{V} \cdot \text{curl}\mathbf{V} \, d\mathbf{r},
\]

(1)
gives the helicity of vortex system, where \( \mathbf{V} \cdot \text{curl}\mathbf{V} \) 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 (Moffatt & Tsinober, 1992).
A non-vanishing helicity implies the symmetry break of turbulence with respect to coordinate system reflections (Moffatt, 1978; Frisch, 1995). The mean helicity, like energy, is an inviscid quadratic constant of motion in barotropic fluids.

However, unlike energy the helicity can be both positive and negative. Its sign determines the predominance of the left-handed or the right-handed spiral motions in the examined flow. If we choose a right-handed Cartesian or orthogonal curvilinear frame for our further consideration, positive mean helicity will be generated in the moist atmosphere under the predominance of cyclonic updrafts and/or anticyclonic downdraft motions. Similarly, negative helicity will be generated for the case of anticyclonic updrafts and/or cyclonic downdraft flows.

Helicity is one of the most important characteristics for describing the structure of vortex fields. This quantity is a topological invariant, which measures the degree of linkage of the vortex lines (Moffatt, 1969, 1978; Moffatt & Tsinober, 1992; Frisch, 1995). The sources of helical turbulence are known to be the force fields of a pseudovector nature, such as magnetic or Coriolis force fields.

In the theory of turbulence, there exists a fundamental hypothesis about a small-scale helical turbulence that under certain conditions may evoke a large-scale instability governing the structure formation.

Thirty years ago in paper (Moiseev et al., 1983), a hypothetical scenario for intensification and sustaining of large-scale vortex disturbances in the atmosphere due to energy transfer from small-scale helical convective turbulence – the helical-vortex instability or so called turbulent vortex dynamo – was proposed as a possible illustration for self-organization of turbulence with the broken mirror symmetry. The theoretical estimates obtained by substituting the specific atmospheric parameters in solutions (Moiseev et al., 1983) were tested to describe tropical cyclone formation in the Earth’s atmosphere as well as to explain the size and structure of large-scale long-lived vortex disturbances in Jovian atmosphere after the collision of comet Shoemaker-Levy 9 with Jupiter in July 1994. The theory showed a very good agreement with the characteristics of observed phenomena in the atmospheres of both planets. A summary of those results was given in a review work by Levina et al. (2000).

A proposed physical scenario for the helical self-organization (Moiseev et al., 1983; Levina et al., 2000) supposed 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 (Montgomery et al., 2006), where simulations started with a pre-cursor mesoscale cyclonic vortex. The incipient process of helical self-organization would have to reveal itself in the non-zero mean helicity generation and consequent increasing of its level. Large helicity should suppress the energy flux to the scale of dissipation due to weakening of nonlinear interactions (Lilly, 1986), thereby favoring an energy accumulation in the inertial range, and then, its transfer to larger scale motions. In this connection, an inverse cascade or nonlocal energy transfer was expected to exist in developed helical turbulence. Under such circumstances, the flow patterns could exhibit a merging of small-scale turbulent cells and such an upscale growth would ultimately contribute to the organization of larger-scale structures.

As a sign that could help to precisely identify genesis of large-scale atmospheric vortex, one envisioned to have an emerging linkage of the system-scale primary (tangential) and secondary (overturning/transverse) circulation in a forming vortex structure. A schematic of such linkage is shown in Figure 2. The authors (Moiseev et al., 1983; Levina et al., 2000) anticipated that the linkage should result in a “helical” feedback between the system-scale circulations that would mean a mutual intensification of both circulations due to energy influx from small-scale moist convective helical turbulence. The initiation of such helical feedback would make the emerging large-scale vortex energy-self-sustaining. Thus the moment of time corresponding to the emergence of the feedback process could be considered as the genesis event for a tropical cyclone.
3. Numerical approach to identify the helical-vortex instability in the atmosphere
A numerical approach for investigation of large-scale helical instability in the atmosphere was proposed in (Levina, 2006; Levina & Burylov, 2006) and first applied in a simpler case, namely, to simulate helical-vortex effects in laminar Rayleigh-Bénard convection by use of an additional helical force. Those simulations demonstrated effects, which were qualitatively new and appeared in a crisis manner. A nonzero helicity of the flow was generated, and after exceeding some its value, the large-scale vortex instability appeared. A key role in the process the vertical component of velocity played, and the corresponding evolutionary equation in the mathematical model (Levina, 2006; Levina & Burylov, 2006) closed a positive feedback loop. The instability evolution observed as an enlargement of horizontal scales of structures what happened by merging of helical vortex cells. The process was accompanied by flow intensification in newly forming larger vortices, similarly to that observed in atmospheric modeling (Montgomery et al., 2006), which was based on hydro-thermodynamic equations for the atmosphere.

It should be particularly pointed out about a distinct enhancement of the heat transfer discovered in experiments (Levina, 2006; Levina & Burylov, 2006). The heat flux through a layer increased with an increase in mean helicity of the flow. A sharp intensification of heat transfer observed after exceeding the threshold of stability, and later during the instability evolution, after each merging of vortex structures. Thus, the effectiveness of heat transfer increased due to two factors, namely, increase in the mean helicity and decrease in a cell number of the convective system. Such energetic expedience suggests to us that a most effective “removal” of accumulating heat might be possibly one of the reasons for helical self-organization of convection in tropical cyclogenesis.

One of the most promising results of the applied approach was that it demonstrated how the onset of large-scale helical-vortex instability could be identified by examining helicity and kinetic energies of the tangential and overturning circulation.

In this paper, we are presenting a very similar analysis of helical and energetic characteristics based on high resolution atmospheric data and aimed at diagnosing TC genesis.

4. A key interaction between convection and vertical shear of horizontal wind
In paper (Montgomery et al., 2006), a dipolar structure of the vorticity anomalies was found that was approximately colocated with the hot towers and an explanation was given of how such vertical vorticity anomalies might be produced. The following vorticity generation mechanism was proposed: The initial mesoscale convective vortex (MCV), with which simulation (Montgomery et al., 2006) starts, provides an environment rich in horizontal and vertical vorticity. As the first updraft forms due to evolving convective instability, it tilts ambient horizontal vorticity into the vertical while at the same time stretching MCV generated vertical vorticity. As the 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. At later times in the simulation(s) the convergence/stretching of near surface (0 < z < 2 km) vorticity by the convective plumes dominates the generation of vorticity by tilting processes.

A rudimentary understanding of the cloud-scale dynamics at early times can be obtained by examining the evolution of the updrafts (Montgomery et al., 2006). Thus, the simulation in Experiment A2 “3 km”, which is discussing in this paper, was initialized with a weak midlevel vortex elevated above the sea surface, with a maximal mean tangential wind at z = 4 km. At radii less than 75 km, the main vortex has a basic-state cyclonic tangential velocity field that increases in magnitude with height below z = 4 km and decreasing above. Ignoring buoyant effects for the time being, we can consider the horizontal vorticity profile at the initial time as being due solely to the vertical wind shear of the initial MCV. As sketched in Figure 3, this 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) \( z = 4 \) km. As positive vertical vorticity is generated in the region of an updraft, vortex tube stretching further intensifies the positive vorticity anomaly. The corresponding VHT’s vorticity dipole structure found in (Montgomery et al., 2006) exhibited just this orientation and magnitude difference, supporting the proposed mechanism. Unlike the tilting term, however, the intensification of vertical vorticity by stretching can be exponential if the convergence is approximately constant during the parcel’s ascent through the tower.

**Figure 3.** Schematic of vortex tilting within the initial MCV. 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) \( z = 4 \) km. The figure is borrowed from (Montgomery et al., 2006).

The described mechanism of horizontal vorticity transformation into the vertical one by a developing convective updraft was also interpreted in (Levina & Montgomery, 2011; Levina, 2013) as an effective way for generation of the linkage of vortex lines of horizontal and vertical components of vorticity, i.e., helicity generation. In work by Levina (2013), a comprehensive quantitative analysis was carried out for this process by using the data of six numerical experiments of Montgomery et al. (2006). Thus, it was found that maximal values of mean helicity generated by the interaction between the very first updraft and MCV within the initial two hours of those experiments were between \( 2.0 - 3.5 \times 10^{11} \) m\(^4\) s\(^{-2}\).

5. Numerical analysis: helical and energetic characteristics
Post-processing of the numerical simulation data of Montgomery et al. (2006) was carried out on the finest of three nested computational grids for subsequent times with a time increment of 10 minutes during 72 hours of numerical experiment. Characteristics were calculated in the computational domain of \( 276 \times 276 \times 20 \) km\(^3\), at first, in Cartesian co-ordinates \((x, y, z)\) by use of uniform finite-difference grid with increments \( \Delta x, \Delta y, \Delta z \). Throughout the post analysis the vertical increment was identical and equal to 500 m; the horizontal increments were \( \Delta x = \Delta y = 3 \) km for numerical experiments discussed in this paper.

We also applied an analysis of system-scale dynamics from a traditional vortex-centric perspective when the Cartesian model data were transformed into a local cylindrical coordinate system. For these purposes we used the “Diagnostic Package” developed and described in (Montgomery et al. (2006), Appendix B).
For our investigation, let us choose a number of helicity and energy characteristics. Between them are: helicity density field, i.e. helicity calculated in each grid point; mean helicity, i.e., helicity density integrated over the computational domain and averaged by a number of grid points, together with its integrated spatial contributions

\[ \mathbf{V} \cdot \nabla \mathbf{V}, \quad < H >, \quad < H_{\text{hor}} >, \quad < H_{\text{ver}} >. \tag{2} \]

In real atmospheric conditions there always exists a definite preferred direction due to gravity. It makes reasonable to introduce in our investigation vertical and horizontal helicity, the latter as a sum of two spatial horizontal contributions. In the subsequent discussion we will use terms “total helicity”, “horizontal helicity”, and “vertical helicity” for \(< H >, < H_{\text{hor}} >, \text{and } < H_{\text{ver}} >\), correspondingly. As it was analyzed and noted (Levina, 2013), non-zero total/horizontal helicity could be generated even when the vertical contribution of helicity vanished. However, that is only possible when the horizontal wind is changing with height, i.e., the occurrence of vertical shear of the horizontal wind. Thus, non-zero horizontal helicity can be considered as a sign of existing or emerging shear flow. Non-zero vertical helicity, being a product of vertical velocity and vorticity, is an indicator of the presence of vortical convection in the examined area.

To identify an emerging energy feedback between the primary and secondary circulation in the forming TC, we use the following set of kinetic energy characteristics:

\[ E = \frac{1}{2} (\mathbf{V})^2, \quad < E >, \quad < E^P >, \quad < E^S >, \tag{3} \]

which include \( E \) – kinetic energy density, and \(< E >\) – averaged full energy in Cartesian coordinates; as well as separate averaged energy contributions calculated in cylindrical coordinates: of the primary tangential field, \(< E^P >\), and secondary, \(< E^S >\), formed by the radial and vertical components of velocity.

6. Diagnosis of TC genesis
Let us now examine how tropical cyclogenesis can be identified based on the new knowledge (Levina & Montgomery, 2010, 2011; Levina, 2013) on helical flow organization and pivotal role of VHTs in this process.

In the majority of numerical experiments (Montgomery et al., 2006), a weak tangential circulation existed in low and mid troposphere (with a maximal tangential wind between 4 and 5 km altitude) from the very first beginning due to the initial MCV. The secondary circulation in six experiments examined in (Levina, 2013) appeared after several hours of flow development as a result of self-organization of vortical cloud convection or did not appear at all in unfavorable environment (Expt. C1, no initial MCV). The time interval needed for the secondary circulation to emerge depended on initial conditions. It should be noted that unlike initially organized tangential circulation, radial and vertical flows contributing to the secondary circulation are chaotic and weak enough during an initial time span. Nevertheless, such motions result in a small non-zero kinetic energy, \(< E^S > \neq 0\). In order to diagnose an emerging secondary circulation, azimuthally mean fields of radial and vertical flow components will be analyzed as well as a number of other hydro- and thermodynamic mean fields.

Let us choose for diagnosing purposes, for instance, Experiment A2 “3km” of (Montgomery et al., 2006). We will use kinetic energy and helicity characteristics (Fig. 4) as well as a set of other data gained from snapshots of spatial velocity, vorticity, helicity and temperature fields at horizontal and vertical cross-sections (not shown). To obtain azimuthal mean values the procedure applied in (Montgomery et al., 2006) was used.

The Expt. A2 started with kinetic energy of the primary tangential circulation, \(< E^P >\), equal to \(0.45 \times 10^{16} \text{ m}^5 \text{ s}^{-2}\) (Fig. 4), entirely generated by the initial MCV, which had the
maximum mean tangential wind 6.8 m s$^{-1}$ at $r = 75$ km and $z = 4$ km. At the lower surface, the initial MCV had a relative vorticity of $O(1 - 2 \times 10^{-4}$ s$^{-1}$). Initially, the secondary transverse circulation was absent that implied vanishing kinetic energy, $< E^S > = 0$. The maximal value of total helicity, $< H >$, generated by the initial conditions in this experiment was $3.3 \times 10^{11}$ m$^4$ s$^{-2}$ (Levina, 2013). This is an order of magnitude higher than $2.0 \times 10^{10}$ m$^4$ s$^{-2}$, which was found insufficient for initiating the upscale organization in Expt. C1 (no initial MCV).

**Figure 4.** TC genesis at $t \sim 10$ h – the linkage of the primary and secondary circulation makes the forming vortex an integral helical system which undergoes self-sustaining amplification process. Vortical convection activity is illustrated by the vertical helicity in the upper panel.

During the first 10 hours, the tangential circulation is slightly weakening against its initial energy value (Fig. 4) and the maximal tangential wind undergoes a decrease from 6.8 m s$^{-1}$ to 6.0 m s$^{-1}$, whilst $< E^S >$ becomes slowly increasing near $t = 5$ h. Our examination of the vertical velocity and vorticity fields confirmed a weak thermoconvective activity with no strong rotating updrafts at that time.

A few rotating convective flows become visible (with maximal vertical velocity about $2.5$ m s$^{-1}$ and cyclonic vertical relative vorticity $3.0 \times 10^{-3}$ s$^{-1}$ at $z = 1$ km) at $t = 6$ h. Near this time a process of merging of convective cells starts. This phenomenon was described in detail, analyzed quantitatively and interpreted in (Montgomery et al., 2006) as a manifestation of upscale organization of atmospheric rotating moist convection. The process of merging is 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. Convective activity is progressing during $t = 6–9$ h when a whole population of convective updrafts emerges, which interact with each other by merging, and result in more intense structures. At this time, one can observe a few cyclonically rotating convective cores - vortical hot towers (VHTs) of different horizontal and vertical sizes and intensity (the maximal vertical velocity and vorticity during these few hours are increasing up to $3.5$ m s$^{-1}$ and $5.0 \times 10^{-3}$ s$^{-1}$, correspondingly, at $z = 1$ km). Within this time interval the most intense updrafts have 5–10 km in diameter and are growing gradually with time in height from 4–6 km up to 8–10 km.
The rotating convective cells start to generate (near $t = 7-8$ h) a non-vanishing and increasing third (vertical) contribution of helicity (Fig. 4, upper panel) and, thereby, a local linkage of vortex lines of horizontal and vertical flow components in a vicinity of each rotating updraft.

Each rotating convective structure contributes simultaneously to both the tangential and overturning circulation, namely, by its vertical vorticity to the former and by its vertical motion to the latter. Thus, such structure represents a natural link between the circulations on its local scale whilst their developed population should help link the primary and secondary circulation on the system scale.

To measure a degree of such linkage is just the main function of the quantity introduced above and known as “helicity”.

Thus, in our case, an increase in the vertical contribution of helicity from zero up to approximately $5.0 \times 10^9 \text{ m}^4 \text{ s}^{-2}$ within 6–9 h results in an amplification of horizontal/total helicity from $1.5 \times 10^{11} \text{ m}^4 \text{ s}^{-2}$ up to $3.0 \times 10^{11} \text{ m}^4 \text{ s}^{-2}$. Just at this time, $t = 6$ h, a slight yet distinct increase in the kinetic energy $E^S$ starts.

Near $t = 10$ h dramatic changes in the flow intensity attract our attention – kinetic energy of the transverse circulation, $E^S$, increases sharply and soon after this, kinetic energy of the tangential circulation, $E^P$, becomes increasing as well (Fig. 4). This emerging mutual intensification of both circulations marks a critical point in a process of TC formation when the vortex becomes self-sustaining. The time after which both $E^S$ and $E^P$ mutually increase may be considered a practical definition for the moment of tropical cyclogenesis.

In order to identify reasons which are behind the observed phenomenon, let us search for explanations in corresponding flow structure and dynamics. Indeed, an intense helical updraft–VHT of about 14 km in height appears just at that time, $t = 10$ h (Fig. 5b,6-left).

![Figure 5](image.png)

**Figure 5.** Azimuthal averages of radial wind, and vertical velocity at $t = 10$ h (a, b), and $t = 12$ h (c, d). The zero contour is omitted. Negative contours are dashed.

The VHT is found to be strong enough to generate a large transverse circulation, of tens of kilometers in horizontal directions and throughout the whole troposphere layer up to 14 km in height – Fig. 5a,b). This gives start to the formation of stable system-scale (hundreds of kilometers horizontally) secondary circulation during $t = 10–12$ h. In Fig. 5c,d plotted for
t = 12 h, one can see the already formed transverse circulation with a pronounced low and middle level inflow, developed rising flow and upper level outflow. The circulation is sustained and linked with the primary circulation by the strong VHT and a number of smaller and less intense rotating convective flows (Fig. 6-right).

Since this point one can observe (Fig. 4) consequently increasing intensity of both the primary and secondary circulation with time, yet, interrupted periodically (∼24 h) due to diurnal cycle. This indicates that a positive feedback has formed between the circulations and resulted in a developing large-scale vortex instability. The feedback is sustained by convective instability and vortical convection in the central region of the circulation. The convective instability there is maintained primarily by latent heat fluxes from the underlying sea surface, which need not increase with wind speed (Montgomery et al., 2009; Montgomery & Smith, 2013). The existence of such rising warm flows suggests a release of potential energy that is converted into kinetic energy of developing large-scale helical vortex. The active feedback provides energy exchange between the primary and secondary circulation and their further mutual intensification. From a vorticity perspective, during the amplification of the system-scale circulation, the cyclonic vorticity consolidates via multiple diabatic vortex mergers and system-scale convergence of ambient and convectively-generated vorticity. The merging of cyclonic vorticity anomalies occurs also via the more familiar dry adiabatic vortex merger of convectively-generated vortex remnants.

Figure 6. Helicity density (×10^{-4} m s^{-2}) in three horizontal cross-sections of 276×276 km^2 at z = 1, 4, 7 km, at t = 10 h (left) and t = 12 h (right).

The foregoing applied analysis suggests that diagnoses using helicity may help provide an answer to the important question of when will cyclogenesis commence given a favorable tropical environment? The findings here indicate that when the primary and secondary circulations become linked by vortical hot towers, the nascent vortex becomes helical. With adequate moisture fluxes from the underlying sea surface to maintain a degree of convective instability in the cumulus zone, the conditions are then set for a self-sustaining amplification process of the system-scale circulation.
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