HELICAL NATURE OF TROPICAL CYCLOGENESIS: WHEN WILL A NASCENT VORTEX BECOME SELF-SUSTAINING ?

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Genesis of Hurricane Karl (2010)

Alt. 14500 m. Flight RF19. NSF/NCAR G-V
14 Sep 2010. GL's photos

TROPICAL CYCLOGENESIS

A universally accepted definition of tropical cyclogenesis does not exist.

Ritchie and Holland (1999, *Mon. Wea. Rev*) define genesis as:

" … the series of physical processes by which a warm core, tropical-cyclone-scale vortex with maximum amplitude near the surface forms".

Montgomery et al. (2012, *BAMS*):

"In this study we will define genesis as the formation of a tropical depression and we impose no formal threshold on wind speed".

Introduction to Tropical Meteorology. *2nd Edition.*
A Comprehensive Online & Print Textbook. Version 2.0, October 2011
Produced by The COMET® Program. University Corporation for Atmospheric Research.

"…tropical cyclogenesis has occurred when the tropical storm has become self-sustaining and can continue to intensify …"

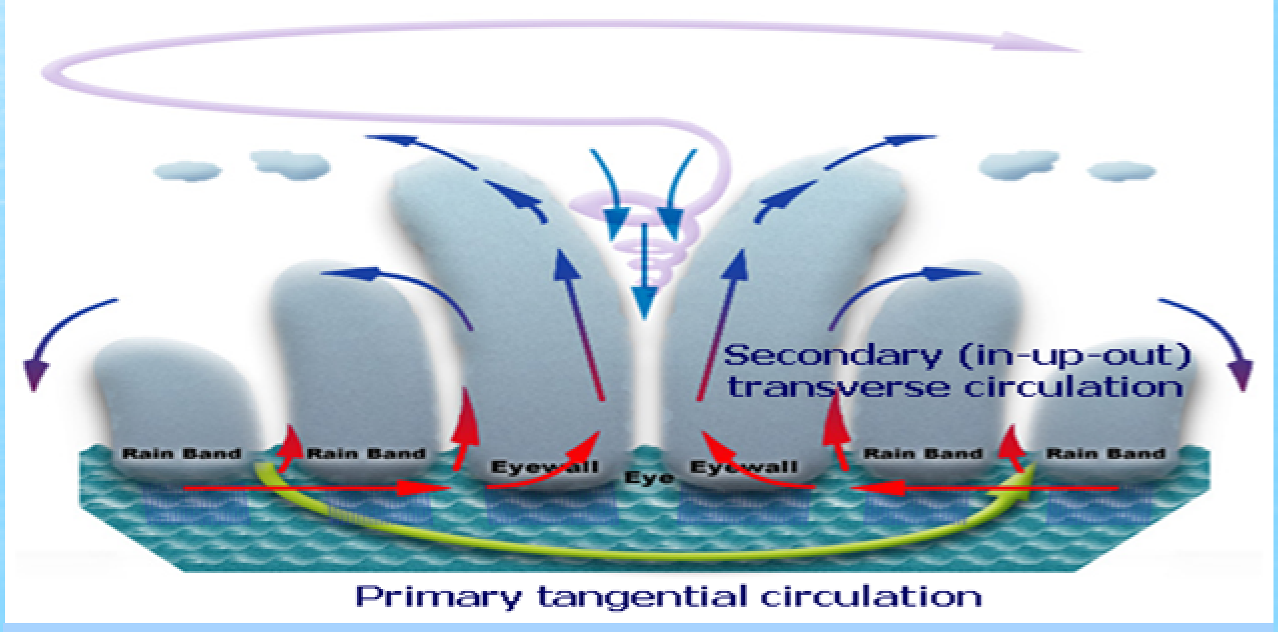
HYPOTHESIS ON THE TURBULENT VORTEX DYNAMO

Mechanism for intensification of large-scale vortex disturbances in the atmosphere –
Moiseev, Sagdeev, Tur, Khomenko, and Shukurov (1983)

In rotating non-homogeneous atmosphere, moist-convective turbulence becomes helical - energy flux to dissipation scales is suppressed and large-scale vortex instability is possible

The first sign of the hypothesized large-scale instability –
generation of the linkage of primary (tangential) and secondary (transverse) circulation on the system scale and the resulting positive feedback that makes the forming vortex energy-self-sustaining

The 1st link (transverse-tangential) – is due to the Coriolis force.
How does the 2nd link (tangential-transverse) work to close the putative feedback loop?
– This was unclear until our finding on VHTs' role



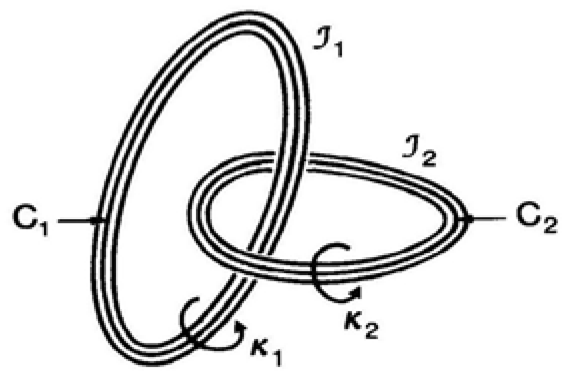
Anatomy of a tropical cyclone in the Northern hemisphere (www.brockmann-consult.de)

HELICITY OF THE VELOCITY FIELD

$$H = \int \vec{V} \cdot curl\, \vec{V}\, d\vec{r}$$

Moffatt, 1969, JFM

$\langle H \neq 0 \rangle$ - break of the mirror symmetry
Large-scale instability is possible



From Moffatt and Tsinober, 1992

- **characterizes a structure of the vector velocity field,**
  topological invariant **measuring the degree of linkage of the vortex lines, and quantifying the flow departure from the mirror symmetry;**
- **inviscid constant of motion in barotropic fluids,**
- **sign of helicity determines a predominance of the left-handed or the right-handed spiral motions in a fluid flow,**
- **favors the energy transfer from small to large scales (inverse cascade),**
  Pouquet et al., 2010-2013, PoF, PhysRevE ; Biferale et al., 2012, PhysRevLett

OUTLINE

Introduction

1. Tracing the pathway to the turbulent vortex dynamo (TVD)
   - The first finding: non-zero integral helicity generation during TC formation that indicates to a possibility of large-scale vortex instability.
   - Search for the large-scale vortex instability: energetics of a forming TC.
   - Analysis of helicity generation on cloud scales - interaction between convection and vertical shear of horizontal wind.
   - VHTs are the connectors of the primary and secondary circulation in TC.
2. State of the art
   - Numerical diagnosis for tropical cyclogenesis based on the TVD concept.
3. Next steps

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G. V. Levina was supported by a few Grants of the RFBR during 2001-2012, and RAS OEMMPU Programs 09-T-1-1005, 12-T-1-1008

A VORTICAL HOT TOWER ROUTE TO TROPICAL CYCLOGENESIS

New scenario of hurricane formation based on self-organization of convective processes

MO6 : Montgomery et al., 2006, *J. Atmos. Sci.*, v. 63, pp. 355-386

The focus was on how an initial midtropospheric mesoscale convective vortex (MCV) may be transformed into a surface-concentrated tropical depression (TD).

A nonhydrostatic cloud model was used to examine the thermomechanics of tropical cyclogenesis by means of RAMS (Regional Atmospheric Modeling System) with 2-3 km horizontal grid spacing:

Nested Grids	3
Number of horiz. grid pts. for grids 1/2/3	a) 40/62/92 b) 60/90/137
Vertical levels	26
Horiz. Coordinate	Cartesian
Horiz. grid incr. for grids 1/2/3	a) 36 km/9 km/3 km b) 24 km/6 km/2 km
Vertical grid increment	400 m at the surface
Vertical grid stretch ratio	1.065
Grid top	22.6 km
Grid time step for 1/2/3	30s/10s/5s
Center latitude	15 degrees
Center longitude	-40 degrees

Cape Verde Islands

Self-organization of vortical convection was observed as:

an enlargement of vortex structures from the size of individual rotating cumulus clouds in the model;

their merging with each other to yield newly forming larger vortices and intensifying circulation on the system scale;

their induced concentration of absolute angular momentum on the system scale circulation.

EXAMINATION OF THE HELICAL NATURE OF TROPICAL CYCLOGENESIS BASED ON SIMULATION RESULTS FROM [M06]

Post processing: Cartesian coordinates - x, y, z ;
i, j - 92x92 – horizontal directions, increment = 3 km;
k - 40 vertical levels, increment = 0.5 km;
Time of process evolution – 72 hours, increment = 10 min.

$$E_{i,j,k}=\frac{1}{2}\left(\vec{V}\right)^2_{i,j,k}\ ,\quad \varepsilon_{i,j,k}=\frac{1}{2}\left(curl\vec{V}\right)^2_{i,j,k}\ ,\quad H_{i,j,k}=\left(\vec{V}\bullet curl\vec{V}\right)_{i,j,k}$$

3D kinetic energy, enstrophy and helicity densities

$\langle E\rangle\ ,\ \langle\varepsilon\rangle\ ,\ \langle H\rangle$ - integral kinetic energy, enstrophy and helicity normalized by number of grid points

Integral kinetic energy $<E^P>$ and $<E^S>$ separately to identify the helical feedback

Vertical velocity, vorticity and helicity – convection/VHTs

Horizontal helicity $<H_{xy}> = <H_x> + <H_y>$ – vertical wind shear

Hydro- and thermodynamic fields in Cartesian and cylindrical coordinates, azimuthal averages, and a number of other characteristics

RAMS SIMULATIONS [M06] TO ANALYZE HELICAL SELF-ORGANIZATION OF CONVECTIVE PROCESSES

Genesis experiments (6 from 19 of M06) analyzed in our current work

Initial MCVortex characterized by max v, **Direct Numerical Simulation !**

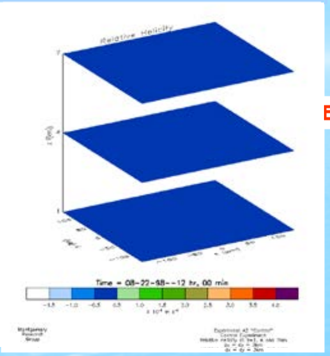
No.	Name	Notes
A1	Control	$\Delta x=\Delta y$=2 km, SST=29°C, max v = 6.6 m s^{-1} at 4 km
* A2	3 km	$\Delta x=\Delta y$=3 km, SST=29°C, max v = 6.6 m s^{-1} at 4 km
B3	Cape-less (3 km)	$\Delta x=\Delta y$=3 km, SST=29°C, max v = 6.6 m s^{-1} at 4 km, low-level moisture decreased by 2 g kg^{-1}
C1	No vortex	$\Delta x=\Delta y$=3 km, SST=29°C
C3	Weak vortex	$\Delta x=\Delta y$=3 km, SST=29°C, max v = 5.0 m s^{-1} at 4 km
E1	Zero Coriolis	$\Delta x=\Delta y$=3 km, SST=29°C, max v = 6.6 m s^{-1} at 4 km

No significant differences between A1 and A2.
Experiments A1, A2, B3, and E1 resulted in TDs after ~ 24-48 h .
A1 and A2 - intensification to hurricanes during 72 h.
In B3 and C3 development notable slower than A2.
In E1 no intensification (of TD vortex) after 24 h.
C1: no intense VHTs and no surface spinup.

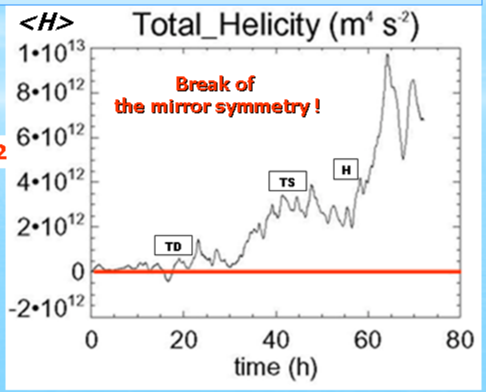
HELICITY EVOLUTION DURING 72 HOURS OF TC FORMATION

LM10 : Levina G.V., and Montgomery M.T., 2010, *Dokl. Earth Sciences.*, v. 434, part 1, pp. 1285-1289

3D HELICITY DENSITY



Expt. A2



Local helicity values

Time (hrs)	H_{local} (m s^{-2})
0 ÷ 10-12	0.002 – 0.004
12 ÷ 25-30	0.008 – 0.4
30 ÷ 72	0.5 – 1.0

Intensity of the forming TC

Max az-mean surface tangential wind

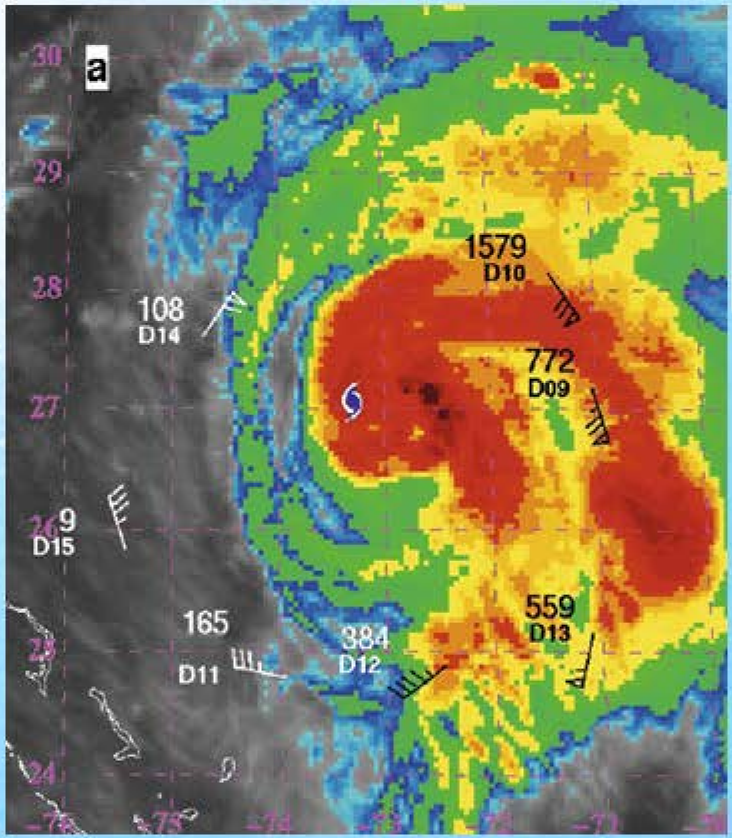
t = 16-18 h	9 m s^{-1}	**TD** formation,
t = 45 h	17.2 m s^{-1}	**TS** formation,
t = 56 h	33.4 m s^{-1}	**H** formation,
t = 60-63 h	42.5 m s^{-1}	**H** Maximal wind

HELICITY CALCULATION BASED ON DIRECT MEASUREMENTS IN TROPICAL CYCLONES – a TEST for NUMERICAL RESULTS

Molinari J., and Vollaro D. 2008, *Mon. Wea. Rev.*, 136, 4355–4372. – [MV08]

Extreme Helicity and Intense Convective Towers in Hurricane Bonnie

Helicity was calculated in Hurricane Bonnie (1998) using tropospheric-deep dropsonde soundings from the NASA Convection and Moisture Experiment (CAMEX). The most extreme values of helicity, among the largest ever reported in the literature, occurred in the vicinity of deep convective cells. These cells reached as high as 17.5 km.



Infrared satellite image at 0100 UTC 25 Aug.
Helicity values (cell motion ≠ 0) and mean winds over 0–6 km.
Sondes D9–D15 were released 2330 UTC 24 Aug − 0153 UTC 25 Aug

Helicity values (cell motion = 0) over 0–6 km were also calculated [MV08].

They can be compared with our results of numerical simulation [LM].

The highest helicity value [**MV08**] was found for D10 on Aug 24 when the maximum surface wind was about 55 $m \cdot s^{-1}$.

In simulations [**LM**] the total 0-6 km helicity reaches its highest value near the simulation time 60 hours when the maximum wind is 42.5 $m \cdot s^{-1}$.

	MV08	LM
Max Helicity 0-6 km	2578 $m^2 \cdot s^{-2}$	2700 $m^2 \cdot s^{-2}$
Max surface wind	55 $m \cdot s^{-1}$	42.5 $m \cdot s^{-1}$

MV 2010, *J. Atmos. Sci.*, 67, 274–284. The study of helicity was extended to 8 tropical cyclones sampled by NASA during CAMEX (1998/2001)

FROM <H>≠0 TO THE VORTEX DYNAMO

- **The non-zero integral helicity found in our works of 2009-2010 was the first example of such phenomenon in a real natural system – the tropical atmosphere of the Earth ;**

  during a long time it was only a hypothesis whether <H>≠0 is possible.

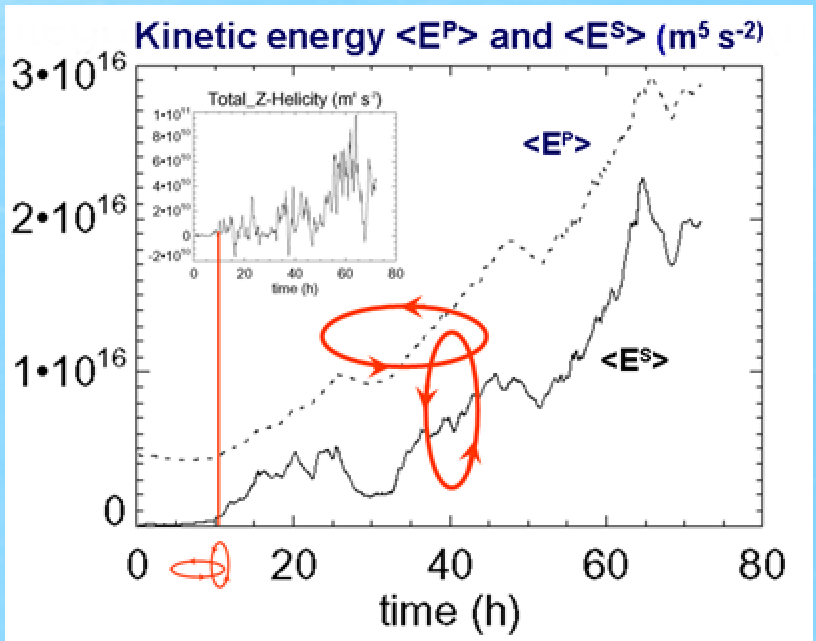
However, this does not necessarily mean that the large-scale vortex instability is underway.

In fact, this only means that there exists a persistent departure of the mirror symmetry in turbulence during TC formation. We have a case of the helical turbulence. The theory of turbulence gives a few examples of large-scale instabilities in helical turbulence, between them – the turbulent vortex dynamo.

- **Diagnosis of the large-scale vortex instability: analysis of the energetics**

t=12 h:

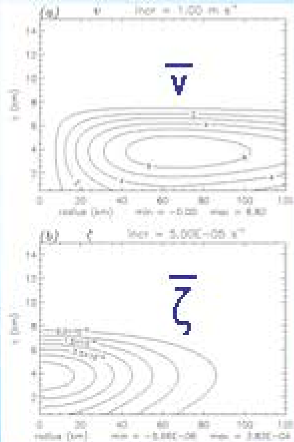
1. Mutual intensification of the primary and secondary circulation starts
2. The Z-helicity increases



What is flow evolution behind these changes at t=12 h ?

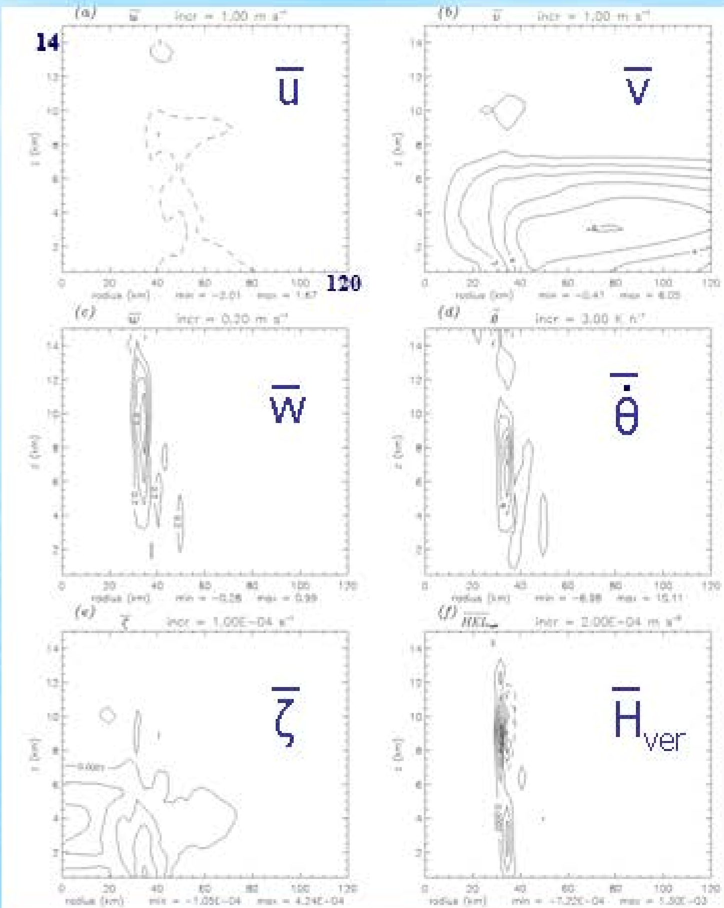
FORMATION OF THE SECONDARY OVERTURNING CIRCULATION IN (u) – UP (w) – OUT (u) FLOW during t = 10 – 12 h

t = 0 h

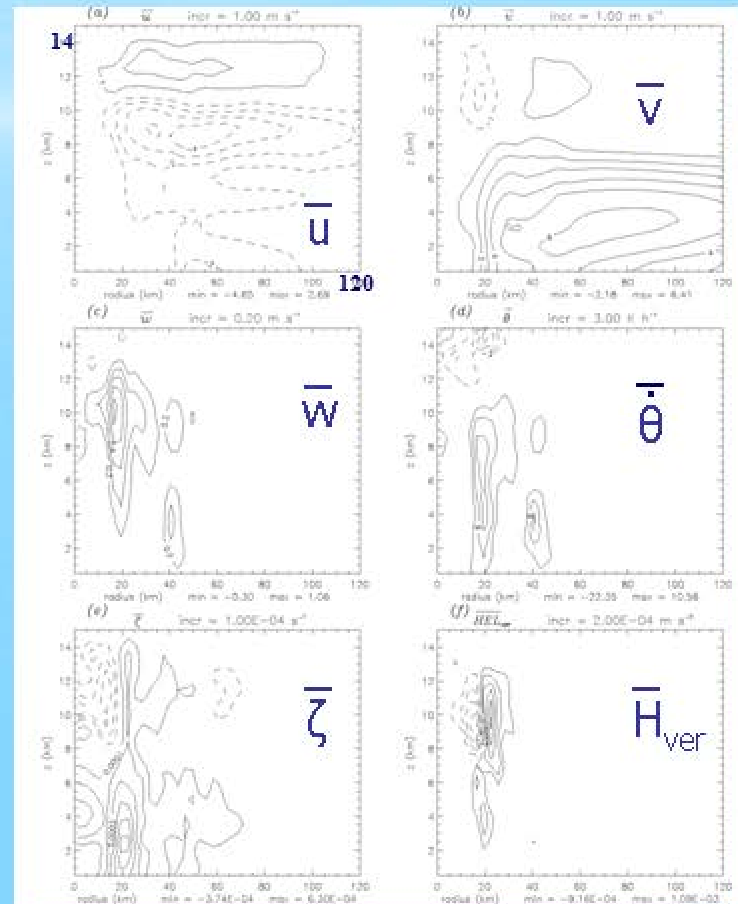


Initial MCV

t = 10 h



t = 12 h



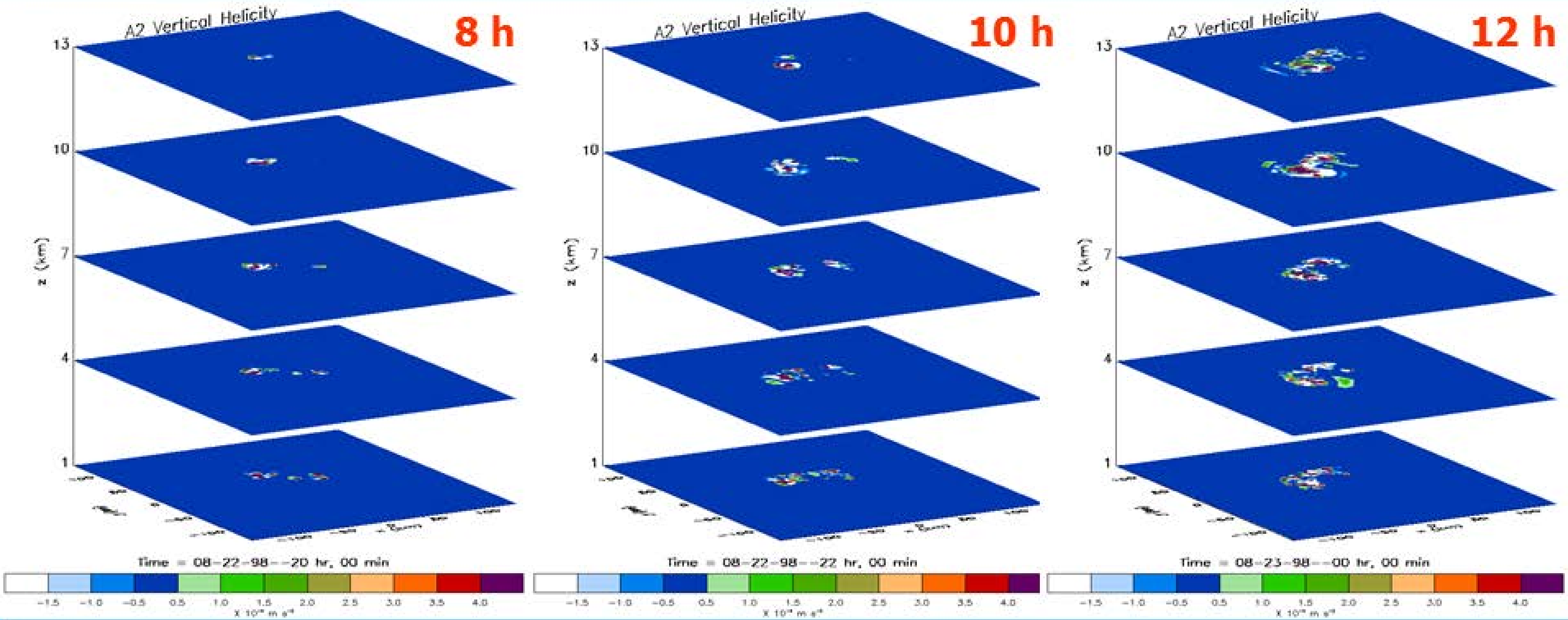
Azimuthally averaged fields: VHTs are well recognized in w, θ, and H_{ver}

u – the radial velocity, v – the tangential velocity, w – the vertical velocity,
θ – the diabatic heating rate, ζ – the relative vorticity, H_{ver} – the vertical contribution of helicity.

FORMATION OF THE SECONDARY OVERTURNING CIRCULATION

VHTs in the VERTICAL HELICITY FIELD : t = 8; 10; 12 hours

Expt. A2: XY – 276 x 276 km, Z – 13 km shown



8 h: one intense rotating updraft reaches 13 km in height ; **10-12 h:** a population of VHTs is forming

THE VERTICAL HELICITY ALLOWS TO DISCERN VERTICAL ROTATING FLOWS:

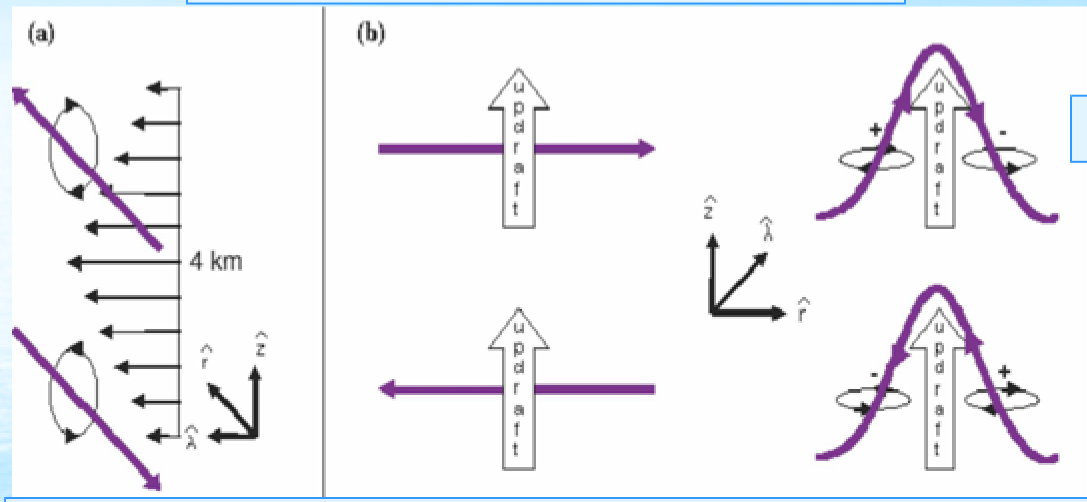
\+ cyclonic updrafts or/and anticyclonic downdrafts

\- cyclonic downdrafts or/and anticyclonic updrafts

VORTICITY-HELICITY GENERATION AND AMPLIFICATION BY VHTs
THE LINKAGE OF VORTEX LINES

1. In the presence of the initial Mesoscale Convective Vortex (MCV) – [M06]

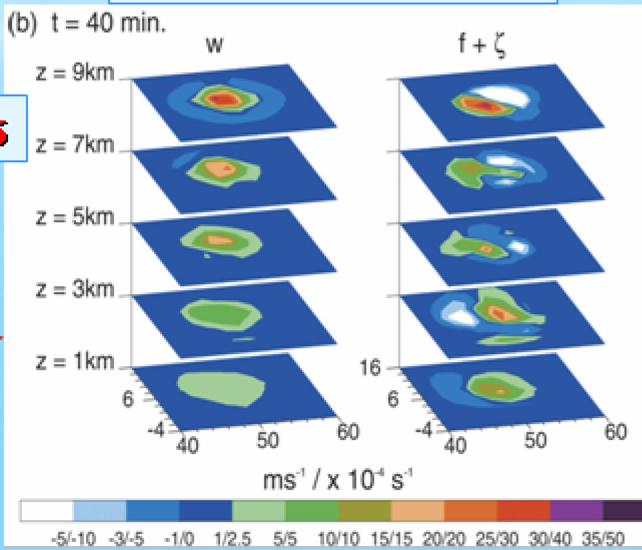
Tilting and stretching of vortex lines



(a) Radial vorticity generated by vertical shear profile of the MCV, V_{max} at z = 4 km

M06

VHT – a vortex dipole



2. NO initial MCVortex – Expt. C1

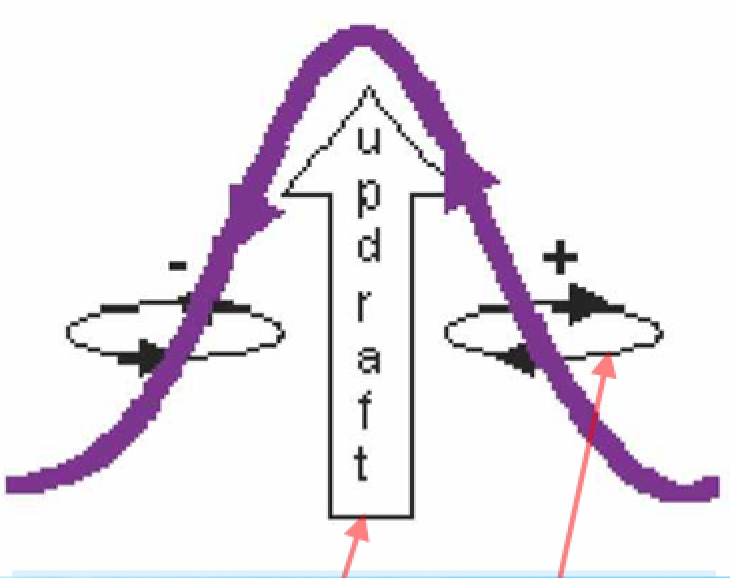
A warm convective updraft creates a horizontal temperature inhomogeneity that results in a local overturning circulation. The circulation is also characterized by vertical shear profile, and **the vertical component of vorticity can be generated very similarly.**

In both cases, this is an effective way for helicity generation on cloud convection scales

VHTs – THE CONNECTORS OF CIRCULATIONS

Levina G.V. Helical Organization of Tropical Cyclones. Preprint NI13001-TOD. 2013. Isaac Newton Institute, Cambridge, UK.

VORTICAL HOT TOWERS WORK AS 'DYNAMICAL STAPLES'



VHT is helical 'by definition'

$$H_z = V_z \left(curl\, \vec{V} \right)_z$$

Each individual VHT:

- contributes to both the horizontal and vertical motion,
- generates a local linkage of vortex lines HELICITY

The vertical contribution of helicity, H_z is the indicator of the rotating vertical flows

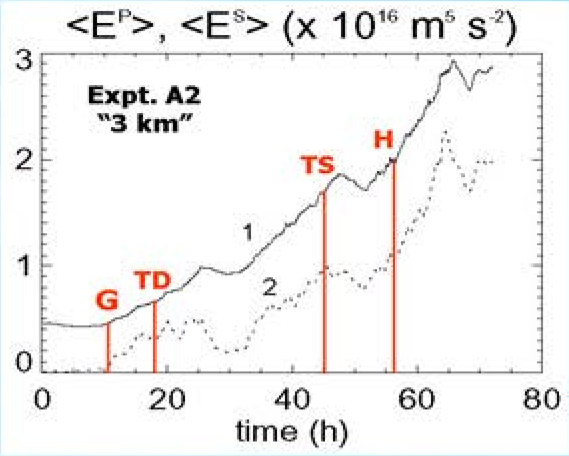
<u>In our work, we consider the broad spectrum of such structures rather than emphasizing the most intense updrafts</u>

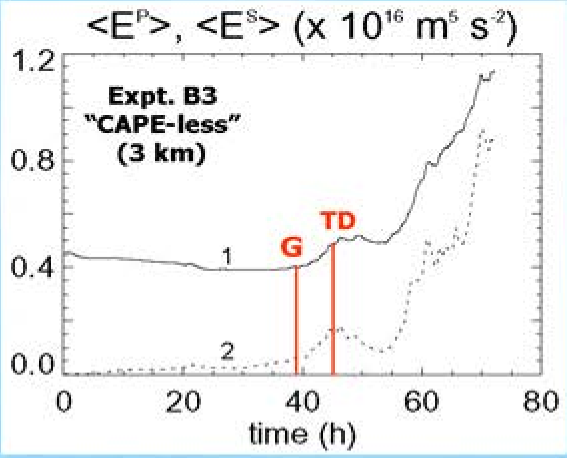
VHTs population contributes to both the horizontal and vertical motion:

- transforms the horizontal vorticity generated by vertical shear profile of the primary tangential circulation into the vertical vorticity and amplifies it by stretching;
- contributes to both the formation and intensification of the secondary overturning circulation, and intensification of the tangential circulation;
- tightly links the primary and secondary circulations on the TC vortex mesoscales.

WHEN WILL A NASCENT VORTEX BECOME SELF-SUSTAINING ?

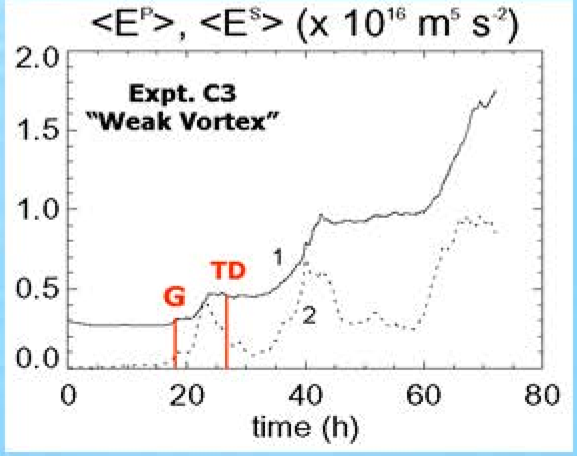
GENESIS TIME – G ?

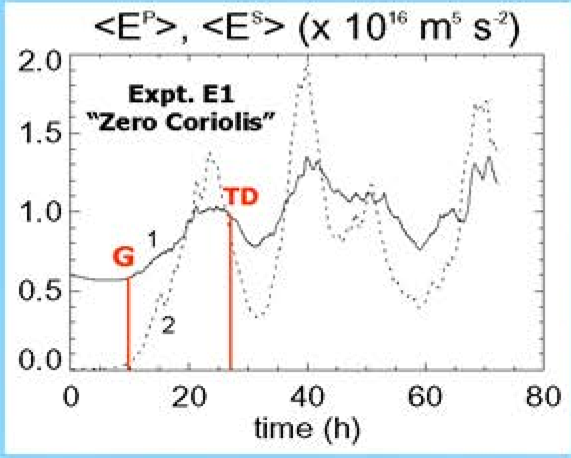




The forming TC becomes self-sustaining when the primary and secondary circulations become linked by rotating convective cores – Vortical Hot Towers.

A warm core surface-concentrated tropical depression (TD) forms a few hours later.





SUMMARY

- **Our approach for diagnosis of tropical cyclogenesis is based on fundamental ideas on self-organization in turbulence and implemented by use of modern cloud-resolving numerical simulations.**
- **We analyze the evolution of structure and energetics of the forming vortex.**
- **The onset of large-scale vortex instability requires a special topology of the vortex velocity field – the newly forming mesoscale vortex becomes energy-self-sustaining when a helical structure of the system-scale circulation organizes.**
- **Such helical mesoscale organization is only possible due to the linkage of tangential and transverse circulation which is realized through rotating convective structures of cloud scales – Vortical Hot Towers (VHTs).**
- **We use :**
  - **the pseudoscalar** $\vec{V} \cdot curl\,\vec{V}$ **- helicity of the velocity field** (helicity density, integral helicity as well as its horizontal and vertical contribution) **to quantitatively analyze the flow topology**,
  - **the integral kinetic energy of the primary and secondary circulation (separately) to diagnose the onset of large-scale vortex instability.**

Our results of 2009-2013 can be found :

https://www.researchgate.net/profile/Galina_Levina/ **https://www.researchgate.net/profile/M_Montgomery/**
https://icmm.academia.edu/GalinaLevina

NEXT STEPS

- **Similar analysis for NSF-PREDICT 2010 data:**

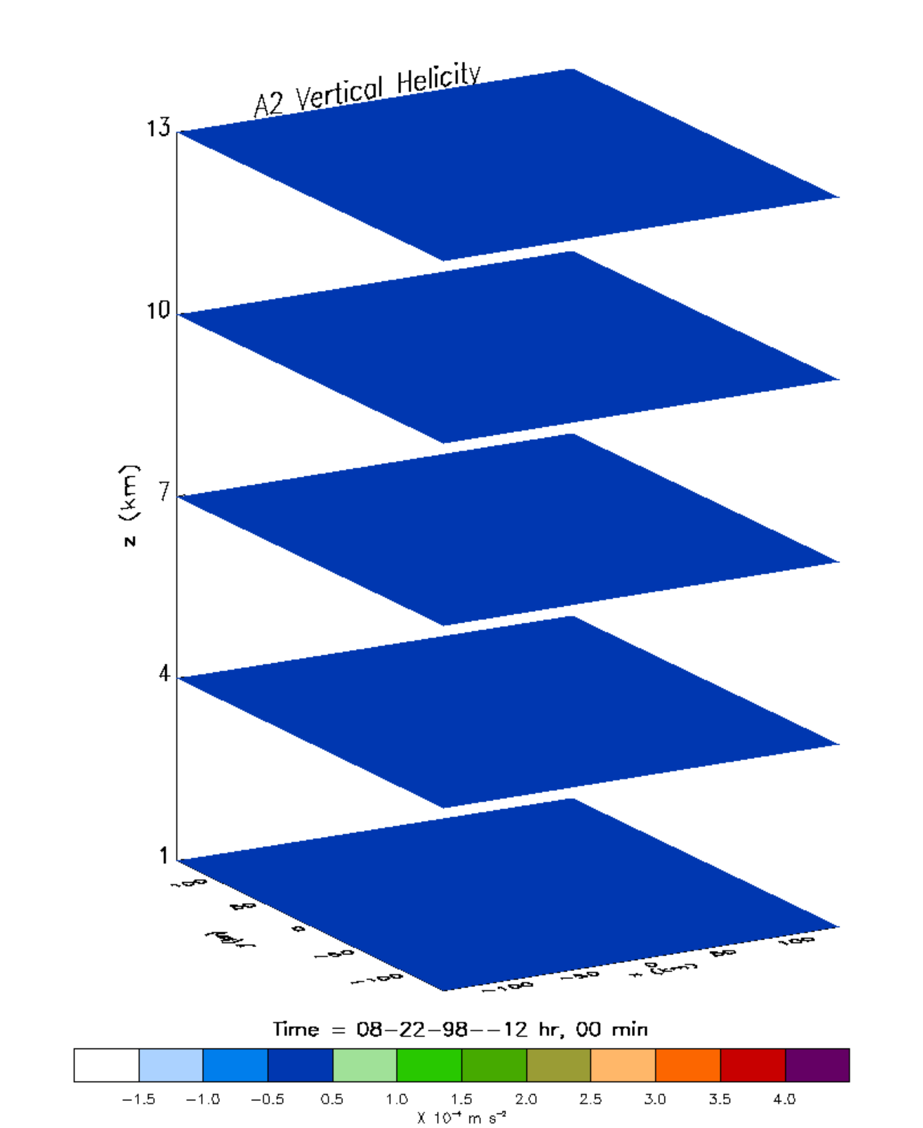
  The Marsupial Paradigm (Dunkerton, Montgomery, Wang, 2009) indicates that 'sweet spot', within which a high-resolution numerical analysis of helical self-organization should be applied.

- **Examination of energy and helicity transfer between flows of different scales.**

- **Does there exist a threshold for the large-scale helical-vortex instability in the atmosphere**

(as it does in the TVD theory and vortical RB convection simulation) ?

THANK YOU FOR YOUR ATTENTION !



08-23-98 00 hr G
08-23-98 06 hr TD
08-24-98 09 hr TS
08-24-98 20 hr H
08-25-98 03 hr Max Wind 43 m/s

The first updraft is generated by the initial 300 s local heating at low levels

Expt. A2. VERTICAL HELICITY: ROTATING CONVECTION

Computer facilities used for RAMS simulation and post-processing in Montgomery Research Group, NPS, Monterey, CA, USA

Dual processor Linux workstation has

- two AMD Opteron CPUs At 2.00GHz each
- 4 GB of RAM
- 1 TB of hard drive space

It runs CentOS 4.7 Linux