Faculty and Researchers | Faculty and Researchers' Publications

2011

# Helical scenario of tropical cyclone genesis and intensification

Levina, G.V.; Montgomery, M.T.

# Helical scenario of tropical cyclone genesis and intensification

**G V Levina**[1,2] **and M T Montgomery**[3,4]

[1] Institute of Continuous Media Mechanics, Ural Branch of the Russian Academy of Sciences, Akademik Korolyov Street, Perm 614013, Russia
[2] Space Research Institute, Russian Academy of Sciences, Moscow, Russia
[3] Department of Meteorology, Naval Postgraduate School, Dyer Road, Monterey CA 93943-5114, USA
[4] Hurricane Research Division, NOAA, Miami, FL, USA

E-mail: `levina@icmm.ru` , `mtmontgo@nps.edu`

**Abstract.** A helical scenario of tropical cyclogenesis and further vortex intensification is proposed based on results of direct numerical simulation of atmospheric flows. The main idea of the scenario consists in a specific topology of helical flows which are characterized by the linkage of vortex lines. Velocity fields resulting from a high resolution numerical simulation by the Regional Atmospheric Modeling System (RAMS) are used to calculate helical and integral characteristics during a tropical cyclone formation. It is shown how non-zero mean helicity is generated by moist convective atmospheric turbulence, which implies a new flow topology with linked vortex lines. A possible role of vortical hot towers (VHTs) is discussed in generating the linkage. It is shown that the linkage results in a positive feedback between the horizontal and vertical circulation in the formation of a larger-scale vortex and contributes to the instability of the macro vortex.

## 1. Introduction. A vortical hot tower route to tropical cyclogenesis

In 2006, Montgomery and co-authors (Montgomery et al., 2006) proposed a new scenario of tropical cyclogenesis within a kinematically and thermodynamically favorable environment of a mesoscale convective vortex. Using near-cloud-resolving simulations, the work demonstrated how a mesoscale tropical depression (TD) vortex could develop from cumulonimbus convection as a result of system-scale convergence and upscale vorticity growth. Within the cyclonic vorticity-rich environment of the mesoscale convective vortex (MCV) embryo, the numerical simulations indicated that deep cumulonimbus towers possessing intense cyclonic vorticity in their cores (the so-called "vortical" hot towers, VHTs) emerged as the preferred coherent structures. The VHTs acquired their vertical vorticity through a combination of tilting of MCV-horizontal vorticity and stretching of MCV and VHT-generated vertical vorticity. Horizontally localized and exhibiting convective lifetimes on the order of one hour, VHTs overcomed the detrimental effects of downdrafts by consuming convective available potential energy in their local environment, humidifying the middle and upper troposphere, and undergoing diabatic vortex merger with neighboring towers. In those simulations the growth of flow scales occurred by both system convergence and multiple diabatic vortex mergers alongside the more familiar dry adiabatic vortex merger of convectively generated remnants. The generated VHTs, each of 10-30

km horizontal scale, eventually resulted in an intense helical vortex (TD) on the atmospheric mesoscale. Meanwhile, during all subsequent stages of vortex intensification from the TD up to the mature hurricane strength, a number of VHTs of different scale and strength were always observed within the vortex circulation.

## 2. Helical nature of tropical cyclogenesis

*2.1. Special features of turbulence lacking the mirror symmetry*
It is useful at this juncture to recall the long-standing classical concept of turbulent flows, in which any large-scale flow structure, for instance a vortex of spontaneous or forced origin, should be destroyed by turbulence, as the developed turbulence tends to restore the broken symmetry (Monin & Yaglom, 1975). Homogeneity or isotropy of turbulence that is violated on large scales is generally recovered on smaller scales, as it follows the Kolmogorov-Obukhov local theory (Kolmogorov, 1941; Obukhov, 1941), and disturbance decay due to turbulent viscosity is accompanied by the energy transfer from the large-scale motion to small-scale turbulent pulsations. Under these conditions the existence of long-lived structures in which the spatial dimension which essentially exceeds the turbulence scale seems to be hardly probable.

*2.2. Helicity of the velocity field*
It would be quite another matter if the broken symmetry can not be restored by turbulence. Such might be the case with the lack of reflection symmetry (mirror-invariance breakdown) which is compatible with the theory of local structure of turbulence. Fluid motions exhibiting this property are called helical and described mathematically by a quantity, which is well-known in fluid dynamics as helicity of the velocity field (Moffatt, 1969). This quantity is defined as the dot product of velocity $\boldsymbol{V}(\boldsymbol{r},t)$ and vorticity $curl\boldsymbol{V}(\boldsymbol{r},t)$ vectors (see, e.g., a review article by Levina et al. (2000) and references therein on helicity and helical turbulence and see also the more recent paper by Pouquet & Mininni (2010)). The volume integral calculated in a specific space domain

$$ H = \int \boldsymbol{V} \cdot curl\boldsymbol{V}\, d\boldsymbol{r} \qquad (1) $$

gives the total (or global) helicity of vortex system, where $\boldsymbol{V} \cdot curl\boldsymbol{V}$ 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 volume-integral of helicity, $\langle H \rangle \neq 0$, 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. 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). To highlight this fundamental meaning of helicity, which the subsequent discussion of our main results will be centered round, let us recall the work by Moffatt (1969) and a figure given by Moffatt & Tsinober (1992), namely, Figure 1 of their paper. Their figure is reproduced here (figure 1) as the simplest possible illustration of this complex topological notion.
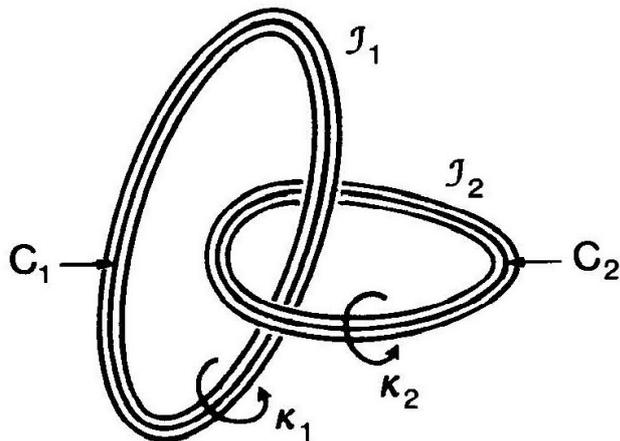
**Figure 1.** Prototype configuration of linked vortex lines that gives nonzero helicity. Borrowed from (Moffatt & Tsinober, 1992).

Let us suppose, for example as it is in (Moffatt, 1969; Moffatt & Tsinober, 1992), that a vorticity distribution in a fluid is zero except in two closed tubes $J_1$ and $J_2$, each of which moves with the fluid. Figure 1 also gives $J_1$ and $J_2$ unknotted (so that each of them can be spanned by a surface, which does not intersect itself), and the vortex lines untwisted within each tube, i.e. each vortex line is a closed curve passing once round the tube, and unlinked with its neighbors in the same tube.

For the two tubes, which have axes $C_1$ and $C_2$, and vanishingly small cross-section, it has been obtained in (Moffatt, 1969; Moffatt & Tsinober, 1992) the following expression:

$$H = \pm 2n k_1 k_2 \,, \tag{2}$$

where $k_1$ and $k_2$ are the circulations associated with each tube, $n$ is the linking (or winding) number of $C_1, C_2$. For example, $n = 0$ if the tubes are unlinked, and 1 if they are singly linked. The sign "+" or "-" should be chosen depending on whether the linkage is right- or left-handed.

Following (Moffatt, 1969; Moffatt & Tsinober, 1992) it is interesting to trace the historical roots of some of the ideas and terminology discussed above. The possibility of linked and knotted vortex lines originates from the famous paper by Kelvin (1868, then Sir William Thomson), in which the "circulation theorem" was established. As to the term "winding number" and the mathematical expression for it, both were applied much earlier by Gauss (1833) to describe the magnetic field of two or more electric current circuits.

Obviously, a real three-dimensional vortex field is much more complicated than that shown in figure 1 and can have both linked and knotted vortex lines, and in a repeated manner. However, it is described and illustrated (Moffatt, 1969; Moffatt & Tsinober, 1992), how an arbitrary vorticity field can be decomposed into a number of simpler fields of trivial topology, and a knotted vortex line may be decomposed into two (or more) linked but unknotted vortex lines by the insertion of a pair (or pairs) of equal and opposite vorticity segments. So that, formula (2) is applicable in all cases.

It is evident, that a flow configuration with nonzero helicity similar to that in figure 1 can be easily generated in different vortex flows of natural and technical origin. Thus, helicity is neither a "mysterious" nor excessive characteristic of a turbulent flow (Unfortunately, after nearly a half

of century filled with impressive studies on helicity and helical flows in theoretical, experimental and numerical turbulence including fields of astro- and geophysics, such an adverse view on helicity can still be often met in the scientific community).

In this study helicity is only assigned to mathematically describe a special vortex flow topology with linked vortex lines and represents the best suited characteristic for this purpose. The nonzero mean helicity reflects the persistent existence of complex flow topology with linked or/and knotted vortex lines which is observed in a whole examined space domain. The increase of mean helicity implies an amplification of the number of linked/knotted vortex lines, and even increased complexity of the flow structure and its increased departure of the mirror symmetry.

It is important to point out that the real spatial structure of the physical vortex fields is always the main matter behind this abstract mathematical characteristic. This should be kept in mind when encountering or using the terms "helicity/helical". So it is in our further consideration and discussion concerning the problem of tropical cyclone formation. Our results clearly demonstrate how nonzero mean helicity can be generated and increased in a natural geophysical system, namely, the tropical atmosphere of the Earth, due to interaction between atmospheric turbulent vortex flows of different scale. Moreover, this newly attained and highly helical topology of the global vortex velocity field can result in new physical effects and under certain critical level of helicity make possible a large-scale vortex instability crowned with tropical cyclone formation.

*2.3. Tropical cyclone formation from the "helical" perspective*
In paper by Levina & Montgomery (2010) the first investigation of tropical cyclone genesis and intensification was conducted from the perspective of helical features of atmospheric flows of different scales, which contributed to the organization of the cyclone. Using the data (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 mean helicity in moist convective atmospheric turbulence that implies a new topology of the flow when it is characterized by linked vortex lines (Moffatt, 1969).

It is important to point out that no external assumptions were imposed on the fluid motions here, i.e., no external forcing terms were imposed to mimic a "helical alpha effect". In other words, the current results are the outcome of a direct numerical simulation subject to the usual caveats of a sub-grid scale closure that is used to remove small scale motions at the horizontal grid scales of the model ($\sim$ 3km).

The velocity fields used for all the calculations in this work were obtained in (Montgomery et al., 2006) by use of three-dimensional non-hydrostatic numerical modeling system comprising time-dependent equations for all three components of velocity, pressure, potential temperature, total water mixing ratio, and cloud microphysics. RAMS utilizes an interactive multiple nested grid scheme which allows explicit representation of cloud-scale features within the finest grid while enabling a large domain size to be used, thereby minimizing the impact of lateral boundary conditions. For all numerical experiments three nested grids were used. A standard radiation boundary condition was used at the lateral boundaries, which assumes that disturbances reaching the boundaries move as linearly propagating gravity waves. A standard Rayleigh friction layer was included at upper levels in order to minimize reflection of gravity waves from the top of the model. All microphysical, radiative, and diffusive parameters were the standard ones employed for tropical summer conditions. The initial temperature distribution was the mean Atlantic hurricane season sounding which was representative of the so-called "non-Saharan-air-layer" air.

For post-processing of the model data we used the finest computational grid for subsequent times with a time increment of 10 minutes during 72 hours of numerical experiment. Characteristics were calculated in the computational domain of $276\times276\times20$ km$^3$ in Cartesian co-ordinates $(x, y, z)$ by use of uniform finite-difference grid with increments $\Delta x$, $\Delta y$, $\Delta z$. The vertical increment in the post analysis was equal to 500 m; the horizontal increments were 3 km.

To analyze the process of self-organization of moist atmospheric convection observed under conditions of tropical cyclogenesis as posed by Montgomery et al. (2006), a set of helical characteristics was computed, as well as some other integral characteristics of the velocity field which were applied in (Levina & Burylov, 2006). In this paper we will present only two of them, which are new in tropical cyclone studies and have been first applied by Levina & Montgomery (2010): three-dimensional relative helicity density

$$H_{i,j,k} = (\boldsymbol{V} \cdot curl \boldsymbol{V})_{i,j,k} \; , \qquad (3)$$

and mean total (global) value of helicity integrated over the whole computational domain $276 \times 276 \times 20$ km$^3$ and normalized by number of grid points:

$$< H > \; . \qquad (4)$$

In figure 2, the mean total helicity (4) evolution is shown during a hurricane vortex formation (lower panel). Two specific moments of time are chosen to present the helicity density (3) distribution at a few different levels along the layer height. The helicity density in the left panel was calculated at $t = 24$ hours that approximately corresponded to tropical depression formation whilst at $t = 72$ hours (right panel) the hurricane vortex already developed.

It is worth recalling here the characteristic values of wind velocity for three stages of tropical cyclone strength. At the stage of tropical depression (TD) the velocity of near surface tangential wind does not exceed 17 m s$^{-1}$, velocity values within 17–33 m s$^{-1}$ correspond to the tropical storm (TS), more than 33 m s$^{-1}$ to the hurricane strength (H). In our case the near surface tangential wind was about 11.5 m s$^{-1}$ at $t = 24$ hours and 38 m s$^{-1}$ at $t = 72$ hours.

As part of our examination of the evolution of the three dimensional helicity field (3), vertical velocity and vertical vorticity were analyzed also. This allowed an identification of the formation of rotating convective structures and a determination of their rotational signature, i.e., cyclonic or anticyclonic.

The undertaken study showed the existence of a spectrum of cyclonically rotating deep convection - vortical hot towers (VHTs) of different horizontal and vertical sizes and intensity. Some of these helical structures were extremely strong. Their ascending vertical velocities sometimes exceeded 30 m s$^{-1}$ during a portion of the numerical experiment, starting near $t = 10 - 15$ h (Montgomery et al., 2006). In figure 2, helical convective motions of different horizontal scales can be clearly observed. Orange, red and dark red regions correspond to strong positive helicity. One can see intense structures that reach 10-30 km of horizontal sizes and extend through the bulk of the troposphere (In figure 2 the fields are only shown up to 7 km).

In our simulation we observed how such structures were forming as the result of merging convective vortices. The process of merging started since the very first hours and was accompanied by an increase in the background helicity in adjacent areas. As the result of subsequent mergers and the system-scale convergence of vorticity forced by the aggregate latent heating of the rotating convective updrafts, a surface-concentrated vortex of tropical depression strength formed after 24 hours of simulation. During further development into a hurricane-strength vortex even more intense vortical hot towers appeared. As we can see in figure 2, a number of strong VHTs exist within the hurricane vortex circulation (right panel).

Different stages in hurricane vortex organization can be distinctly traced using the analysis of the total helicity evolution. Figure 2 (lower panel) shows an initial period of approximately 10 hours, which is needed for development of intense small-scale helical convection and the process of merging of convective structures. During next 10-15 hours, a self-organization process continues and leads to formation of tropical depression vortex which has essentially larger scales. A local peak in the total helicity corresponds to this event at approximately 24-25 hours. Further
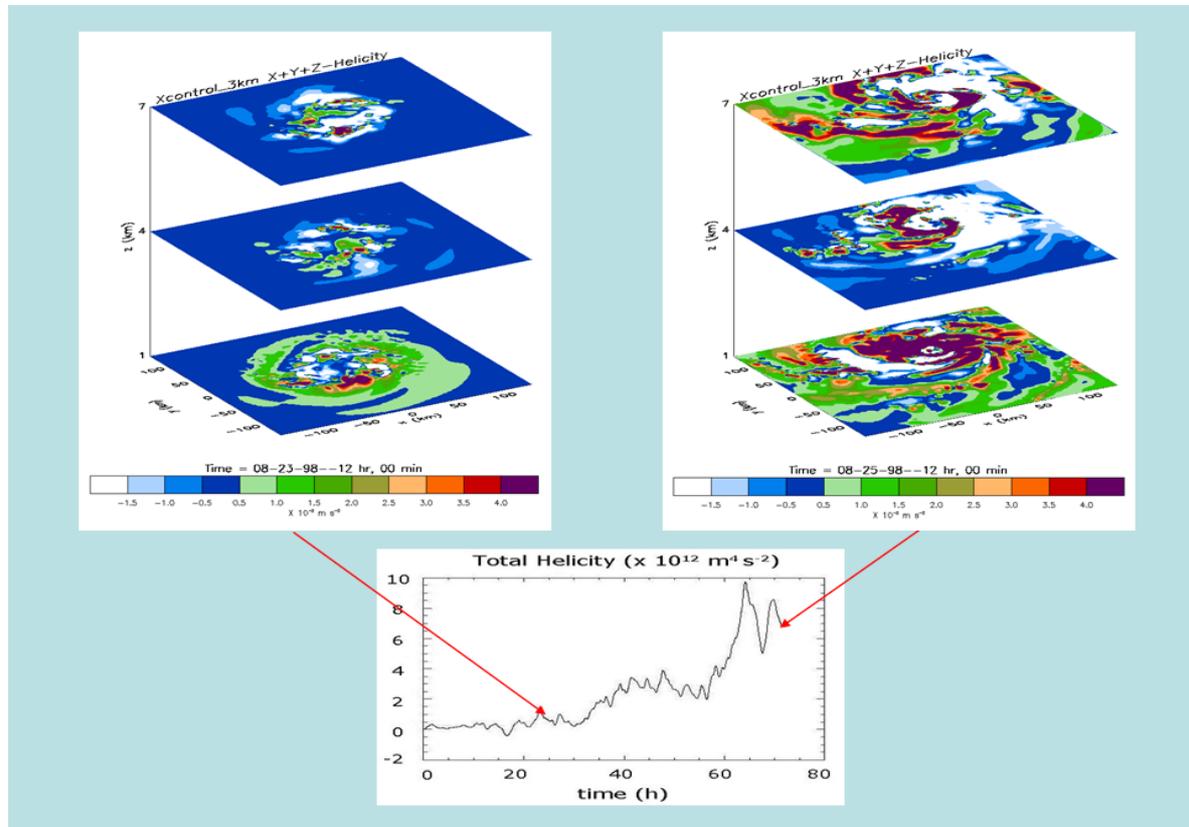
**Figure 2.** Helicity density ($\times 10^{-4}$ m s$^{-2}$) in three horizontal cross-sections of $276{\times}276$ km$^2$ at $z = 1, 4, 7$ km is shown for tropical depression (left) and mature hurricane (right), and mean total helicity ($\times 10^{12}$ m$^4$ s$^{-2}$) integrated over the computational domain $276{\times}276{\times}20$ km$^3$ during 72 hours of hurricane vortex evolution is given in the lower panel.

intensification of tropical depression up to hurricane force until the end of simulation time at 72 hours can be traced as a strong increase in helicity values.

It should be pointed out that helicity demonstrates quite a special behavior. During the first 15-17 hours the integral helicity is close to zero, and there exist short time periods when it becomes negative. However, after approximately 18 hours of simulation time helicity becomes distinctly positive and increasing. Analysis of vertical velocity and vertical vorticity for these conditions shows that such positive helicity is a result of the predominance of locally cyclonic updrafts. Non-zero helicity means a break of the mirror symmetry of atmospheric turbulence and this permits the generation of a large-scale instability (Frisch, 1995).

In our forthcoming presentation we examine from "the helical perspective" three numerical experiments from paper (Montgomery et al., 2006), which resulted in the hurricane strength vortex (successful case), tropical depression (intermediate case), and that of no surface vortex development whatsoever (unsuccessful case). We calculate and analyze helical and integral characteristics of the cyclogenesis and intensification process for the problem as posed by Montgomery et al. (2006). We consider a set of characteristics recommended in paper (Levina & Burylov, 2006) for diagnosing a positive helical feedback between the horizontal and vertical circulation in a forming large-scale vortex structure. Using this framework in conjunction with recent developments in the theory of tropical cyclone intensification (Montgomery & Smith,

2011), we discuss how the helical vortex feedback works.

We analyze also the pivotal role of vortical hot towers in generating and sustaining the feedback at different stages of the vortex evolution. Helical and integral characteristics for the successful, intermediate and unsuccessful numerical experiments are compared to pinpoint the significance of HELICAL flow topology in tropical cyclone genesis and intensification.

## Acknowledgments

## References

FRISCH, U. 1995, *Turbulence: The Legacy of A.N. Kolmogorov*, (Cambridge, Cambridge University Press).

GAUSS, C. F. 1833, *Werke* (Göttingen, Königlichen Gesellschaft der Wissenschaften), **5**, p. 605, note of Jan. 22.

KOLMOGOROV, A. N. 1941, The local structure of turbulence in incompressible viscous fluid for very large Reynolds number. *Dokl. Akad. Nauk SSSR.* **30**, 9–13 (in Russian). Reprinted in *Proc. R. Soc. Lond., Ser.* A **434**, pp. 9–13, 1991.

LEVINA, G. V. & BURYLOV, I. A. 2006, Numerical simulation of helical-vortex effects in Rayleigh-Bénard convection. *Nonlin. Processes Geophys.* **13**, pp. 205–22.

LEVINA, G. V., MOISEEV, S. S. AND RUTKEVICH, P. B. 2000, Hydrodynamic alpha-effect in a convective system. In "Advances in Fluid Mechanics" *Nonlinear Instability, Chaos and Turbulence*, vol. 2, (ed. L. Debnath & D. N. Riahi), (Southampton, WITPress), pp. 111–62.

LEVINA, G. V. & MONTGOMERY, M. T. 2010, A first examination of the helical nature of tropical cyclogenesis. *Doklady Earth Sciences.* **434, Part 1**, pp. 1285–89.

MOFFATT, H. K. 1969, The degree of knottedness of tangled vortex lines. *J. Fluid Mech.* **35**, pp. 117–29.

MOFFATT, H. K. 1978, *Magnetic Field Generation in Electrically Conducting Fluids*, (Cambridge, Cambridge University Press).

MOFFATT, H. K. & TSINOBER, A. 1992, Helicity in laminar and turbulent flow. *Annu. Rev. Fluid Mech.* **24**, pp. 281–312.

MONIN, A. S. & YAGLOM, A. M. 1975, *Statistical Fluid Mechanics*, vol. 2, (ed. J. Lumley), (Cambridge, MA, MIT Press).

MONTGOMERY, M. T., NICHOLLS, M. E., CRAM, T. A. AND SAUNDERS A. B. 2006, A vortical hot tower route to tropical cyclogenesis. *J. Atmos. Sci.* **63**, pp. 355–86.

MONTGOMERY, M. T. & SMITH, R. K. 2011, Paradigms for tropical-cyclone intensification. *Q. J. R. Meteorol. Soc.* **137**, (accepted pending revisions).

OBUKHOV, A. M. 1941, Spectral energy distribution in a turbulent flow. *Izv. Akad. Nauk SSSR, Ser. Geogr. Geofiz.* **5** (4–5), pp. 453–66 (in Russian).

POUQUET, A. & MININNI, P. D. 2010, The interplay between helicity and rotation in turbulence: implications for scaling laws and small-scale dynamics. *Phil. Trans. R. Soc.* A **368**, pp. 1635–62.

THOMSON, W. (LORD KELVIN) 1868, On vortex motion. *Trans. Roy. Soc. Edin.* **25**, pp. 217–60.