ECAS 2021

The 4th International Electronic Conference on Atmospheric Sciences

16–31 JULY 2021 | ONLINE

Chaired by: PROF. DR. ANTHONY R. LUPO

atmosphere MDPI

HOW DOES CYCLOGENESIS COMMENCE GIVEN A FAVORABLE TROPICAL ENVIRONMENT?

Galina Levina

Space Research Institute RAS, Moscow, Russia

levina@iki.rssi.ru

M O T I V A T I O N

The absence of a universally accepted definition of tropical cyclogenesis and the lack of accurate diagnosis for the birth of a hurricane vortex remain among the major challenges of modern tropical meteorology.

The forecast of the developing vortex and the entire system of warning the population about a possible emergency situation fundamentally depend on the solution of these problems.

Montgomery et al., *Bulletin of the American Meteorological Society*, February 2012. P. 169 :

"… an enhanced ability to anticipate the path along which genesis may occur, even though **THE EXACT TIMING OF GENESIS REMAINS UNCERTAIN due to the chaotic influence resulting from moist convection**."

WE PROPOSE HOW:

– **THE EXACT TIMING OF GENESIS CAN BE IDENTIFIED;**

– **THE CHAOTIC INFLUENCE FROM MOIST CONVECTION CAN BE QUANTIFIED.**

OUTLINE

Introduction.

1. Diagnosis of tropical cyclogenesis

1.1. Onset of pre-depression large-scale vortex instability

1.2. Cloud-resolving numerical analysis of tropical cyclone (TC) formation:

- the vertical helicity field to localize & quantify vortical convection,
- vortical hot towers (VHTs) and the formation of the secondary circulation (SC),
- VHTs diagnostic patterns for the onset of instability: helicity field

1.3. GOES Imagery:

- VHTs in the temperature field

2. Genesis of Atlantic Hurricane Isaias (2020)

3. Outcome and Perspective

Publications, presentations, data:

https://www.researchgate.net/profile/Galina_Levina
https://iki-rssi.academia.edu/GalinaLevina

HURRICANES: MONITORING AND PREPAREDNESS

N H C https://www.nhc.noaa.gov/
National Hurricane Center Miami, Florida

TD – tropical depression, V ≤ 17 m/s
TS – tropical storm, V = 18-32 m/s ; gets a name
H – hurricane, V ≥ 33 m/s ; categories 1-5 (≥ 70 m/s)

Before 2017: ALARM – TC ! announcement when **TD/TS** is detected.

There are enough cases when, despite all efforts, TD stage is missed and TC is identified at its next stage – TS, and dangerously close to heavily populated terrains.

Since 2017: ALARM – Potential TC ! threat of **TS/H** conditions.

The threat of bringing tropical storm or hurricane conditions to land areas within 48 hours.

Designation, e.g. in 2020 NINE – 36 hours later, declared as **TS** and named **Isaias** near Puerto Rico.

DIAGNOSIS OF TROPICAL CYCLOGENESIS

Basic hypothesis: the theory of the turbulent vortex dynamo (Moiseev et al., 1983).

This implies a large-scale vortex instability in the atmosphere due to an **inverse energy cascade in 3D helical turbulence**, in which the energy flux to dissipation scales is hindered.

Data source: idealized cloud-resolving RAMS simulation

- **Montgomery et al., 2006, JAS, – [M06]**
  "A vortical hot tower route to tropical cyclogenesis" ,
  Experiments A1, A2, B3, C1, C3, E1;
- **Nicholls and Montgomery, 2013, ACP,**
  "An examination of two pathways to tropical cyclogenesis …",
  Experiment A2.

Published: doi:10.1088/1742-6596/1640/1/012023
Levina G. V. Birth of a hurricane: early detection of large-scale vortex instability 2020 *J. Phys.: Conf. Ser.*

DIAGNOSIS OF TROPICAL CYCLOGENESIS

Stages in our researches (Levina&Montgomery, 2009-2015) to diagnose the Genesis

Stage 1. Is the atmospheric turbulence during TC formation helical? – Analysis of helicity.

Yes. – Generation of non-zero integral helicity has been found.

"A first examination of the helical nature of tropical cyclogenesis", 2010.
https://doi.org/10.1134/S1028334X1009031X

Stage 2. Search for the large-scale vortex instability – Analysis of integral kinetic energy.

Vortex dynamo theory: the first sign of the hypothesized large-scale instability is the generation of the linkage of primary (tangential) and secondary (transverse) circulation on the system scale manifesting as the positive feedback – mutual intensification of the circulations, which makes the forming vortex energy-self-sustaining.

The instability has been discovered!

"When will cyclogenesis commence given a favorable tropical environment?", 2015.
https://doi.org/10.1016/j.piutam.2015.06.010

DIAGNOSIS OF TROPICAL CYCLOGENESIS

FROM NON-ZERO HELICITY TO THE TURBULENT VORTEX DYNAMO

Important Note!

The non-zero mean helicity (calculated as an integral over a domain of a forming TC - 276 x 276 x 20 km with space increments 3, 3, and 0.5 km, correspondingly, and normalized by the number of grid points) **found in our works 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 $\langle H \rangle \neq 0$ 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, among them – **the turbulent vortex dynamo.**

Analysis of the energetics is needed to diagnose the instability!

DIAGNOSIS OF TROPICAL CYCLOGENESIS

Stages in our researches (Levina&Montgomery, 2009-2015) to diagnose the Genesis

Stage 1. Analysis of helicity.

The results were first presented at the 29th Hurricanes Conference in May 2010.

Stage 2. Analysis of integral kinetic energy.

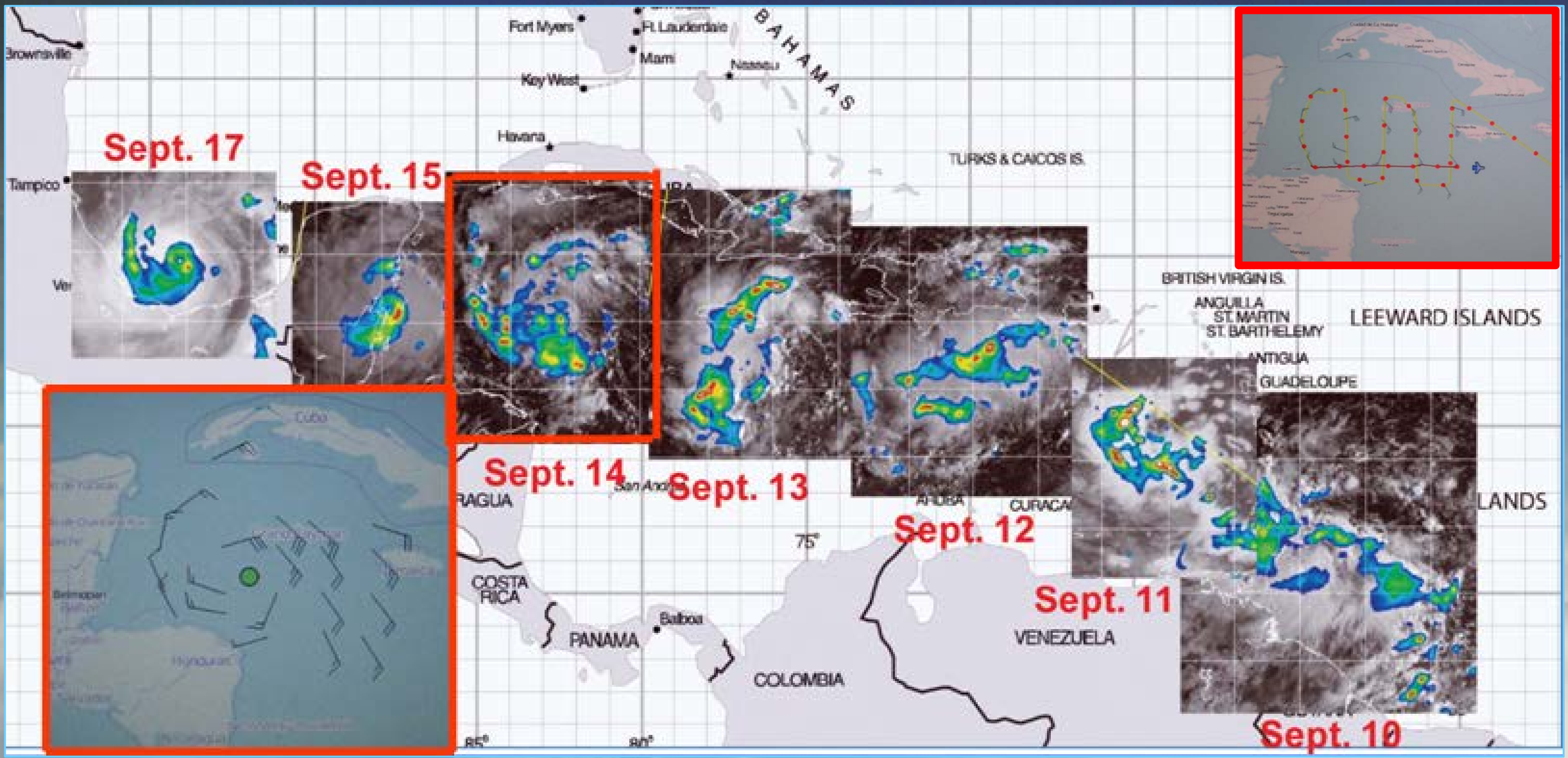
Shortly thereafter, working at NPS in Monterey in May-June 2010, the first results about the onset of instability were obtained for 4 numerical experiments [M06].

In all cases, the onset of instability occurred several hours before the formation of tropical depression.

That was extremely surprising since the authors of the dynamo theory themselves from the very beginning assumed its application to explain the formation and intensification of the tropical depression.

Based on our finding, my goal in the NSF-NCAR PREDICT Field Experiment (August-September 2010, Saint-Croix Island, U.S.V.I.) was to find where the theory of vortex dynamo could be applied in tropical cyclone research.

TROPICAL CYCLONE KARL (2010)

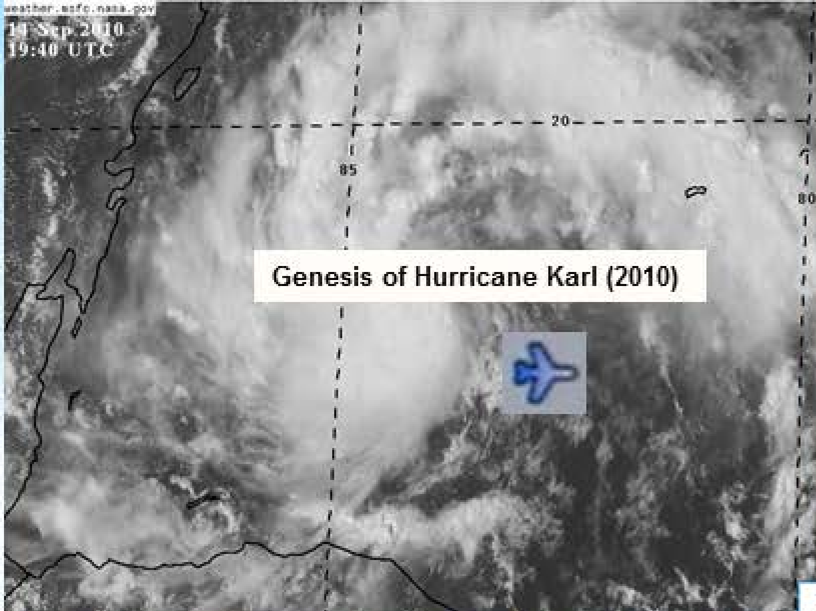


An area of potential cyclogenesis (‘Marsupial Pouch’) has been monitored by aircraft of NASA, NOAA, NSF-NCAR, and USAF since 10 September. RF19 was the 6th NSF-NCAR G-V flight:

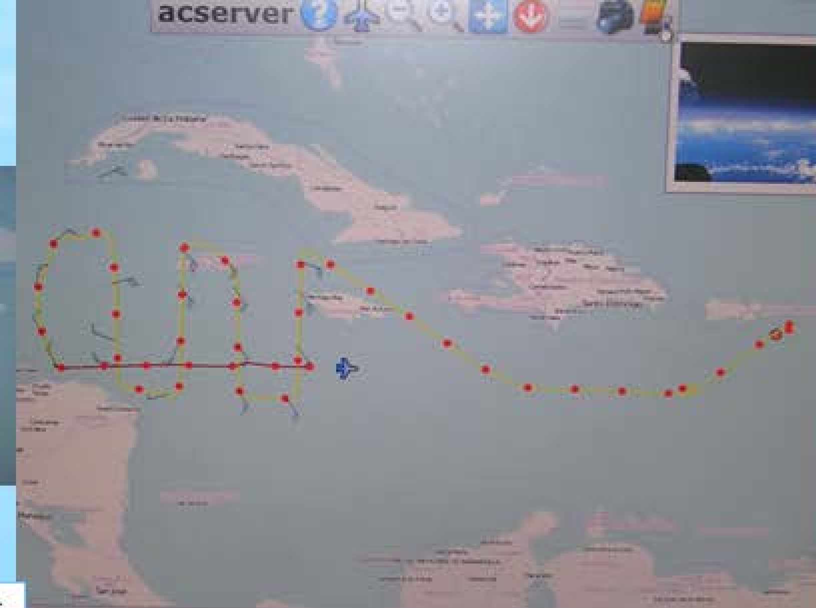
- the closed surface wind circulation was found,
- Tropical Storm Karl was born with max wind ~ 20 m·s^{-1}

Pictures are borrowed from the reports of PREDICT Science Director M.T. Montgomery and RF19 Mission Scientist C. López-Carillo, and Montgomery et al. (2012, *BAMS*).

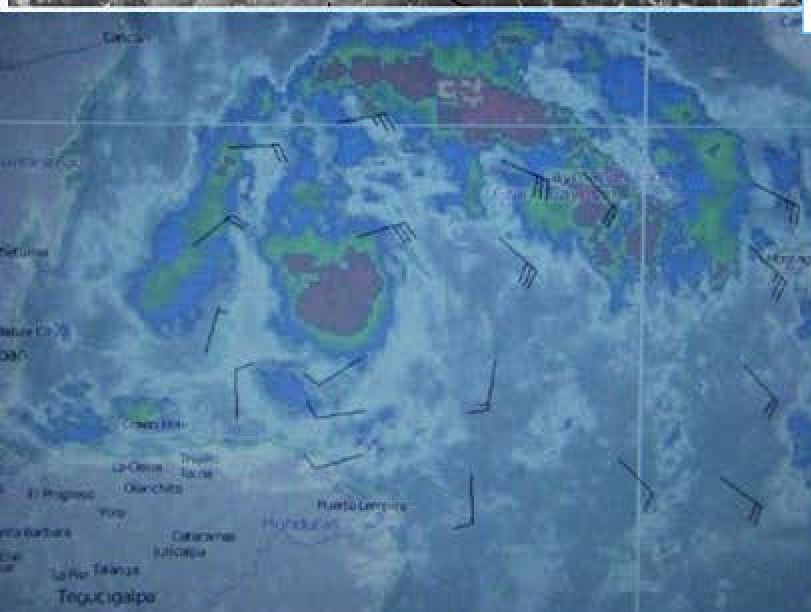
Karl Genesis
14.09.2010
as seen from G-V



Genesis of Hurricane Karl (2010)



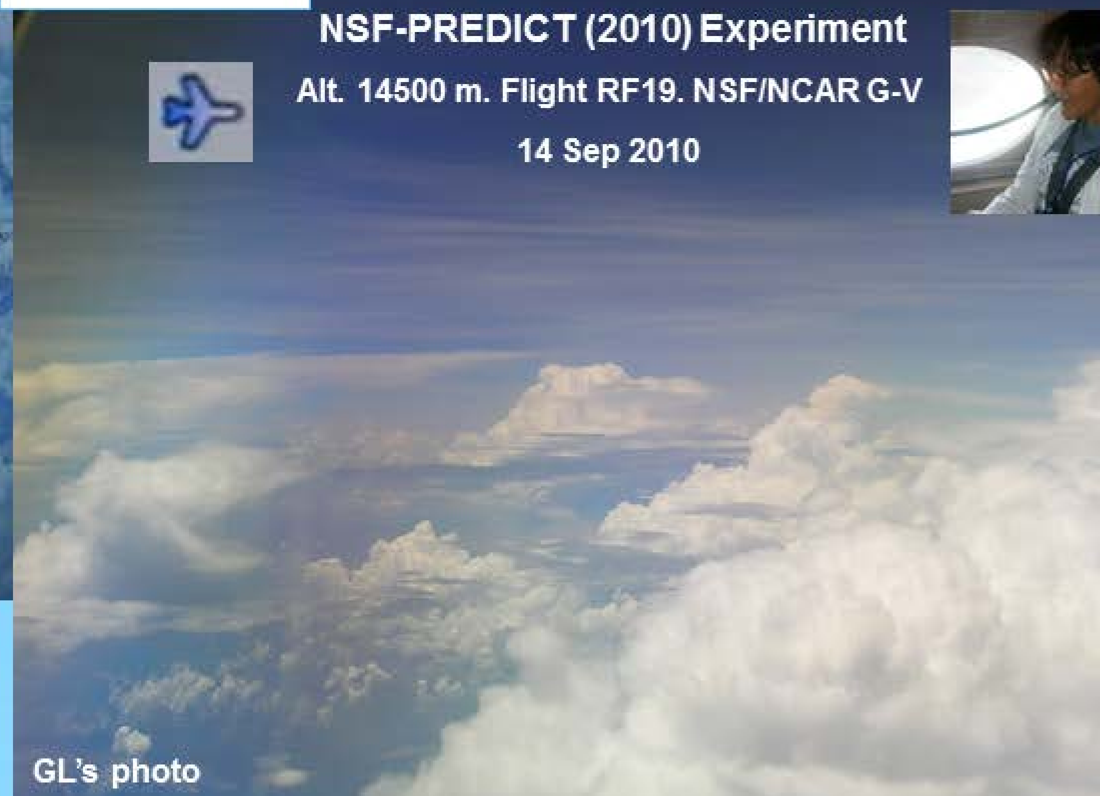
18.00 – 20.00 UTC



NSF-PREDICT (2010) Experiment

Alt. 14500 m. Flight RF19. NSF/NCAR G-V

14 Sep 2010



GL's photo

3 pictures are borrowed from the reports of PREDICT Science Director M.T. Montgomery and RF19 Mission Scientist C. López-Carillo.

"PREDICT" OUTCOME & MOTIVATION

The absence of a universally accepted definition of tropical cyclogenesis and the lack of accurate diagnosis for the birth of a hurricane vortex remain among the major challenges of modern tropical meteorology.

The forecast of the developing vortex and the entire system of warning the population about a possible emergency situation fundamentally depend on the solution of these problems.

Montgomery et al., *Bulletin of the American Meteorological Society*, February 2012. P. 169 :

"… an enhanced ability to anticipate the path along which genesis may occur, even though **THE EXACT TIMING OF GENESIS REMAINS UNCERTAIN due to the chaotic influence resulting from moist convection**."

WE PROPOSE HOW:

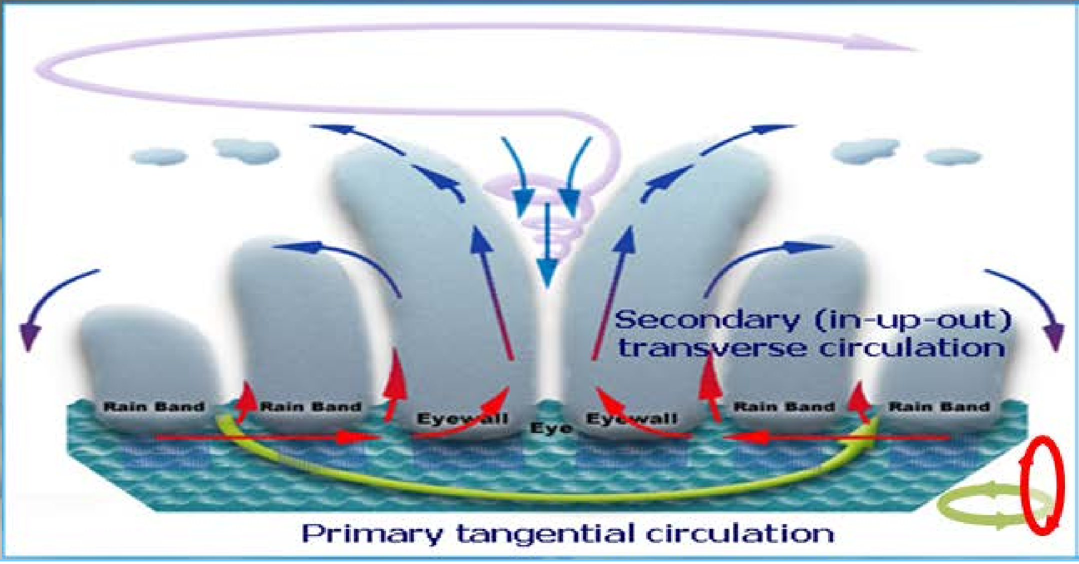
– THE EXACT TIMING OF GENESIS CAN BE IDENTIFIED;

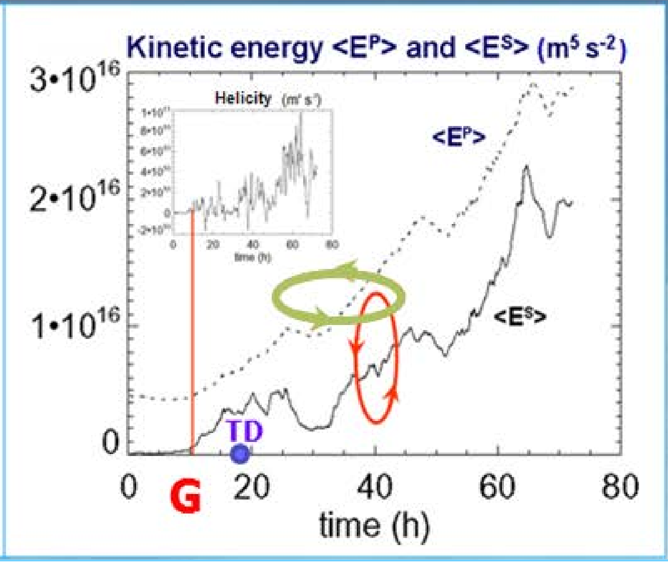
– THE CHAOTIC INFLUENCE FROM MOIST CONVECTION CAN BE QUANTIFIED.

DIAGNOSIS OF TROPICAL CYCLOGENESIS

WHEN will a nascent vortex become energy-self-sustaining?
– when the mutual intensification of the primary and secondary circulation begins!

ANALYSIS OF THE ENERGETICS





Diagnosis of TC Genesis – «G».

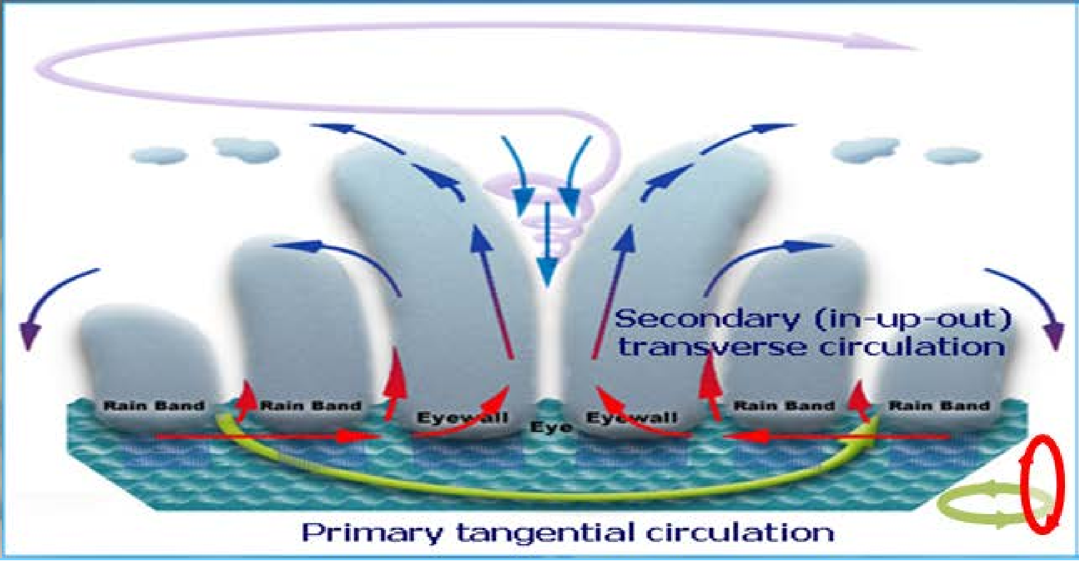
– can be implemented using modern atmospheric modeling systems

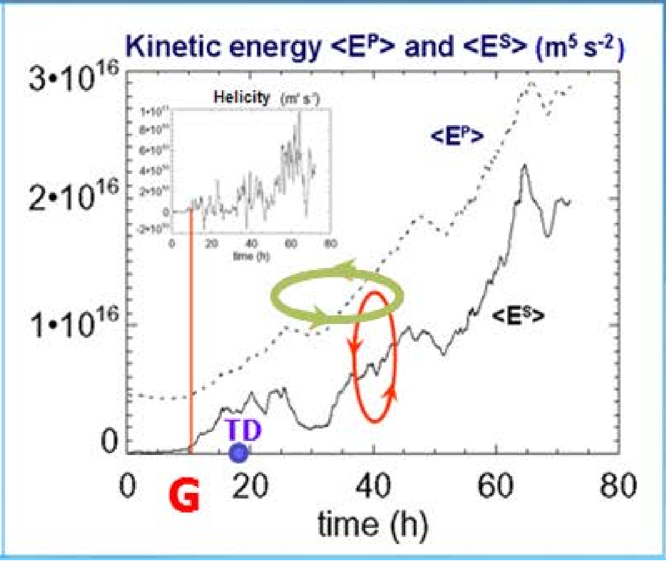
Cloud-resolving numerical analysis of the evolution of the kinetic energy of the **primary** circulation, **EP,** and the **secondary** circulation, **ES,** in a forming tropical cyclone (**TC**) makes it possible to determine the time **G**, when their mutual amplification begins and the forming vortex becomes energy-self-sustaining and intensifying.
The further evolution of the vortex leads to the formation of a tropical depression (**TD**) over the next few hours.

DIAGNOSIS OF TROPICAL CYCLOGENESIS

WHEN will a nascent vortex become energy-self-sustaining?
– when the mutual intensification of the primary and secondary circulation begins!

ANALYSIS OF THE ENERGETICS





Diagnosis of TC Genesis – «G».

– can be implemented using modern atmospheric modeling systems

For diagnosing of the large-scale instability, an analysis of system-scale dynamics was applied 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 by Montgomery et al. (2006), Appendix B. Thus, in cylindrical coordinates, the kinetic energy, **EP**, is determined as the square of the tangential velocity while the energy, **ES**, is defined as the sum of the squares of the radial velocity (“in” and “out”; fig.) and the vertical velocity (“up”; fig.).

NO AXIAL SYMMETRY !

KEY ROLE OF VORTICAL HOT TOWERS – VHTs

VHTs – intense rotating deep moist convection

The population of VHTs provides the linkage of the primary and secondary circulation in the forming vortex on system mesoscales.

VHTs provide all physics behind the vortex-motive force in the turbulent vortex dynamo theory:

Latent heat release,

Rotation,

Interaction between shear and vortical convection,

Non-zero helicity on cloud scales.

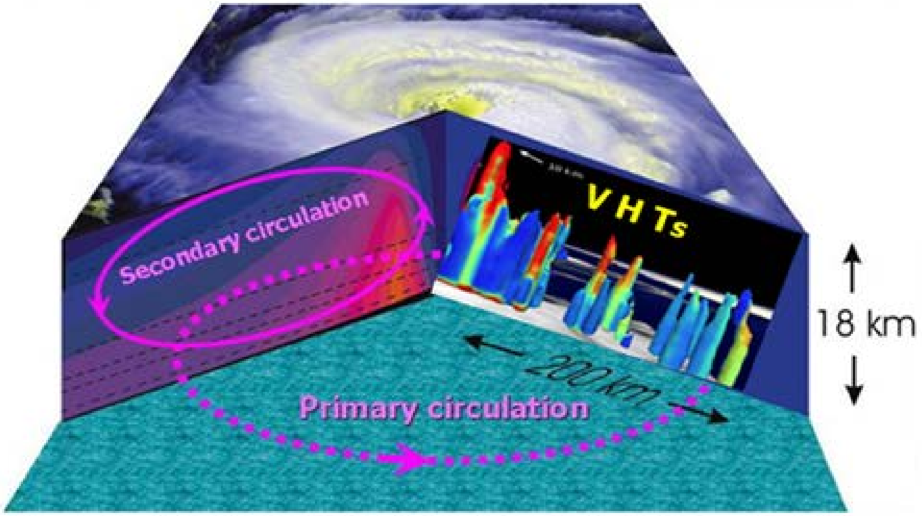
Levina G. V. ***Open Journal of Fluid Dynamics*****, 2018, 8, 86-114.**

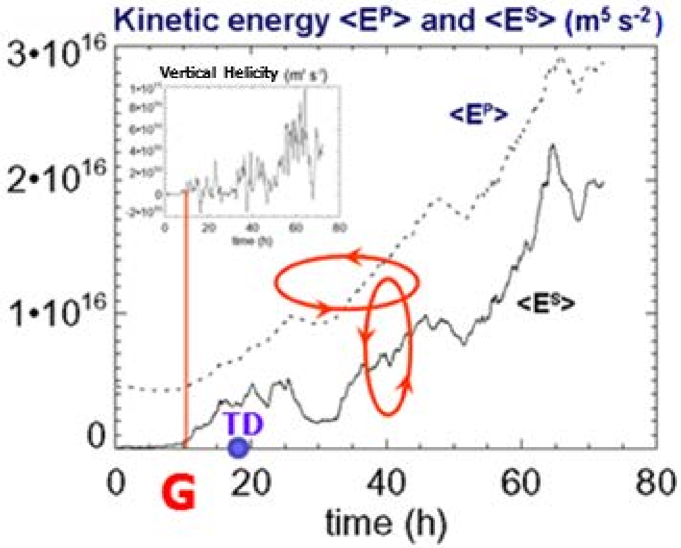
2020: TO DIAGNOSIS OF OBSERVED TCs

DIAGNOSIS OF TROPICAL CYCLOGENESIS

Diagnosis with patterns of the vertical helicity and temperature fields

Time **G** also marks a cardinal change in the structure of developing vortex system. The large-scale vortex instability commences nearly simultaneously with formation of the secondary circulation (SC). Thus, the onset of instability can also be traced with patterns of the corresponding physical fields.





Numerical Diagnosis of TC Genesis – «G». Experiment A2 [M06]

VHTs are the main actors providing the SC formation and maintenance.
They are known to perfectly be recognized in the fields of the vertical helicity and temperature.

[M06] – Montgomery M. T., Nicholls M. E., Cram T. A., Saunders A. B. 2006, *J. Atmos. Sci.*, 63, 355-386.

DIAGNOSIS OF TROPICAL CYCLOGENESIS

What happens on cloud & system scales? VHTs & nascent vortex evolution?

A new method was developed and applied, which allows localizing rotating convective flows.
To this purpose, we used the helicity density (not an integral), i.e., helicity values – h , calculated in each point of the finite-difference grid, specifically, its vertical spatial contribution – h_z ,

$$h = \boldsymbol{V} \cdot \boldsymbol{\omega} = u\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right) + v\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right) + \boxed{w\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)}.$$

The vertical helicity field can serve as a kind of filter for recognizing rotating convective cells.

Cloud scale (vertical helicity) and system scale (integrals of kinetic energy & helicity) analysis was carried out for the following 4 experiments from [M06] : A2 , B3 , C3 , and E1

No.	Name of experiment	Max v (m s^{-1}) at $z = 4$ km	Description of experiment ($\Delta x = \Delta y = 3$ km, SST = 29°C)
A2	3 km	6.6	Metamorphosis to surface vortex successful. Mean near-surface tangential wind ~13 m s^{-1} at 24 h, and 46 m s^{-1} at 72 h
B3	CAPE-less (3 km)	6.6	Low-level moisture decreased by 2 g kg^{-1}. Metamorphosis successful, but slower rate of development. Mean near-surface tangential wind ~9 m s^{-1} at 48 h
C3	Weak Vortex	5.0	Metamorphosis successful, but slower rate of development. Mean near-surface tangential wind ~9 m s^{-1} at 72 h. Circulation very asymmetric even at 72 h
E1	Zero Coriolis	6.6	Coriolis parameter set to zero ($f = 0$). Metamorphosis successful. Develop surface-concentrated vortex as in A1, but no subsequent intensification observed through 72 h

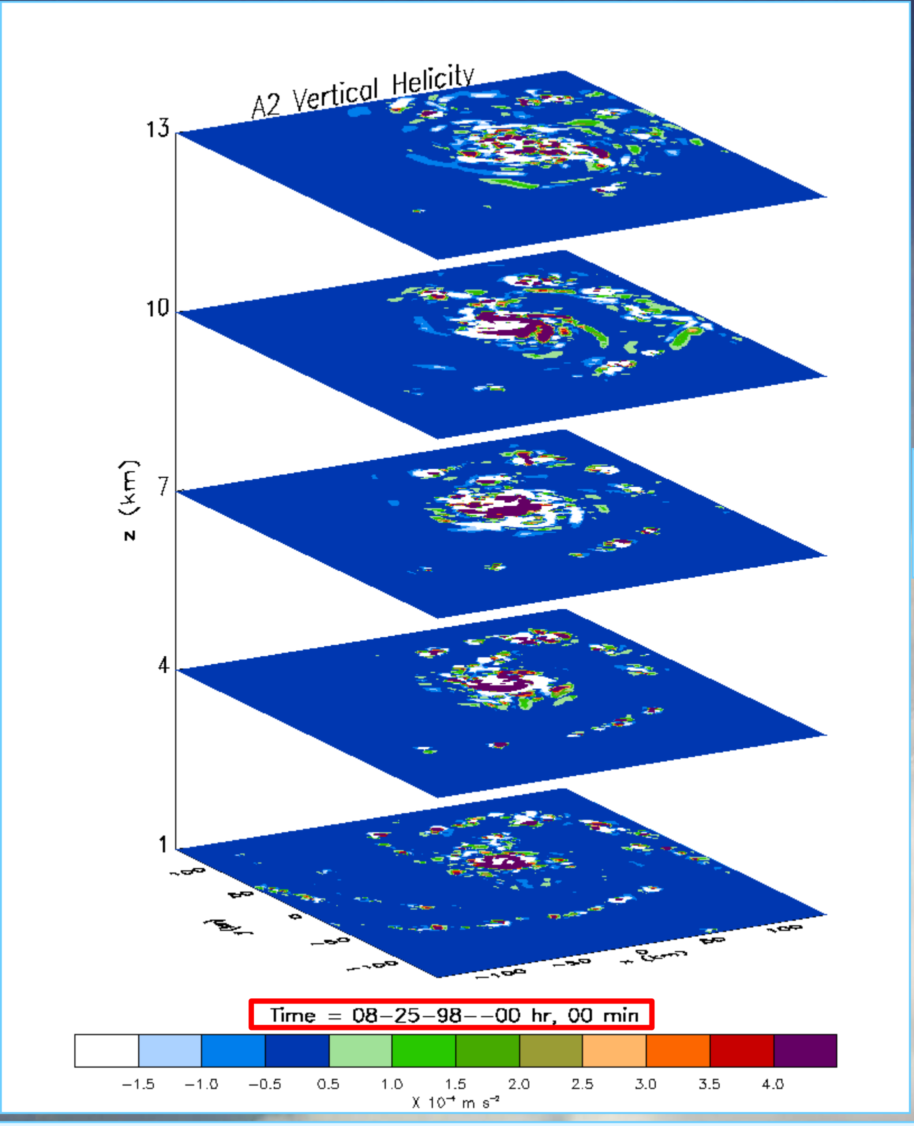
SST—Sea Surface Temperature; CAPE—Convective Available Potential Energy.

[M06] – Montgomery M. T., Nicholls M. E., Cram T. A., Saunders A. B. 2006, *J. Atmos. Sci.*, 63, 355-386.

VORTICAL CLOUD CONVECTION

POSITIVE HELICITY:
cyclonic updrafts &
anticyclonic downdrafts,

NEGATIVE HELICITY:
cyclonic downdrafts &
anticyclonic updrafts



08-22-98 12 hr Start
08-23-98 00 hr G
08-23-98 04 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

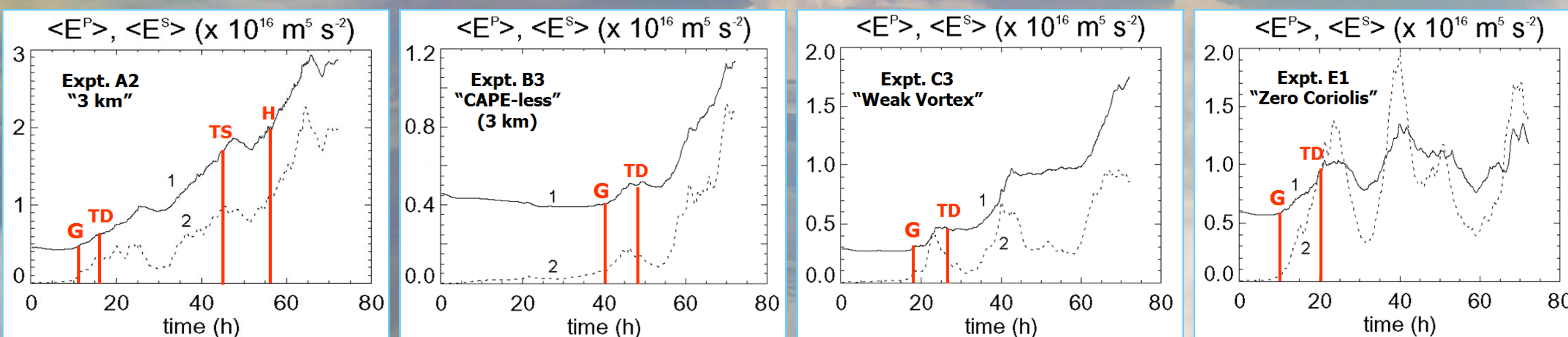
Expt. A2 [M06]. VERTICAL HELICITY: VORTICAL CONVECTION

DIAGNOSIS OF TROPICAL CYCLOGENESIS

What happens on cloud & system scales? VHTs & nascent vortex evolution?

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

Experiment	The first VHT ≥ 13 km in height		Genesis Instability Start Time (h)	Tropical Depression	
	Time (h)	Max Vertical Helicity (ms^{-2})		Time (h)	V (ms^{-1})
A2	8	1.3×10^{-3}	12	16	9.4
B3	38	6.1×10^{-4}	40	48	8.8
C3	18	1.4×10^{-3}	18	26	7.5
E1	8	5.2×10^{-4}	10	20	8.2



Evolution of the kinetic energy of primary (1) and secondary (2) circulation, shown respectively by solid and dotted line. Red lines mark the energy magnitudes, and, at the time moments corresponding to:

G – a mutual intensification of both circulations starts and the nascent vortex becomes energy-self-sustaining;

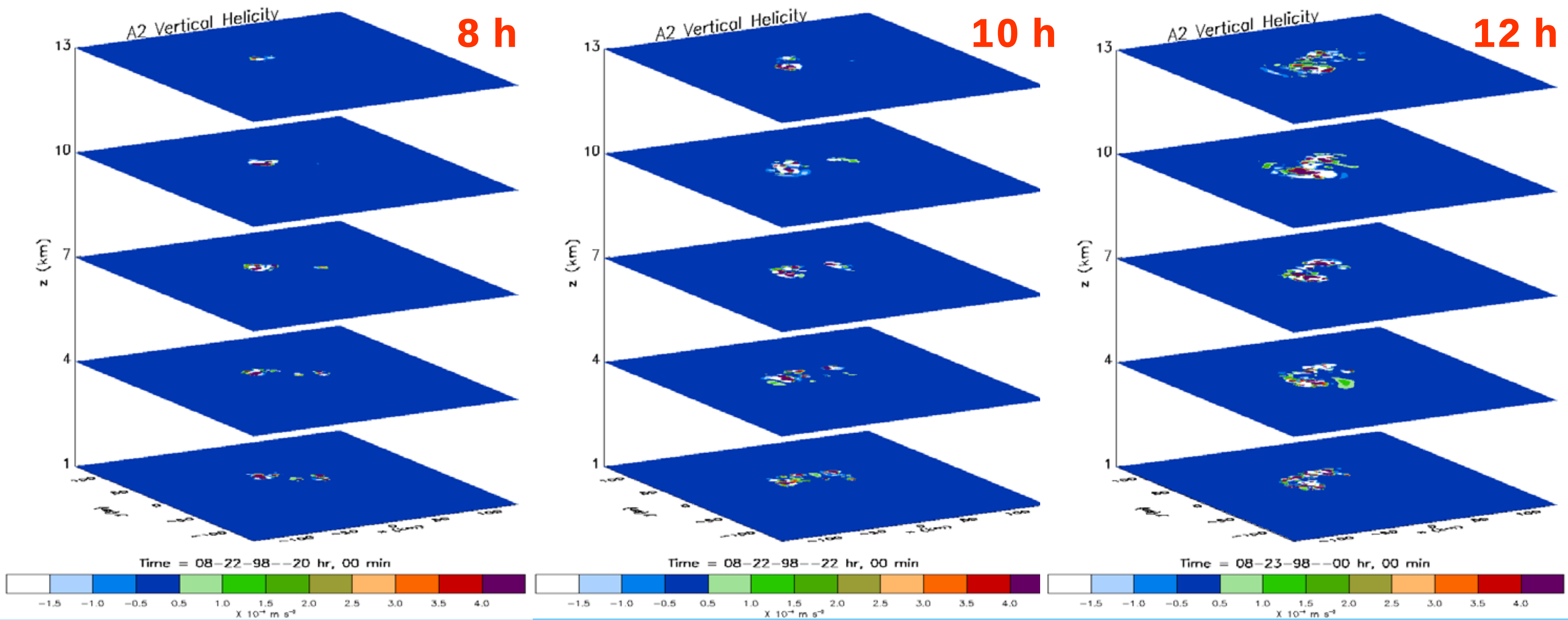
TD – the tropical depression is formed; TS – the vortex reaches the intensity of tropical storm;

H – the vortex intensifies up to hurricane strength.

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

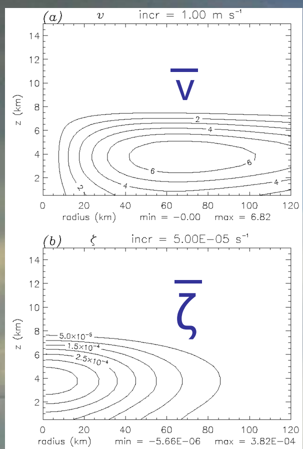
THE VERTICAL HELICITY ALLOWS LOCALIZATION OF VERTICAL ROTATING FLOWS:

+ cyclonic updrafts or / and anticyclonic downdrafts

- cyclonic downdrafts or / and anticyclonic updrafts

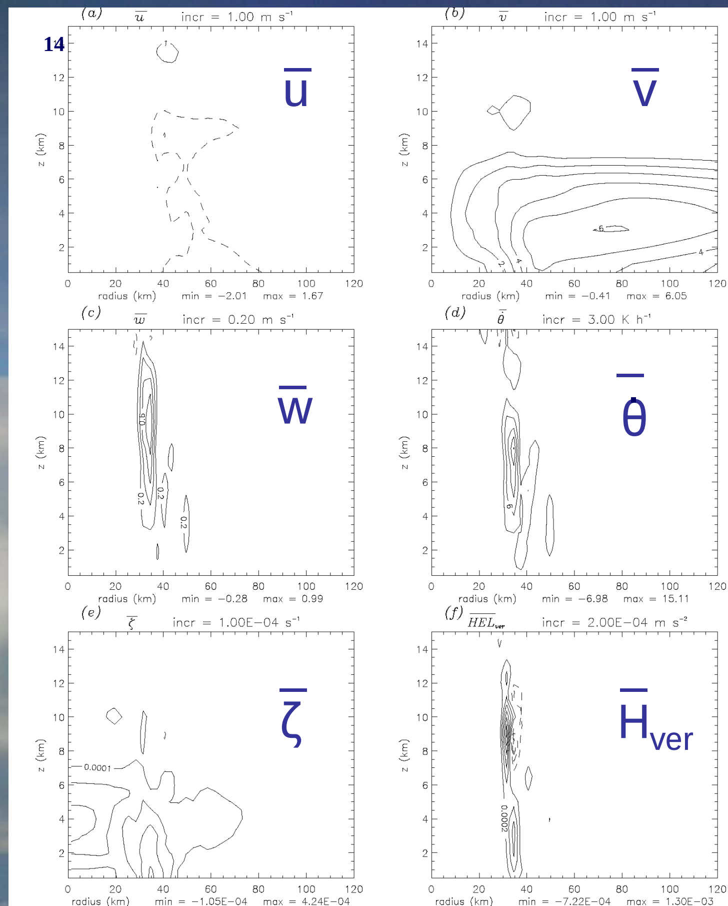
FORMATION OF THE SECONDARY OVERTURNING CIRCULATION
IN (u) – UP (w) – OUT (u) FLOW during t = 10 – 12 h

t = 0 h

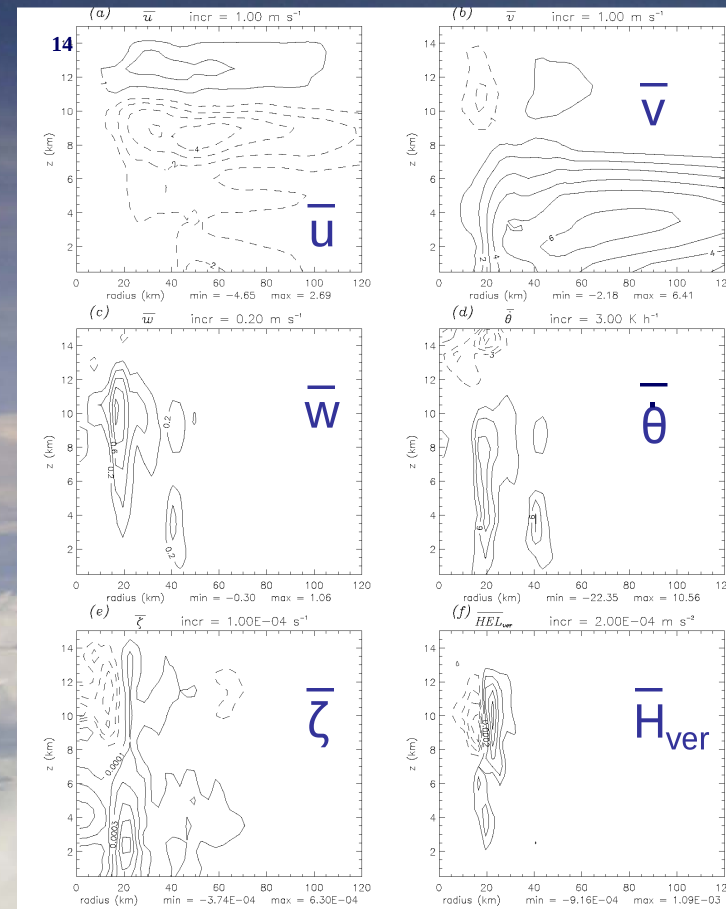


Initial MCV

t = 10 h



t = 12 h



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

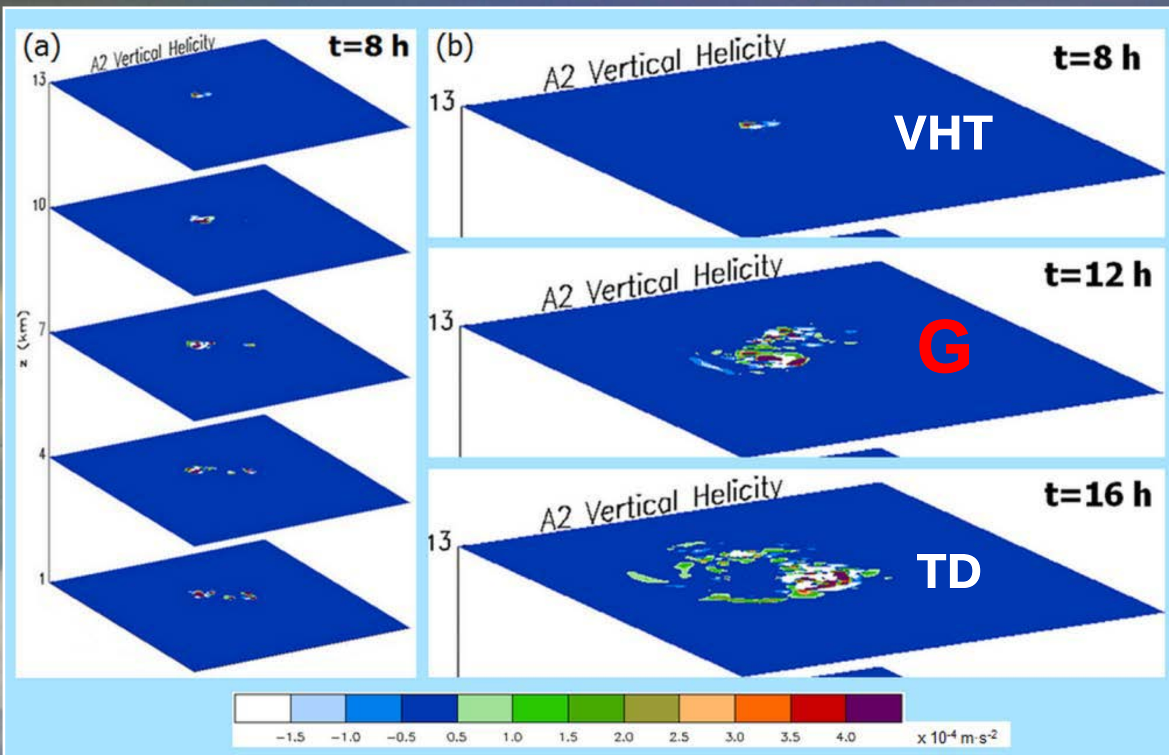
u – the radial velocity, v – the tangential velocity, w – the vertical velocity,

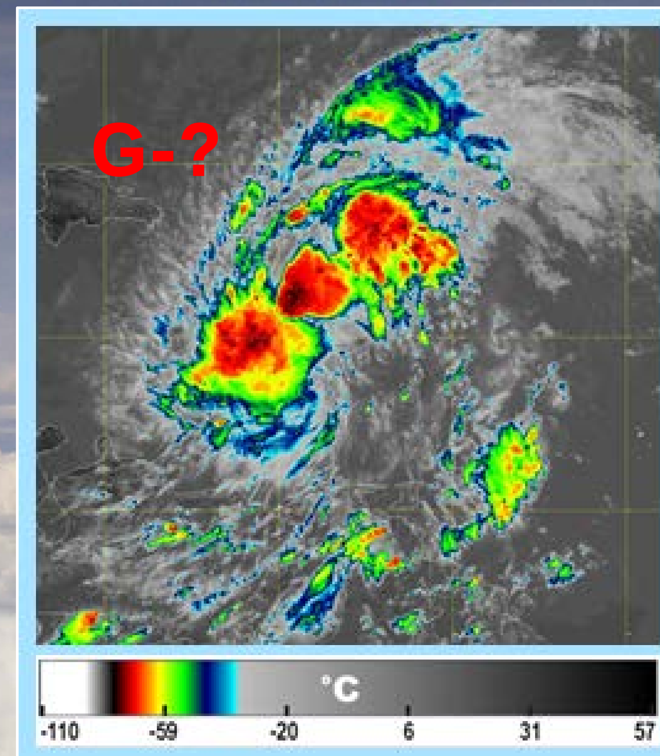
θ – the diabatic heating rate, ζ – the relative vorticity, H_{ver} – the vertical contribution of helicity.

DIAGNOSIS OF TROPICAL CYCLOGENESIS

VHTs patterns in the vertical helicity field (numerical RAMS simulation)

VHTs – temperature field (satellite data)





***t* = 8 h:** **the first VHT ≥ 13 км** (a, b);
***t* = 12 h: G – the onset of instability!** (b);
***t* = 16 h: TD is formed** (b).

(b) *z*=13 km: the upper level of computational domain 276 x 276 km.

Infrared satellite image.
Dark red and black color – strong updrafts – **"Overshooting Cloud Tops" ≥ 13 km.**

SUMMARY OF NUMERICAL ANALYSIS

FUNDAMENTAL:

• Crucial role of VHTs has been emphasized in the onset of new large-scale vortex instability in the tropical atmosphere;

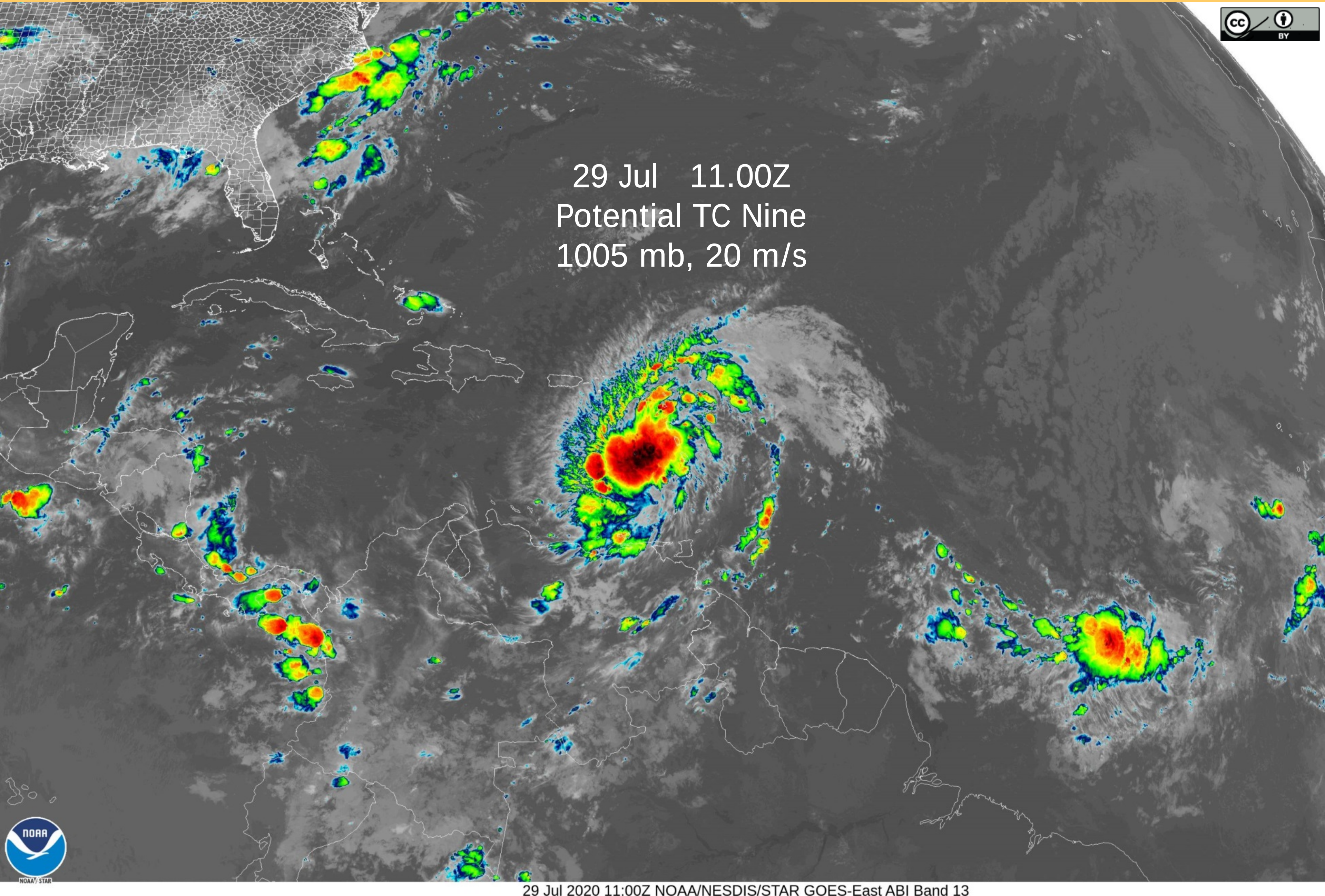
• Interpretation of tropical cyclogenesis as a pre-depression large-scale helical-vortex instability allows:
- providing the exact time when cyclogenesis commences,
- quantifying the chaotic influence resulting from moist convection.

PRACTICAL:

• Helicity and its spatial contributions have been introduced into cloud-resolving numerical analysis to quantitatively examine the new instability;

• The field of the vertical helicity has first been proposed and applied as a filter to precisely localize atmospheric vortical convection.

2020: FORMING HURRICANE ISAIAS



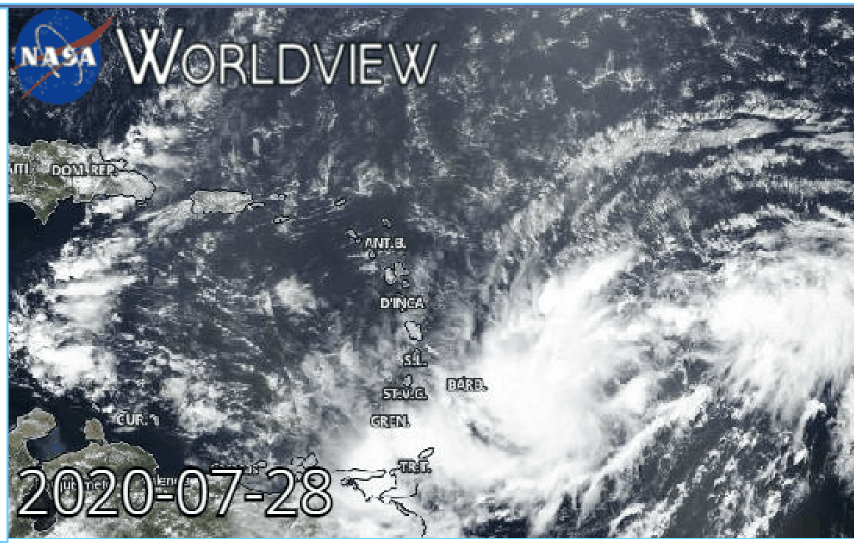
PRE-ISAIAS 23-29 July 2020

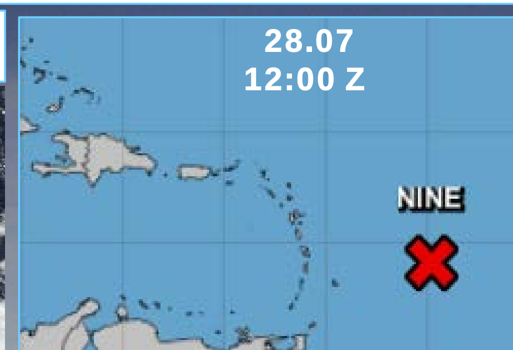
23 July. An easterly wave off the coast of Africa was first identified by NHC. When traveling over warm tropical waters, the wave developed a broad area of low pressure and intensifying convection, and became more organized.

28 July. The system was approaching the Leeward Islands.

Satellite data showed that the system did not have a well-defined center. Surface observations showed gale-force winds about 15-18 m/s.

Therefore, a threat of TC genesis prompted to designate Potential Tropical Cyclone (TCP) – Nine (×) – on July 28.

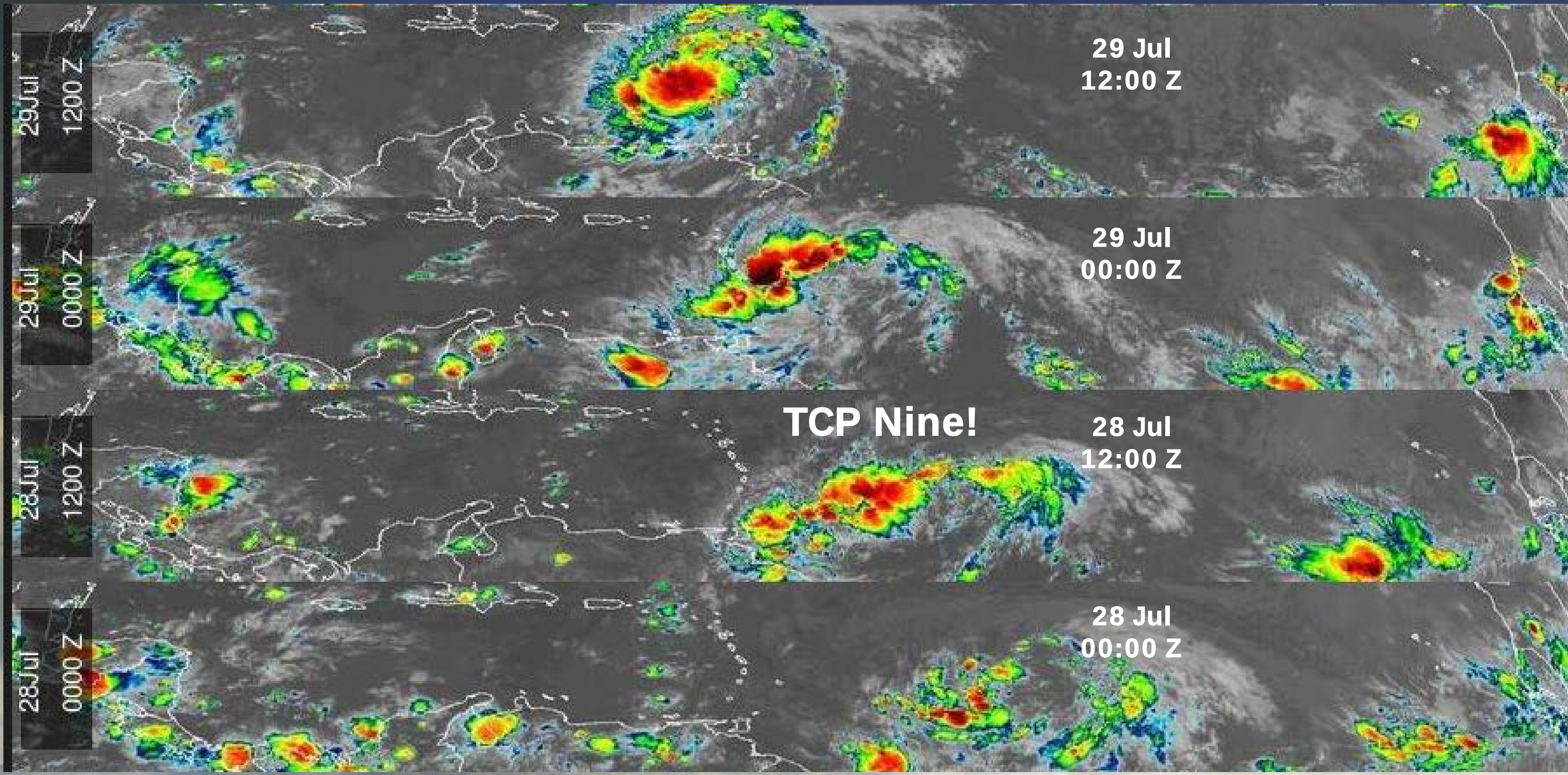




28-29 July. The situation continued to remain very uncertain, since the Air Force Reserve reconnaissance aircraft, several hours later, also failed to detect a well-defined center of circulation.

30 July. As a formed tropical cyclone **TCP Nine** was identified only 36 hours later, and **at the stage of tropical storm with winds approximately 23 m/s.** The vortex named **TS Isaias** was located to the South of Puerto Rico – 250 km, and Dominicana – 430 km.

PRE-ISAIAS 28-29 July 2020



After years of working with patterns of vortical convection from idealized simulations, and here, comparing them with patterns of 'Overshooting Cloud Tops' in satellite data, the author suggests the onset of large-scale vortex instability between 00:00 Z – 12:00 Z (TCP Nine was designated) 28 July, while later, 29 July – already well developed instability.

Hovmöller diagram is courtesy of Dr. Brian McNoldy, University of Miami.

SUMMARY AND PERSPECTIVE

- Interpretation of tropical cyclogenesis as a pre-depression large-scale helical-vortex instability via examination of system-scale dynamics (analysis of the kinetic energy and helicity) allows:
  - providing the exact time when cyclogenesis commences,
  - quantifying the chaotic influence resulting from moist convection.

- Based on the VHTs role in the formation and maintenance of the secondary circulation and, therefore, of the whole mesoscale vortex system, we propose how the onset of large-scale instability can be diagnosed with VHTs patterns in the fields of temperature and vertical helicity.

- **Practical Significance:** we propose the fundamental ground and quantitative analysis for the term "Potential Tropical Cyclone" introduced by NOAA/NWS/NHC since 2017. The onset of instability/beginning of TC genesis is **perfect to designate TCP !**

- **For the operational diagnosis of instability**, we suggest the analysis of GOES Imagery supported by cloud-resolving numerical modeling. Diagnosis with VHTs patterns also opens an effective opportunity to leverage the most modern tools of AI and Machine Learning.

This work was supported by the research project "Monitoring" No. 01200200164 (Russia); the post-processing for the cloud-resolving simulation was supported in part by the U.S. National Science Foundation, Grant ATM-0733380.

THANK YOU FOR YOUR INTEREST !