How do tropical cyclones form?

For a cyclone to form several preconditions must be met:

1. Warm ocean waters (of at least 26.5°C) throughout a sufficient depth (unknown how deep, but at least on the order of 50 m). Warm waters are necessary to fuel the heat engine of the tropical cyclone.

2. An atmosphere which cools fast enough with height (is "unstable" enough) such that it encourages thunderstorm activity. It is the thunderstorm activity which allows the heat stored in the ocean waters to be liberated for the tropical cyclone development.

3. Relatively moist layers near the mid-troposphere (5 km). Dry mid levels are not conducive for allowing the continuing development of widespread thunderstorm activity.

4. A minimum distance of around 500 km from the equator. Some of the earth's spin (Coriolis force) is needed to maintain the low pressure of the system. (Systems can form closer to the equator but it's a rare event)

5. A pre-existing disturbance near the surface with sufficient spin (vorticity) and inflow (convergence). Tropical cyclones cannot be generated spontaneously. To develop, they require a weakly organised system with sizeable spin and low level inflow.

6. Little change in the wind with height (low vertical wind shear, i.e. less than 40 km/h from surface to tropopause). Large values of wind shear tend to disrupt the organisation of the thunderstorms that are important to the inner part of a cyclone.

Having these conditions met is necessary, but not sufficient as many disturbances that appear to have favourable conditions do not develop.

http://www.bom.gov.au

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So: how do they form? !!!

http://www.bom.gov.au

Lead PI: Michael Montgomery, Naval Postgraduate School & NOAA-HRD

Science Steering Committee: Chris Davis (NCAR), Lance Bosart (Albany, SUNY), Andy Heymsfield (NCAR), Michael Montgomery,(NPS), Rob Rogers (NOAA/HRD)

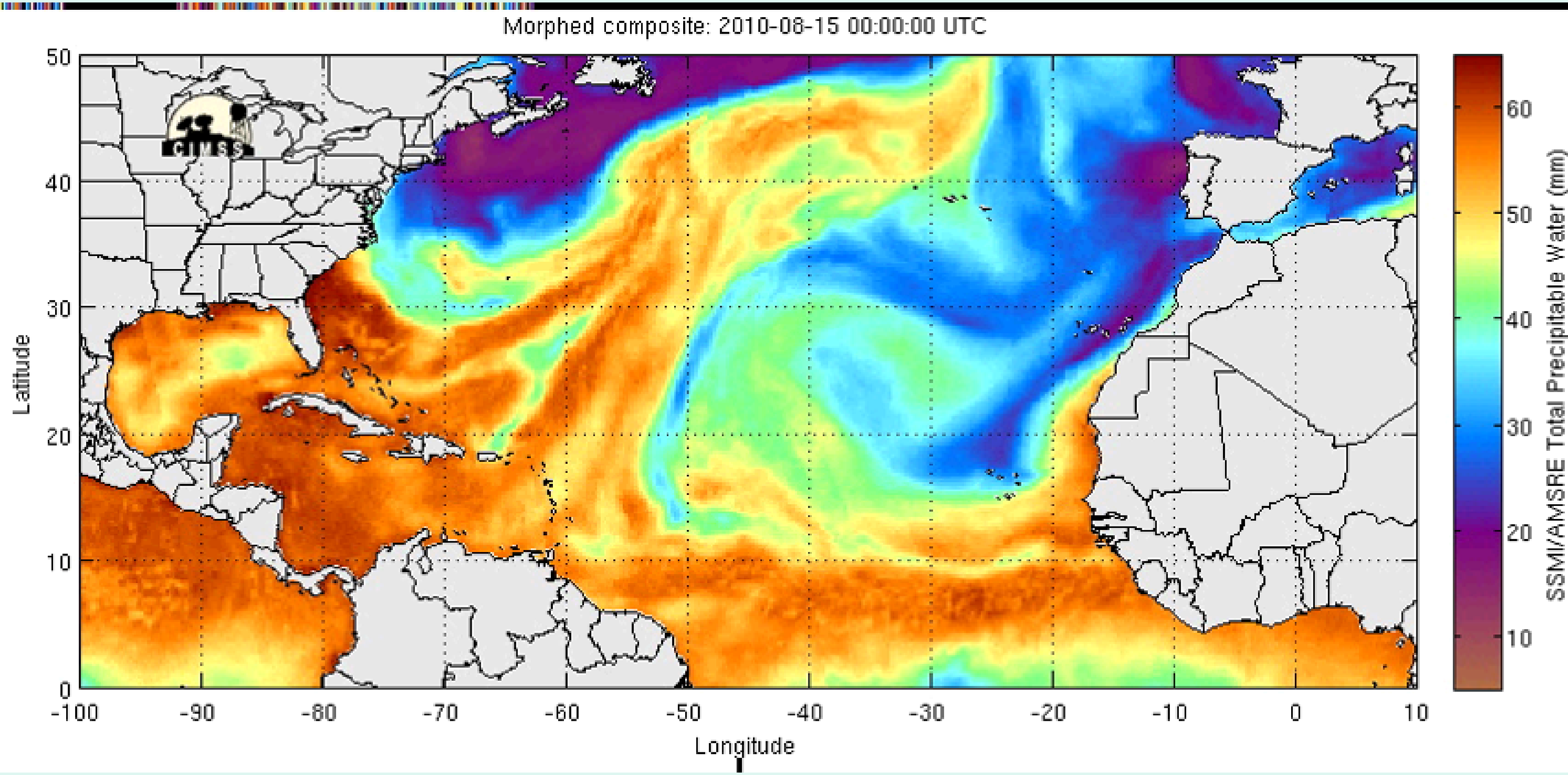
Participating Universities and Organizations: NPS, NWRA, Albany, Miami, Wisconsin, Penn State, Purdue, Munich, Illinois, Howard, CU, Oregon State, Princeton, Univ. Illinois

Work presented here in collaboration with: Tim Dunkerton, Roger Smith, Zhuo Wang, Mark Boothe, Chris Davis, Michael Bell and the PREDICT team.

PREDICT

August 15 - September 30, 2010

PRE-Depression Investigation of Cloud systems in the Tropics



Morphed composite: 2010-08-15 00:00:00 UTC
Latitude
Longitude
50
40
30
20
10
0
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
SSMI/AMSRE Total Precipitable Water (mm)
60
50
40
30
20
10

3 New Hypotheses

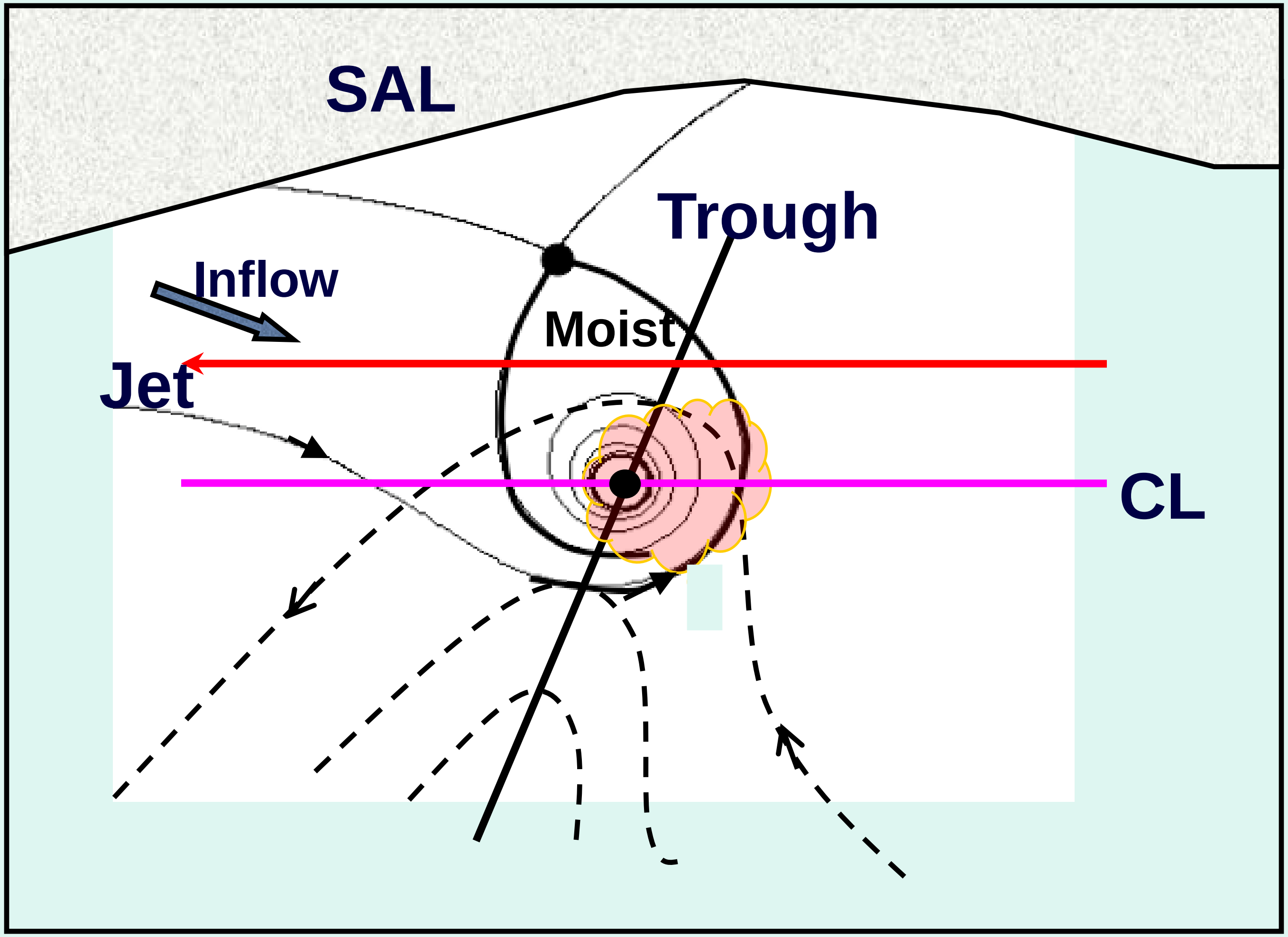
- H1: Wave breaking or roll-up of cyclonic vorticity near the critical surface in the lower troposphere (>600 hPa) provides favorable environment and focal point for aggregation of convectively-generated cyclonic vorticity anomalies.

- H2: The wave critical layer is a region of closed circulation, where air is repeatedly moistened by deep convection and also protected from dry air entrainment to some extent.

- H3: The parent wave is maintained and possibly enhanced by diabatically amplified mesoscale vortices within the wave. (Heating is most effective when intrinsic frequency --> 0.)

The “baby” proto-vortex is carried along in the “pouch” (CL cat’s eye) by the “mother” wave until it is strengthened into an independent and self-sustaining vortex.

Old and New Flow Geometry

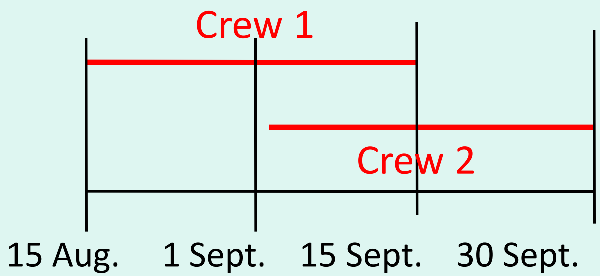


Our hypothetical pathway for genesis via tropical waves may be regarded as a marsupial theory of tropical cyclogenesis in which the “juvenile” proto-vortex is carried along by the “mother” wave until it is ready to be “let go” as an independent & self-sustaining vortex.

PREDICT (PRE-Depression Investigation of Cloud-systems in the Tropics)

- 15 August – 30 Sept. 2010
- Base: St. Croix Virgin Islands
- NCAR G-V: ~173 research hours used
- 26 flights, 8 disturbances
  - Test (1)
  - PGI27 (2)
  - PGI30 (2)
  - PGI36 – Fiona – (3)
  - PGI38 – ex-Gaston- (5)
  - PGI44 – Karl – (6)
  - PGI46 – Matthew – (4)
  - PGI50 – Nicole – 2
  - PGI48 (1)

• 558 dropsondes used



Double-crewed G-V, 2-15 Sept.

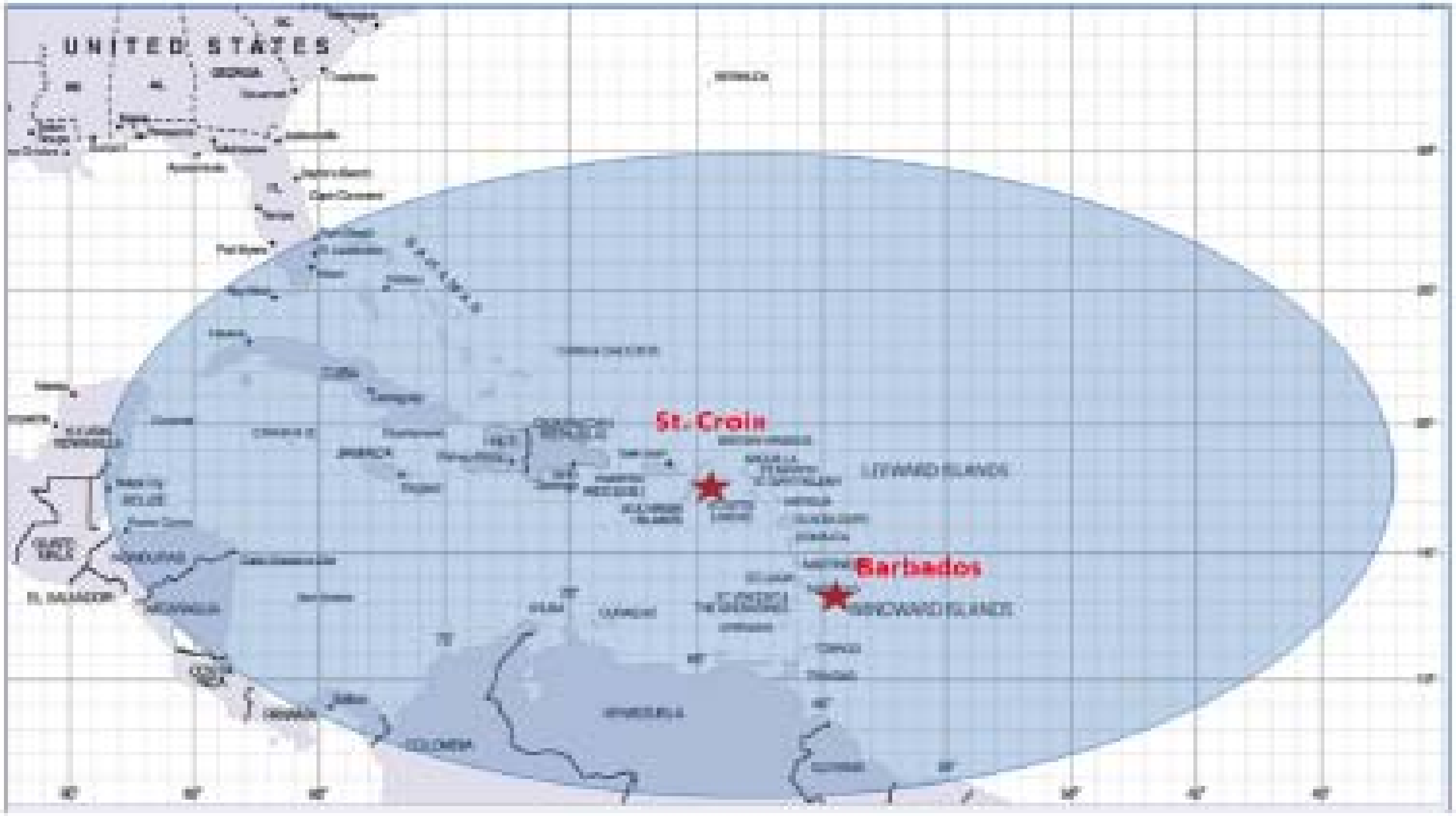


Figure 1. PREDICT domain. The primary base of operations was St. Croix, USVI, with an alternate of Barbados.

THE PRE-DEPRESSION INVESTIGATION OF CLOUD-SYSTEMS IN THE TROPICS (PREDICT) EXPERIMENT

Scientific Basis, New Analysis Tools, and Some First Results

BY MICHAEL T. MONTGOMERY, CHRISTOPHER DAVIS, TIMOTHY DUNKERTON, ZHUO WANG, CHRISTOPHER VELDEN, RYAN TORN, SHARANYA J. MAJUMDAR, FUQING ZHANG, ROGER K. SMITH, LANCE BOSART, MICHAEL M. BELL, JENNIFER S. HAASE, ANDREW HEYMSFIELD, JORGEN JENSEN, TERESA CAMPOS, AND MARK A. BOOTHE

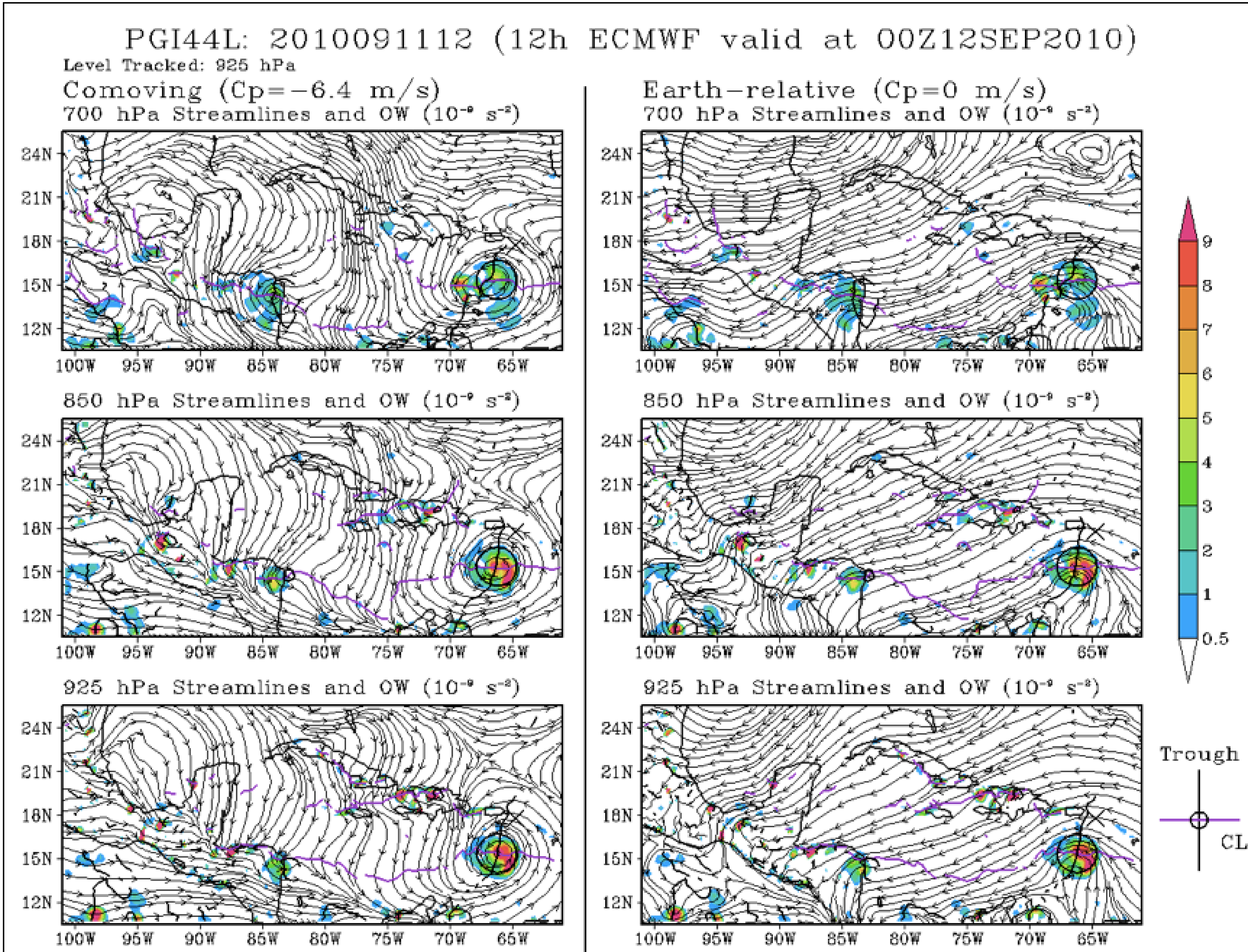
A field study involving 25 flights into Atlantic tropical disturbances tested the principal hypotheses of a new model of tropical cyclogenesis, known as the marsupial paradigm.

A longstanding challenge for hurricane forecasters, theoreticians, and numerical weather forecast systems is to distinguish tropical waves that will develop into hurricanes from tropical waves that will not. While tropical easterly waves occur frequently over the Atlantic and east Pacific, only a small fraction of these waves (~20%; e.g., Frank 1970) evolve into tropical storms when averaged over the hurricane season. The problem was insightfully summarized by Gray (1998): "It seems unlikely that the formation of tropical cyclones will be adequately understood until we more thoroughly document the physical differences between those systems which develop into tropical cyclones from those prominent tropical disturbances which have a favorable climatological and synoptic environment, look very much like they will develop but still do not."

The formation of tropical cyclones (TCs) is one of at understanding the science of tropical cyclone formation. These include the National Aeronautics and Space Administration (NASA) Tropical Cloud Systems and Processes (TCSP) experiment in 2005 (Halverson et al. 2007), the NASA African Multi-Disciplinary Monsoon Analyses (NAMMA) project in 2006 (Zipser et al. 2009), and the Tropical Cyclone Structure experiment in 2008 (TCS-08; Elsberry and Harr 2008). Adding the results of earlier efforts such as the Tropical Experiment in Mexico (TEXMEX; Bister and Emanuel 1997; Raymond et al. 1998) and even serendipitous observations of the early intensification of Hurricane Ophelia in the Hurricane Rainband and Intensity Change Experiment (RAINEX; Houze et al. 2006), and occasional observations from reconnaissance aircraft (Reasor et al. 2005), we have a collection of studies that have sampled pieces of a large and complex scientific puzzle. However, with the exception of the TCS08

ECMWF Forecast in the Marsupial Framework for storm PGI44L

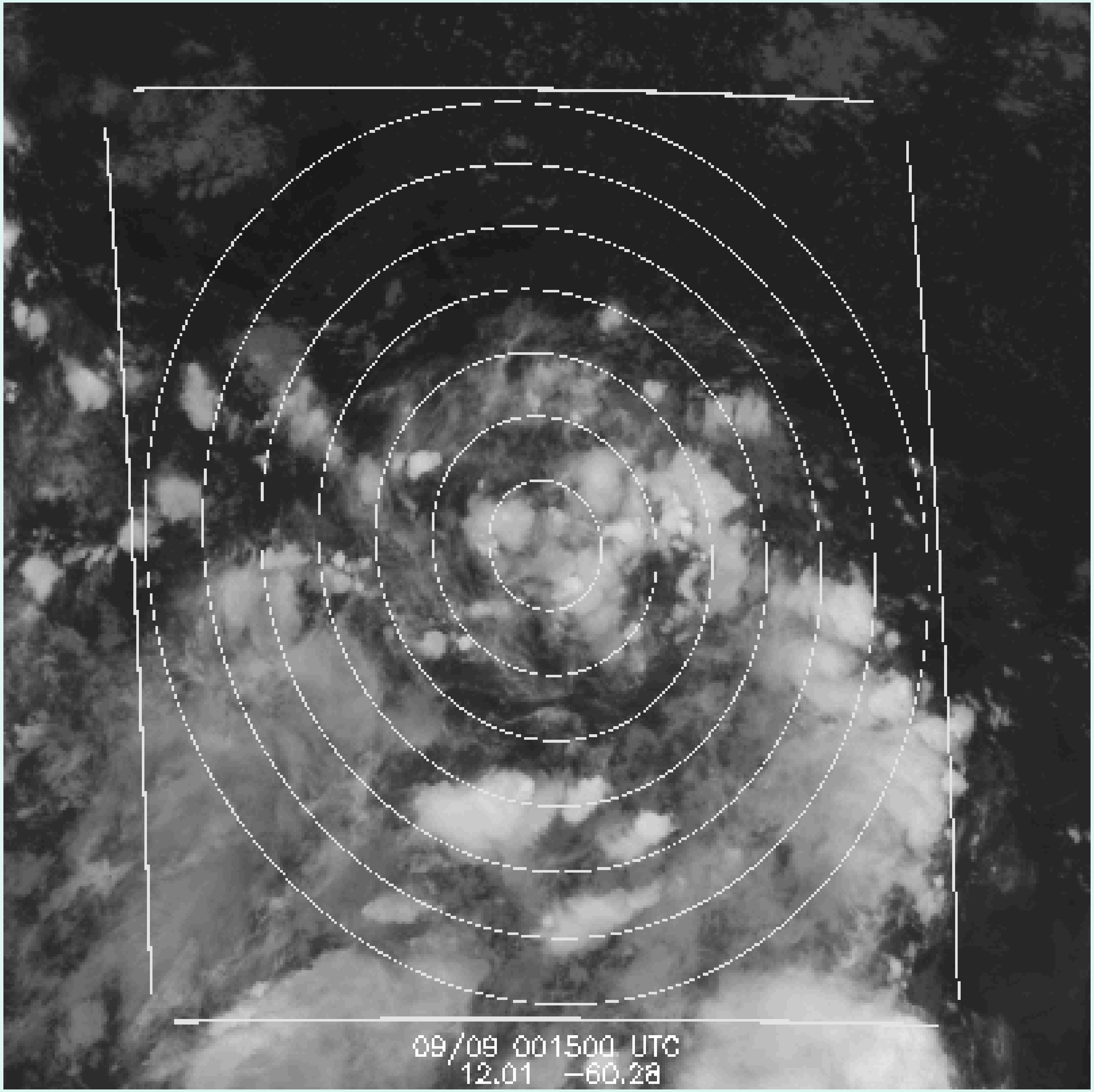
Loop Mode		Animate Frames			Dwell First		Dwell Last		Adjust Speed		Advance One		Frame Number: 2
NORMAL	SWEEP	REW	STOP	FWD	DEC	INC	DEC	INC	--	++	-1	+1	



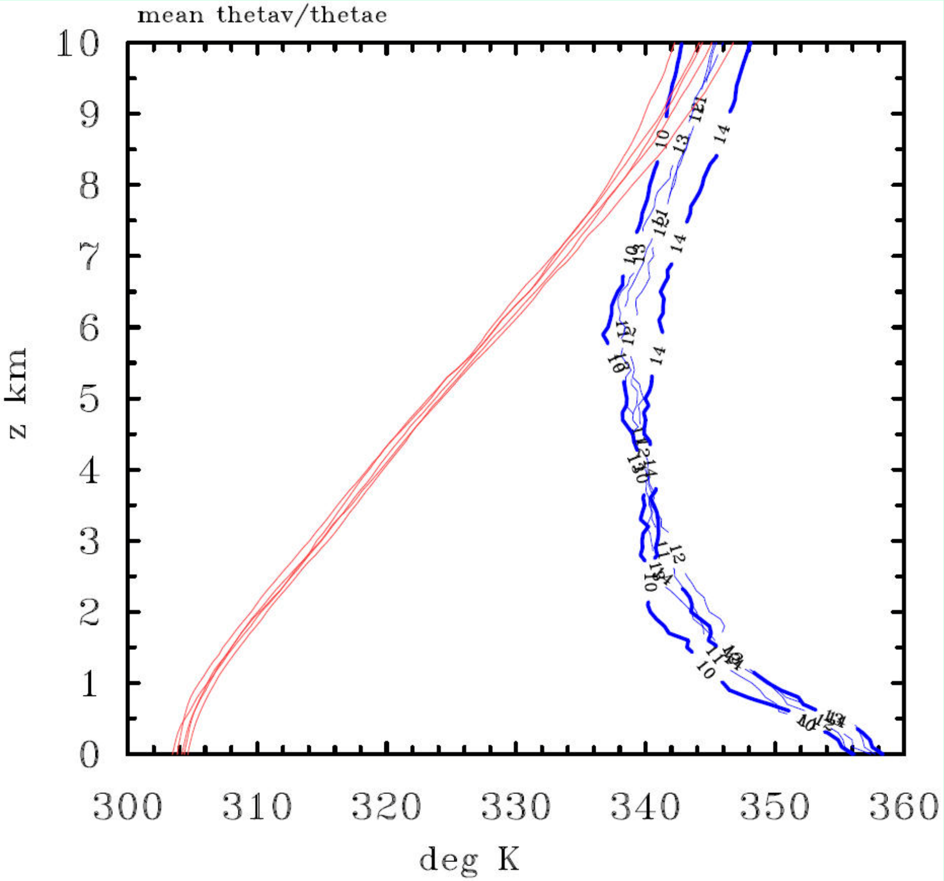
Pouch centric movie of pre-Karl's moist convection viewed through IR cloud top temperatures

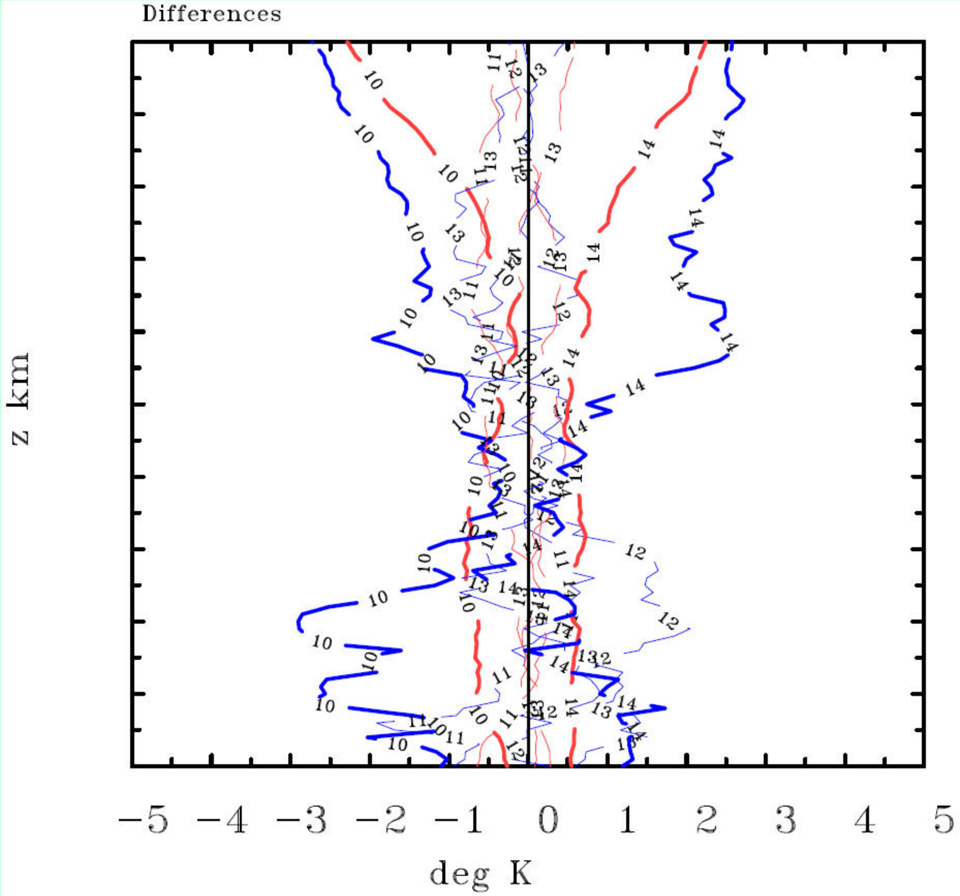
Play Video

Courtesy of Dave Ahijevych & Chris Davis NCAR-MMM


09/09 001500 UTC
12.01 -60.28

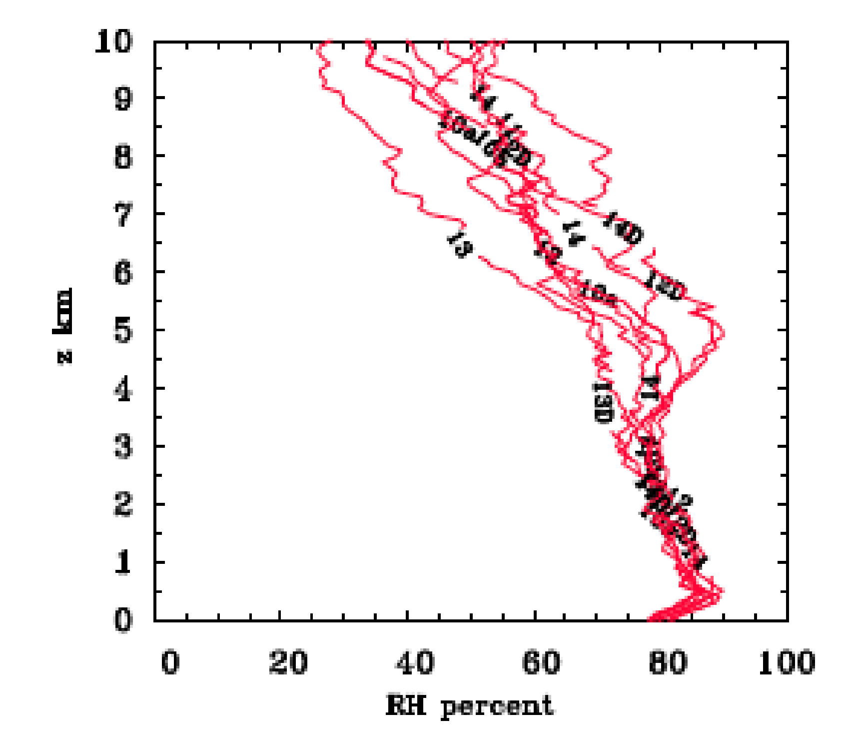
PGI44L pre-Karl





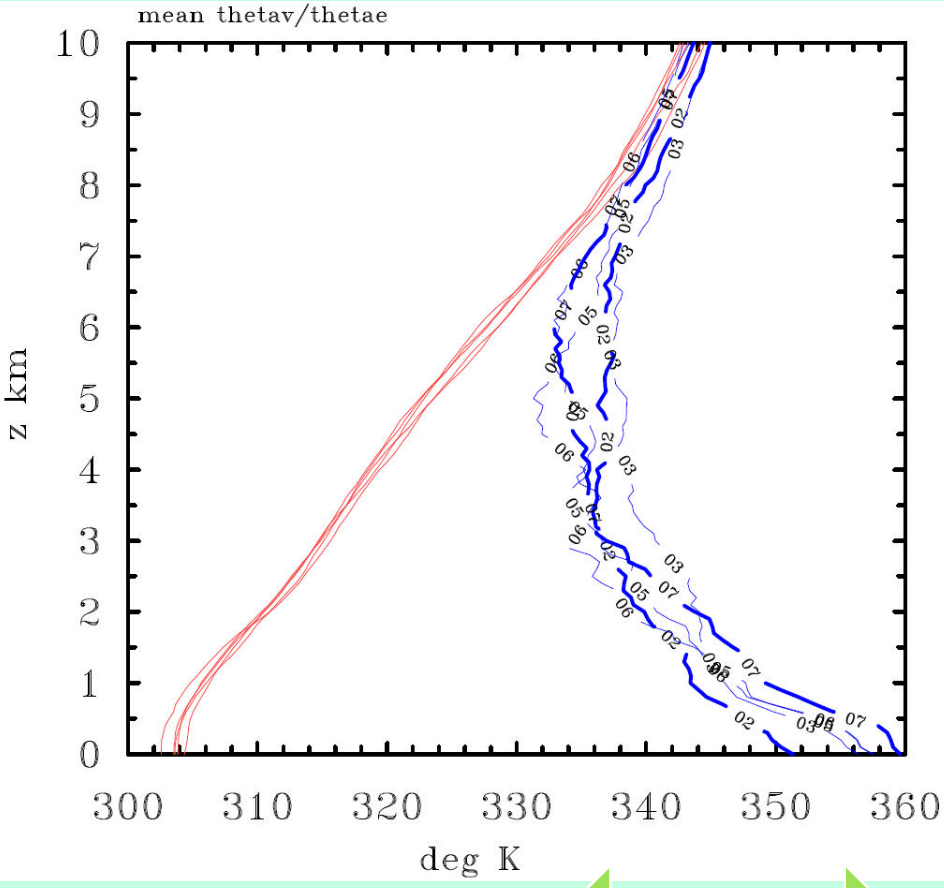
~17 K

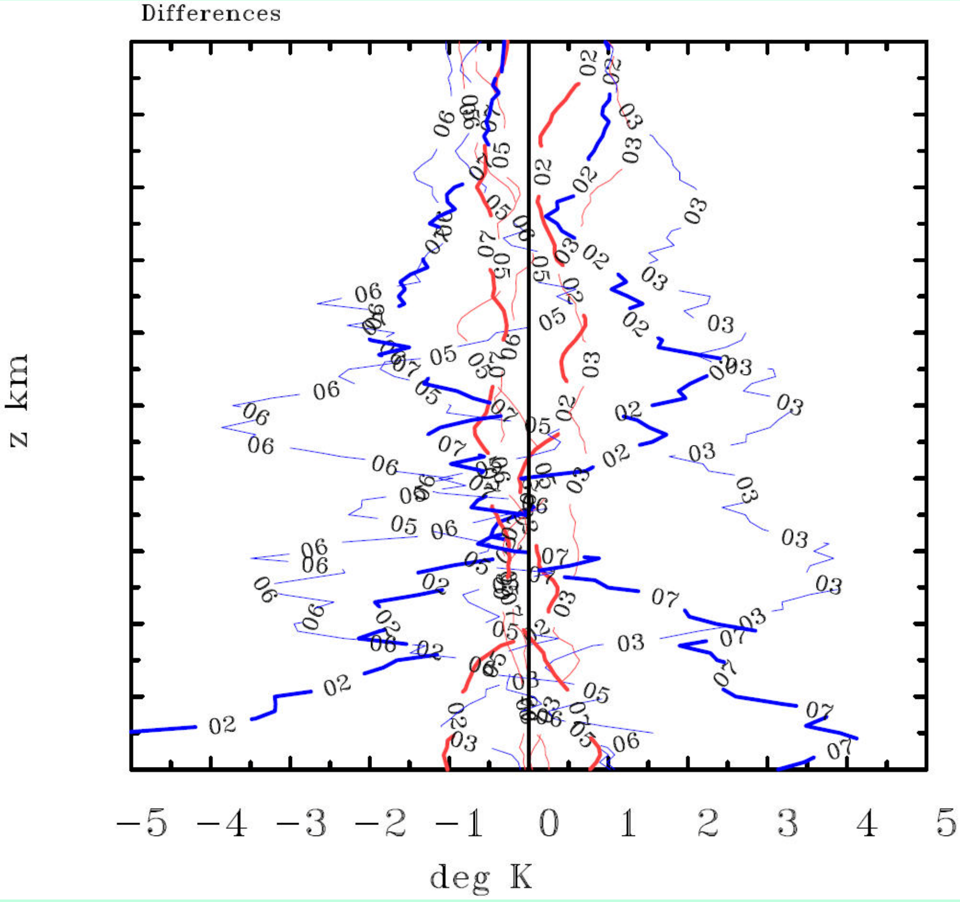
Pre-Karl Pouch-Averaged Relative Humidity



Vertical profiles of the day-to-day variability in system-mean relative humidity from the mean profile of all days for pre-Karl during the period 10-14 September. The thick curves mark the first and last days of the sequence. Numbers on curves refer to the date. A letter 'D' refers to a DC8 flight.

PGI38L (ex-GASTON)





~25 K

QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY
Q. J. R. Meteorol. Soc. 137: 1–18 (2011)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/qj.000

Observations of the convective environment in developing and non-developing tropical disturbances

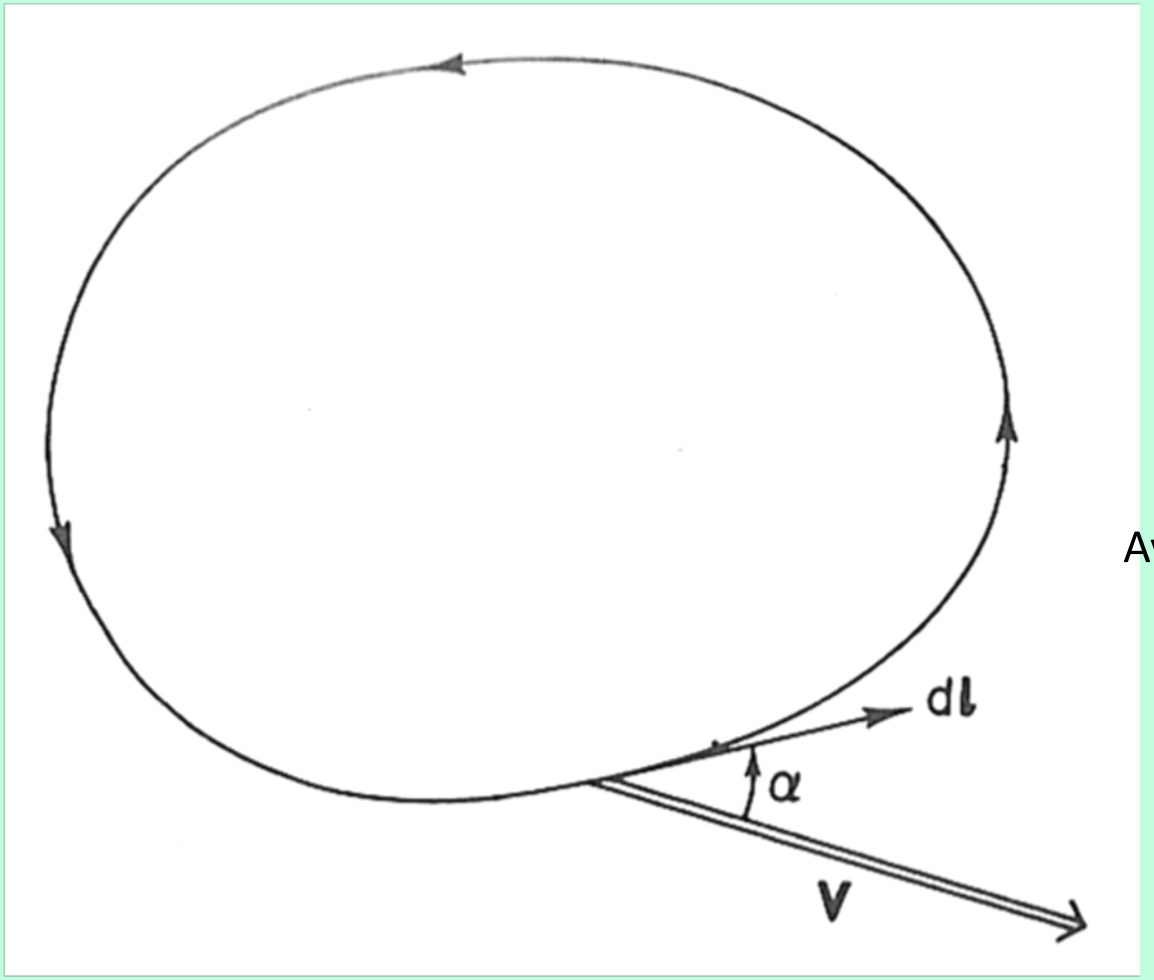
Roger K. Smith[a] [1] and Michael T. Montgomery[b]
[a] *Meteorological Institute, University of Munich, Munich, Germany*
[b] *Dept. of Meteorology, Naval Postgraduate School, Monterey, CA & NOAA's Hurricane Research Division, Miami, FL, USA.*

- **The most prominent difference between the non-developing system and the two systems that developed was the much larger reduction of θ_e between the surface and a height of 3 km, typically 25 K in the non-developing system, compared with only 17 K in the systems that developed.**

- **Conventional wisdom would suggest that, for this reason, the convective downdraughts would be stronger in the non-developing system and would thereby act to suppress the development.**

- **Here we invoke an alternative hypothesis that the drier mid-level air weakens the convective updraughts and thereby weakens the amplification of system relative vorticity necessary for development.**

Circulation



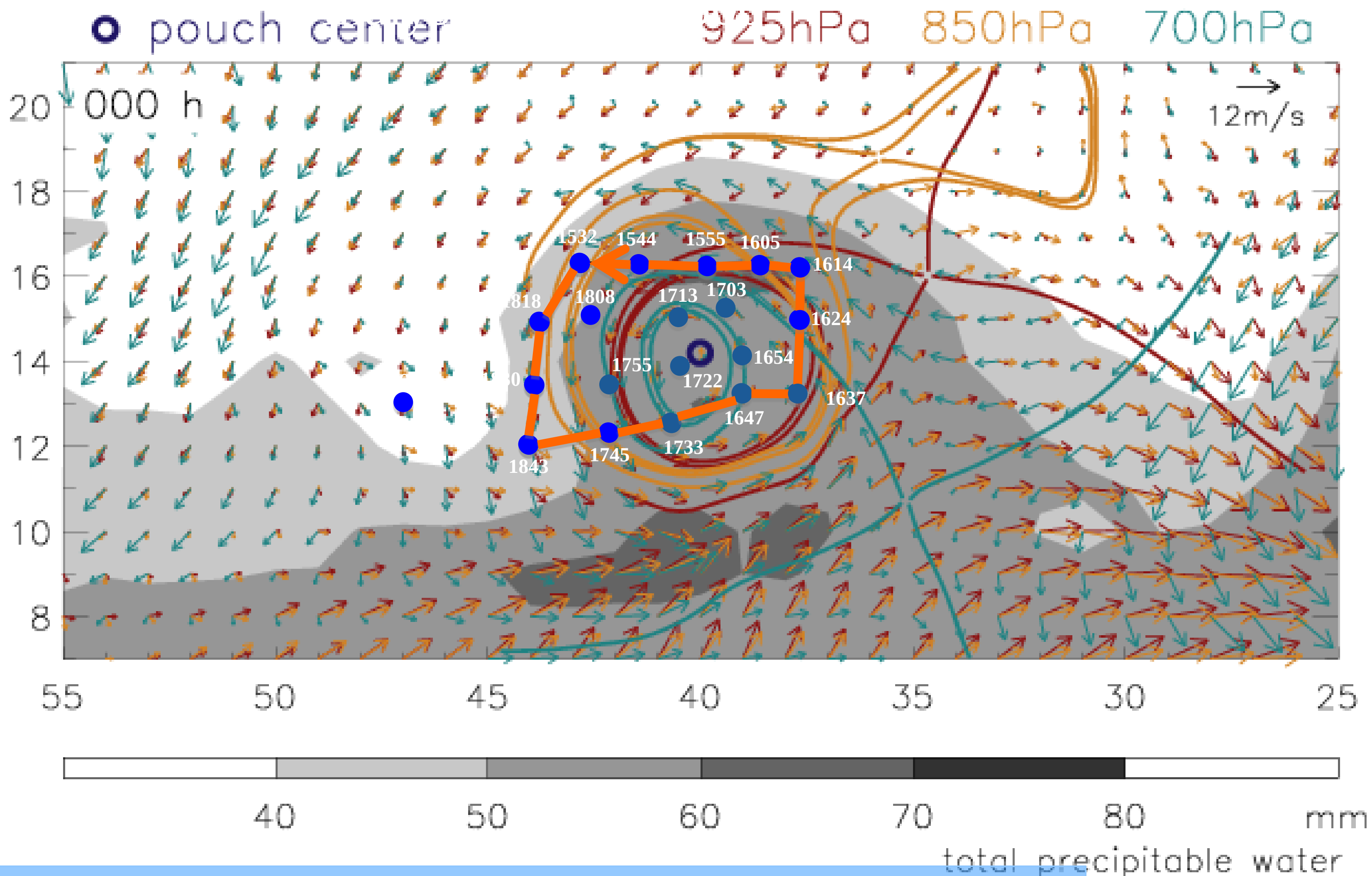
$$C = \oint V \cdot dl$$

Average vorticity=
C / area

Average tangential cyclonic wind=
C / perimeter

Holton, An Introduction to Dynamic Meteorology (2nd Ed.)
Figure 4.1

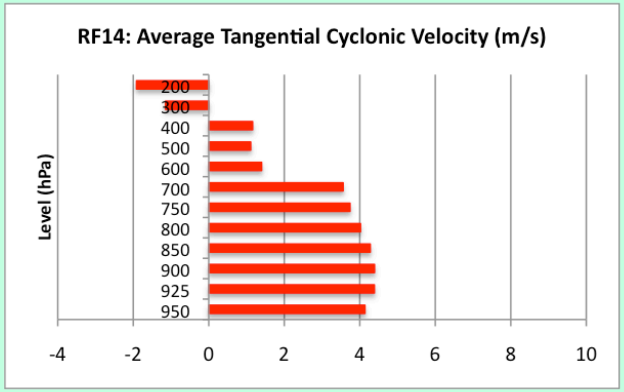
Gaston
ECMWF Dividing Streamline



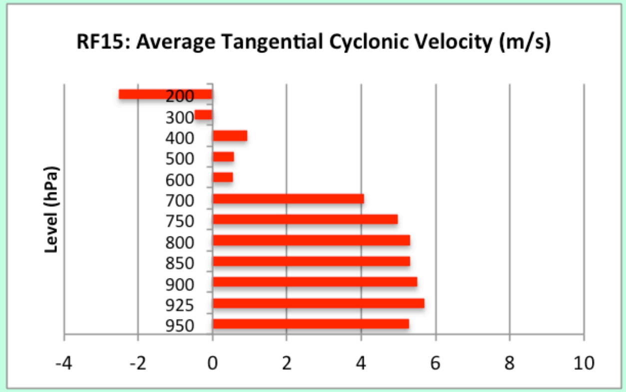
Outer points are used to create a circulation path

Pre-Karl

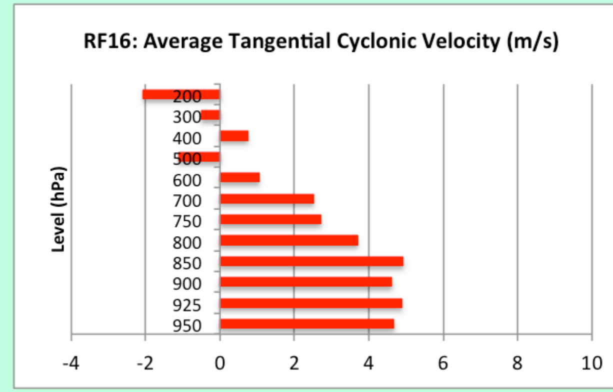
Sept 10



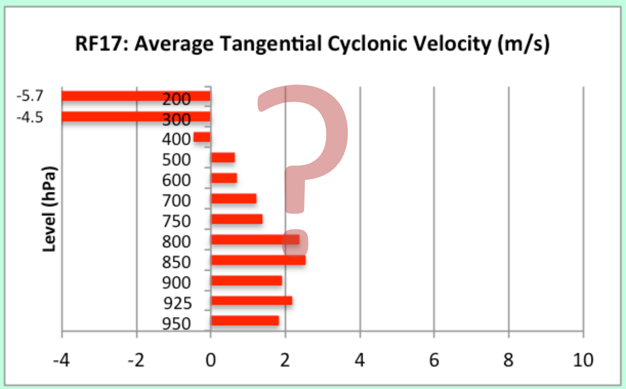
Sept 10



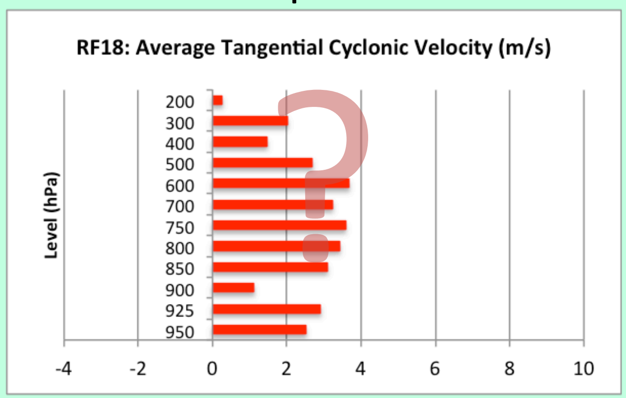
Sept 11



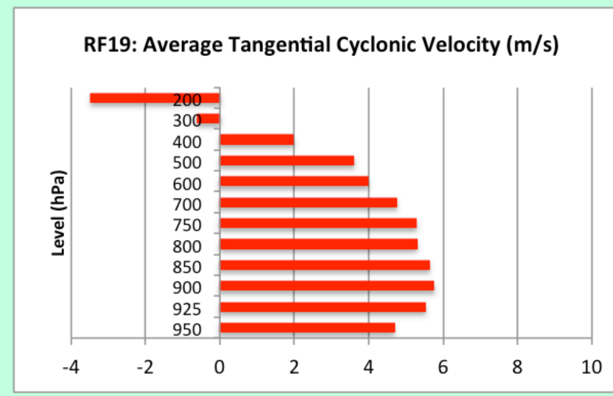
Sept 12



Sept 13



Sept 14



Sept 10 - 1st flight
- Cyclonic up to 400 hPa
- Strongest wind below 600 hPa

Sept 10 – 2nd flight … Similar to 1st flight, but
- Weak mid-levels became weaker
- Strong low-levels became stronger

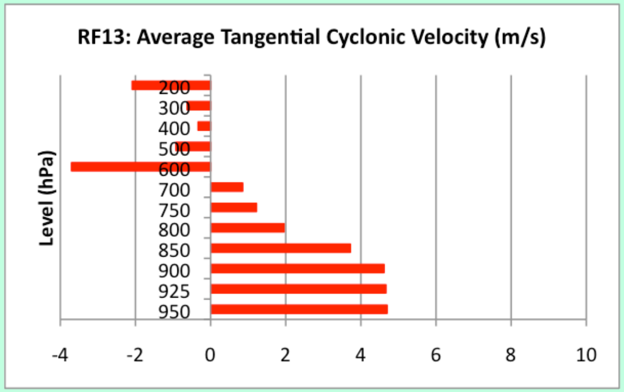
Sept 11
- Strongly cyclonic only up to 600 hPa

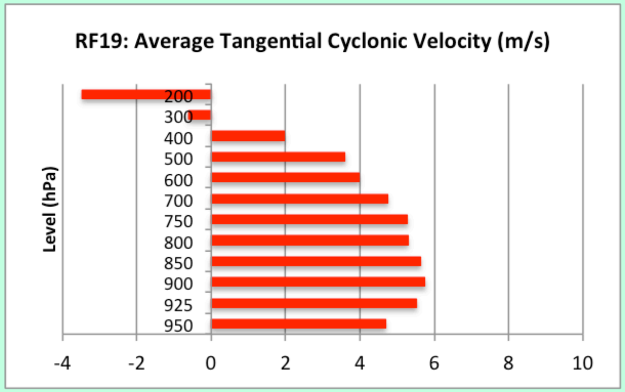
Sept 12-13: Missed portions?

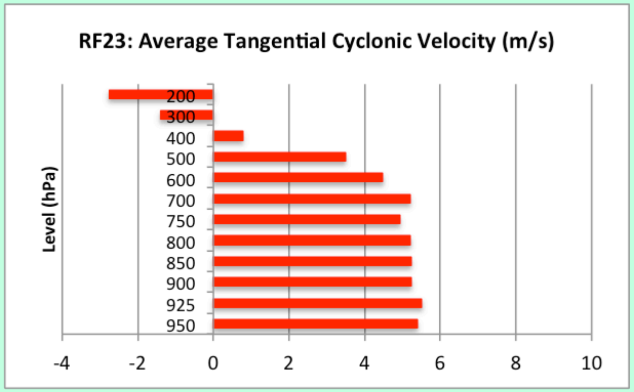
Sept 14 … Intensifies
- Cyclonic up to 400 hPa
- Wind max at 900 hPa ~5.5 m/s

Comparison of Last Flights

Gaston Sept 7	Karl Sept 14	Matthew Sept 24

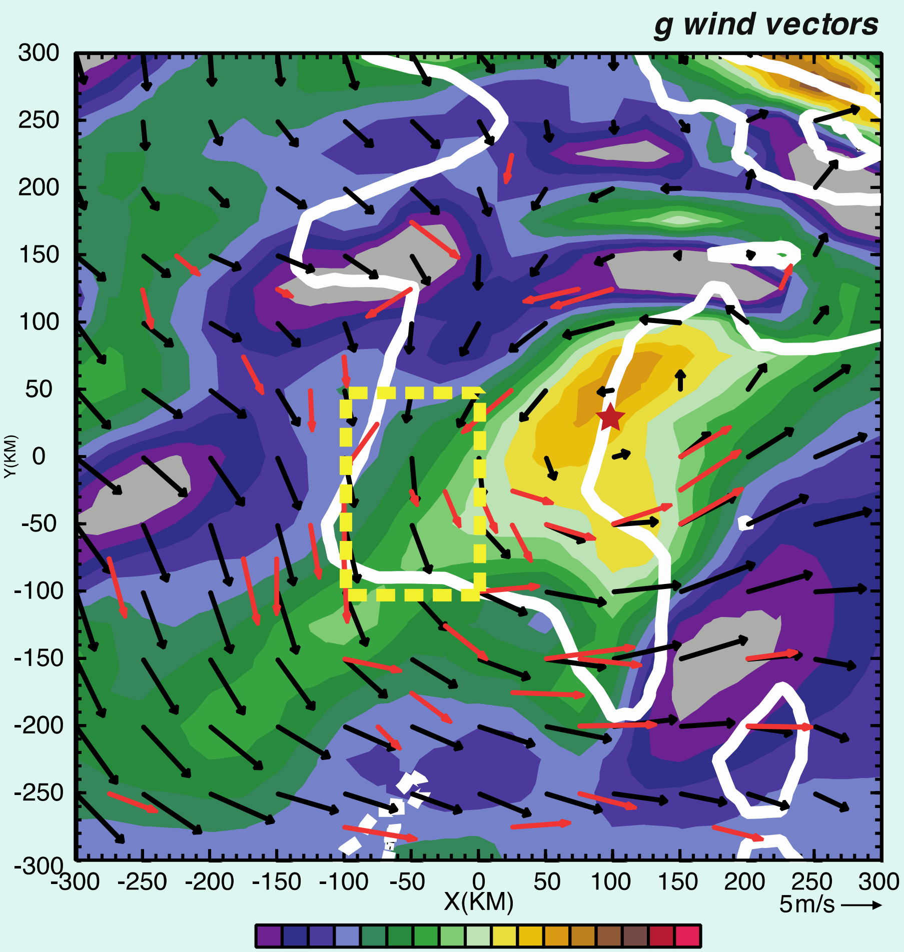




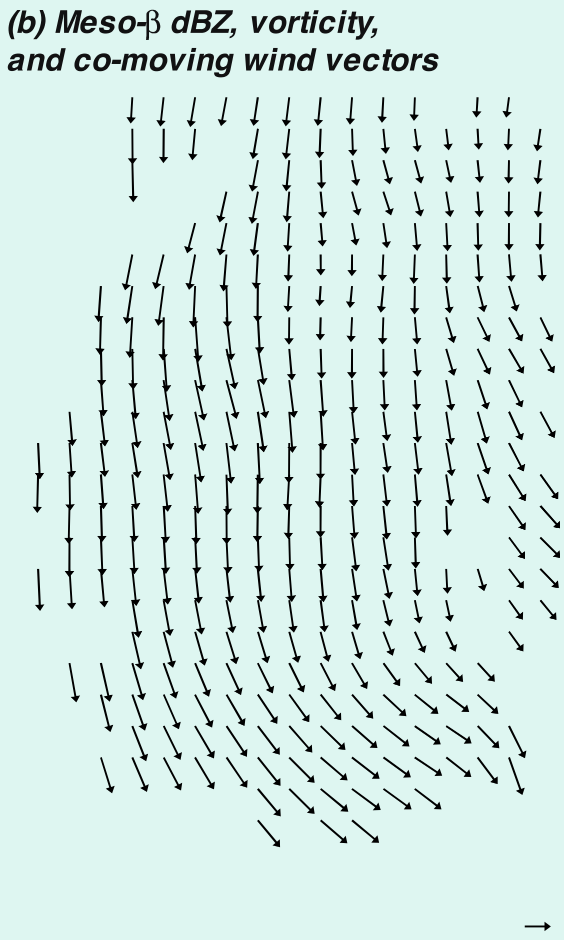


- Gaston's maximum winds not much less than other two storms, but they are confined to a shallow layer
- Gaston cyclonic circulation only up to 700 hPa, Karl and Matthew are cyclonic up to 400 hPa

SAMURAI Analysis of pre-depression Karl on 13 September



ECMWF Background field combined with dropsonde analysis

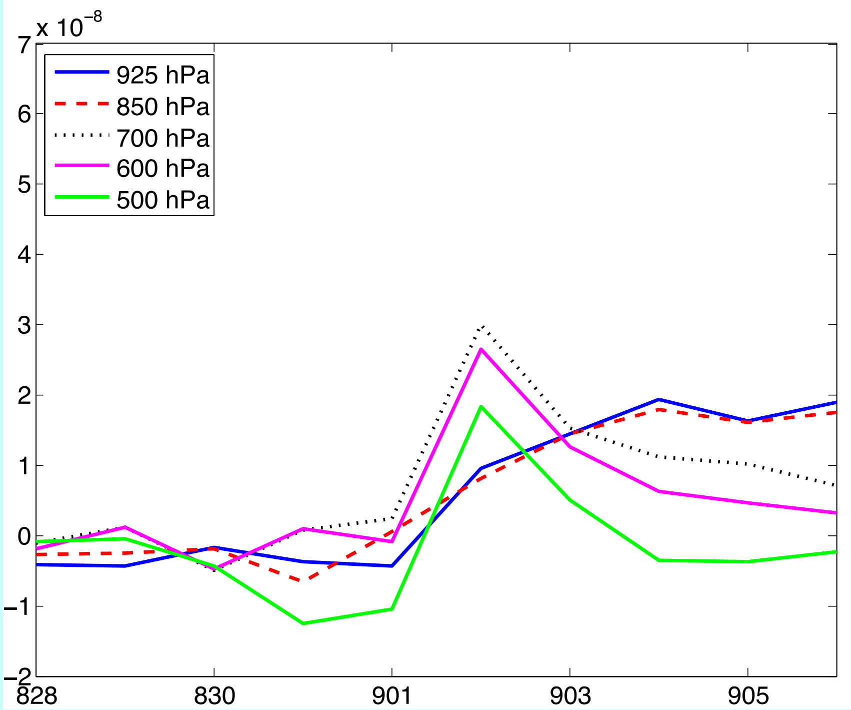


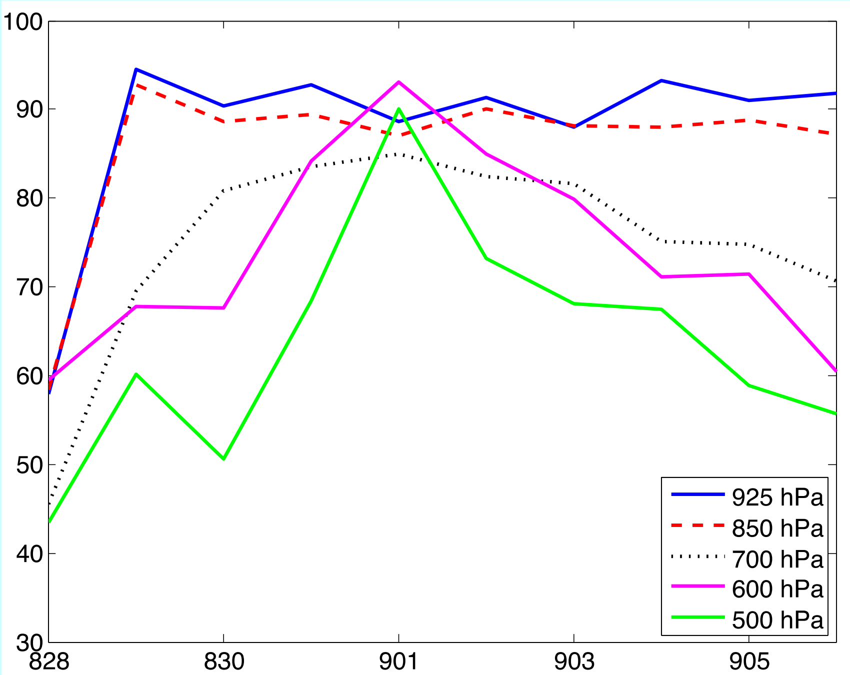
NOAA P3 TDR dual Doppler analysis

From Bell and Montgomery 2012, in preparation

Pouch-averaged time series

Pouch-averaged OW (s^-2) **Pouch-averaged RH**

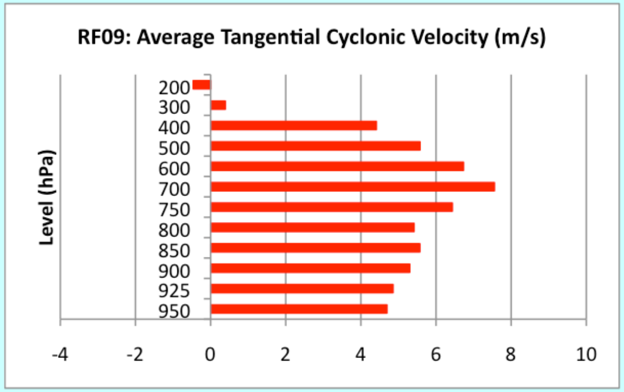


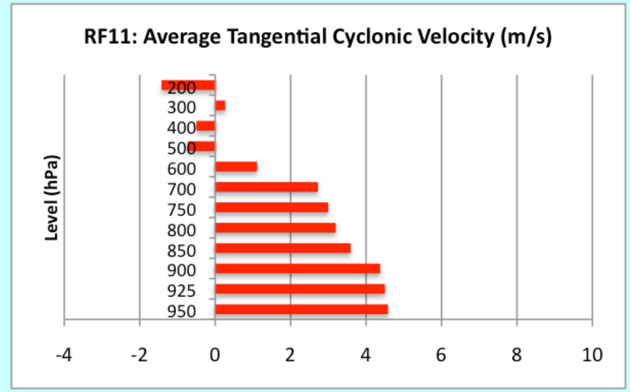


Date Date

Rutherford and Montgomery, 2011, Atmos. Chem. Phys. Discuss.

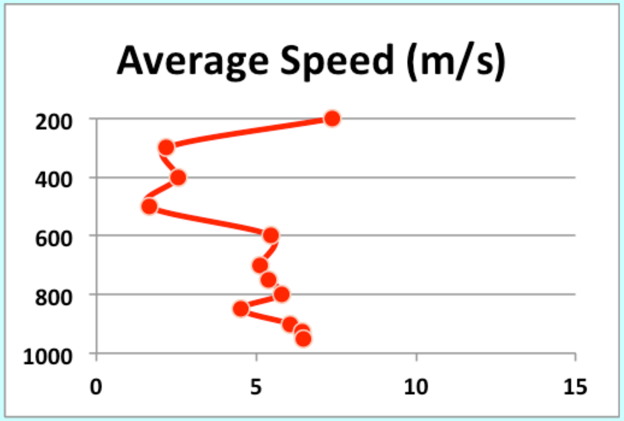
Sept 2
Weak convection
to NW

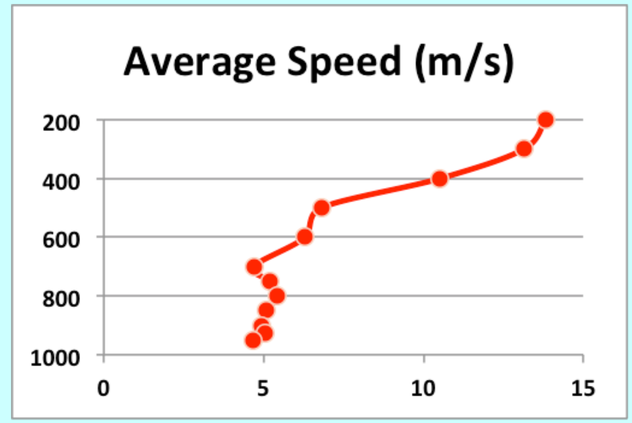




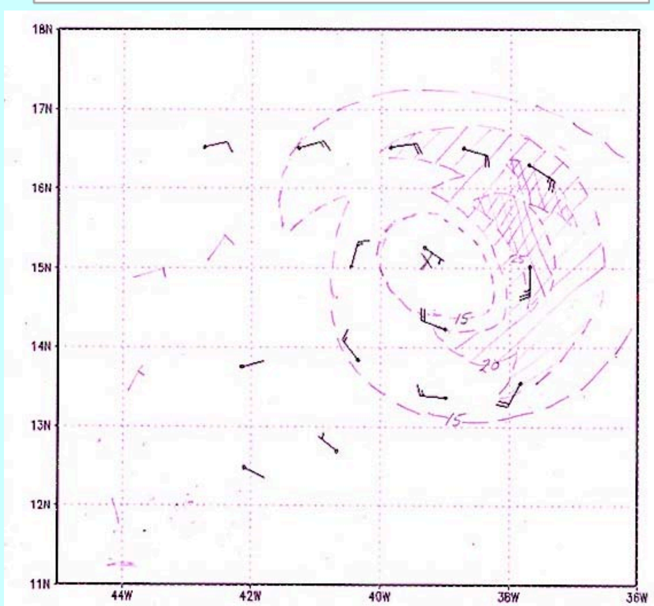
Sept 5
Flaring convection
to SW

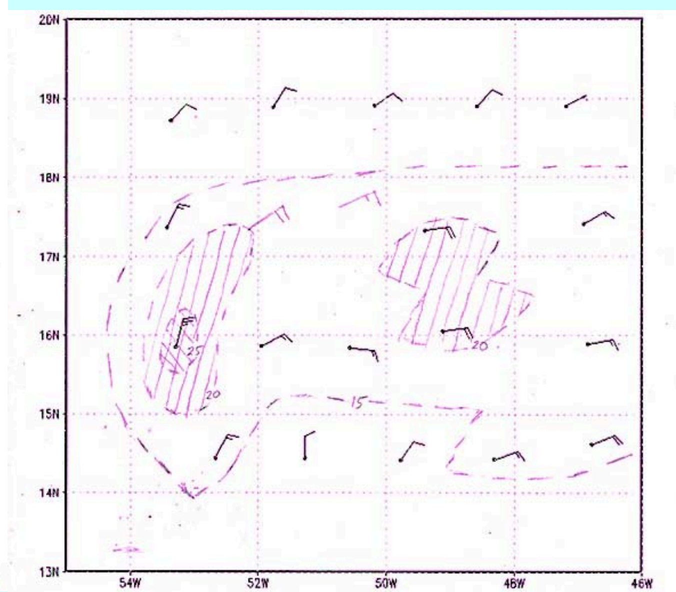
Average earth-relative wind speed (m/s) for each of the 12 levels

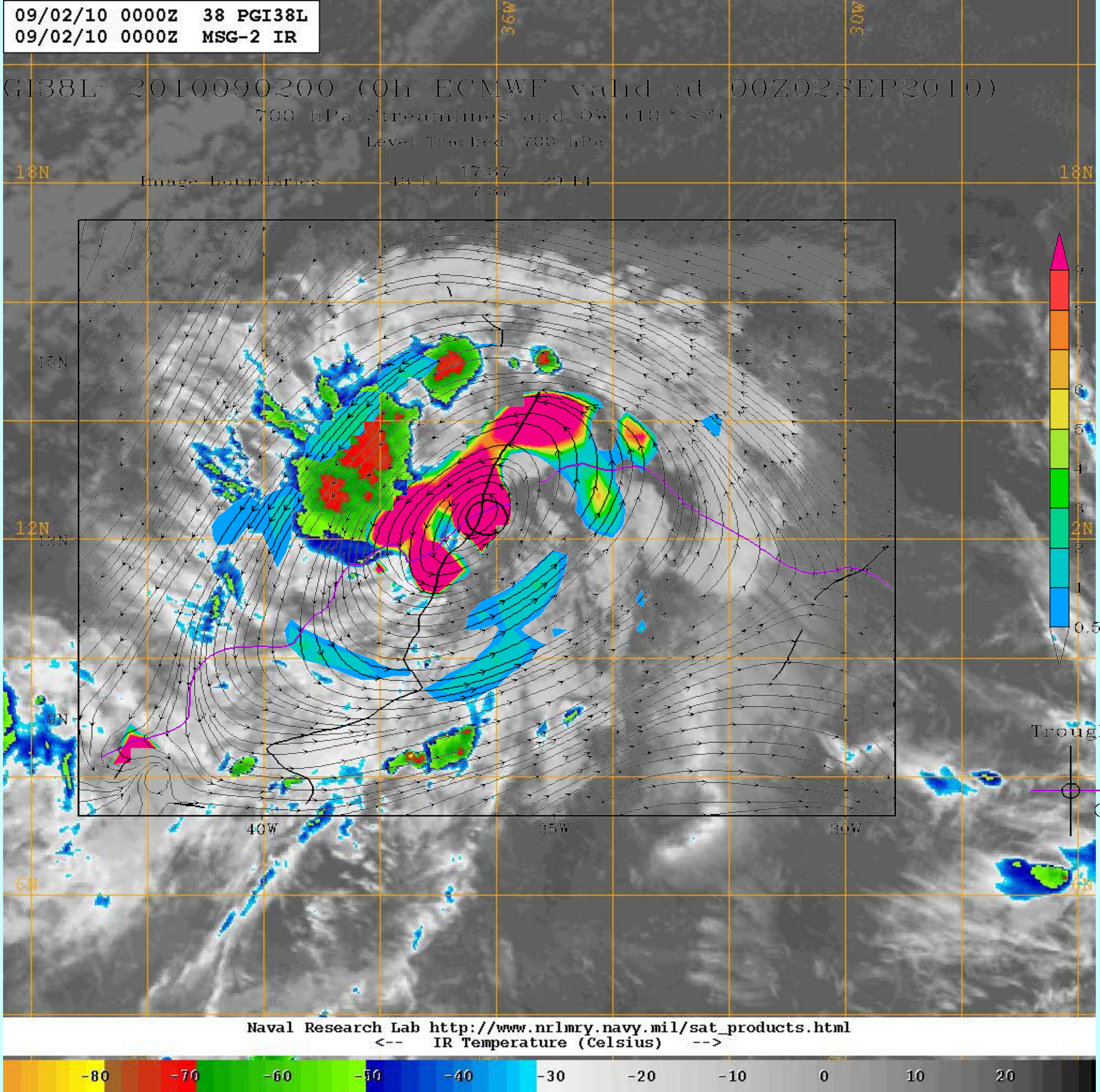




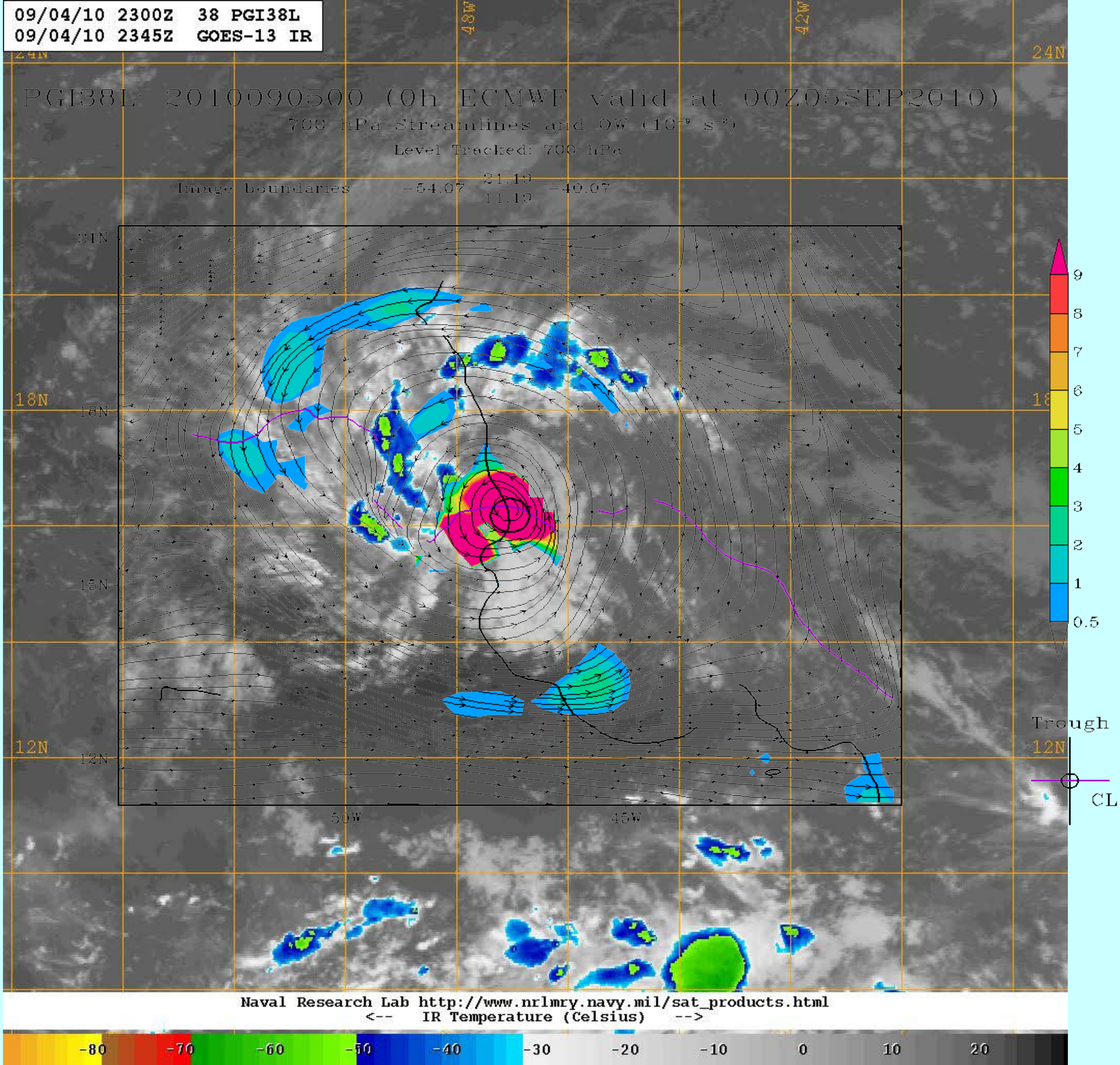
500-hPa earth-relative winds (kt)



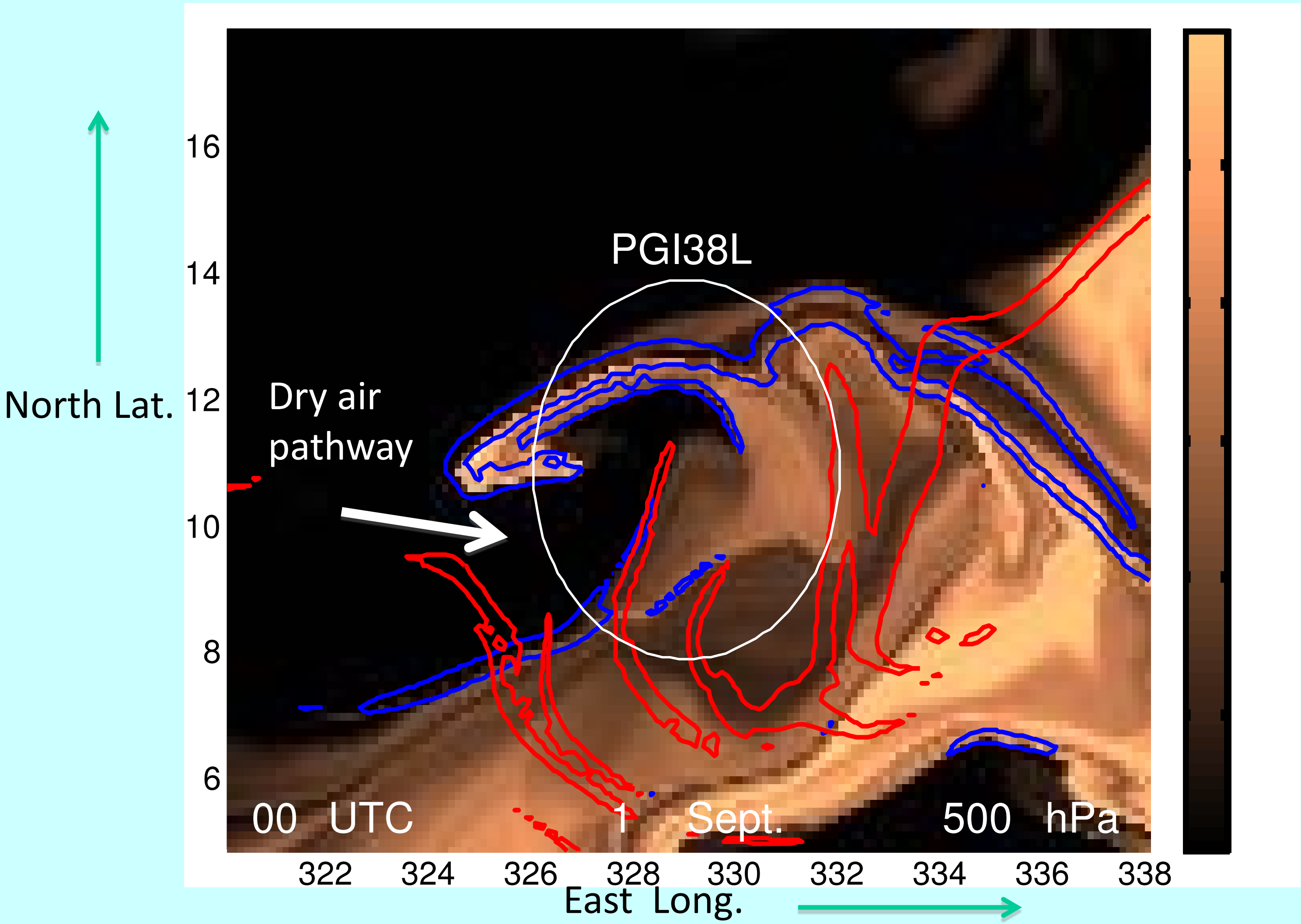




09/02/10 0000Z 38 PGI38L
09/02/10 0000Z MSG-2 IR
PGI38L: 2010090200 (0h ECMWF valid at 00Z02SEP2010)
700 hPa Streamlines and OW (10⁻⁹ s⁻²)
Level Tracked: 700 hPa
Image boundaries -43.14 17.37 7.37 -29.14
18N
15N
12N
9N
6N
40W
35W
30W
36W
30W
Trough
CL
9
8
7
6
5
4
3
2
1
0.5
Naval Research Lab http://www.nrlmry.navy.mil/sat_products.html
<-- IR Temperature (Celsius) -->
-80 -70 -60 -50 -40 -30 -20 -10 0 10 20


09/04/10 2300Z 38 PGI38L
09/04/10 2345Z GOES-13 IR
PGI38L 2010090500 (0h ECMWF valid at 00Z05SEP2010)
700 hPa Streamlines and OW (10^{-9} s^{-2})
Level Tracked: 700 hPa
Image boundaries -54.07 21.19 -40.07 11.19
24N
21N
18N
15N
12N
48W
42W
50W
45W
9
8
7
6
5
4
3
2
1
0.5
Trough
CL
Naval Research Lab http://www.nrlmry.navy.mil/sat_products.html
<-- IR Temperature (Celsius) -->
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20

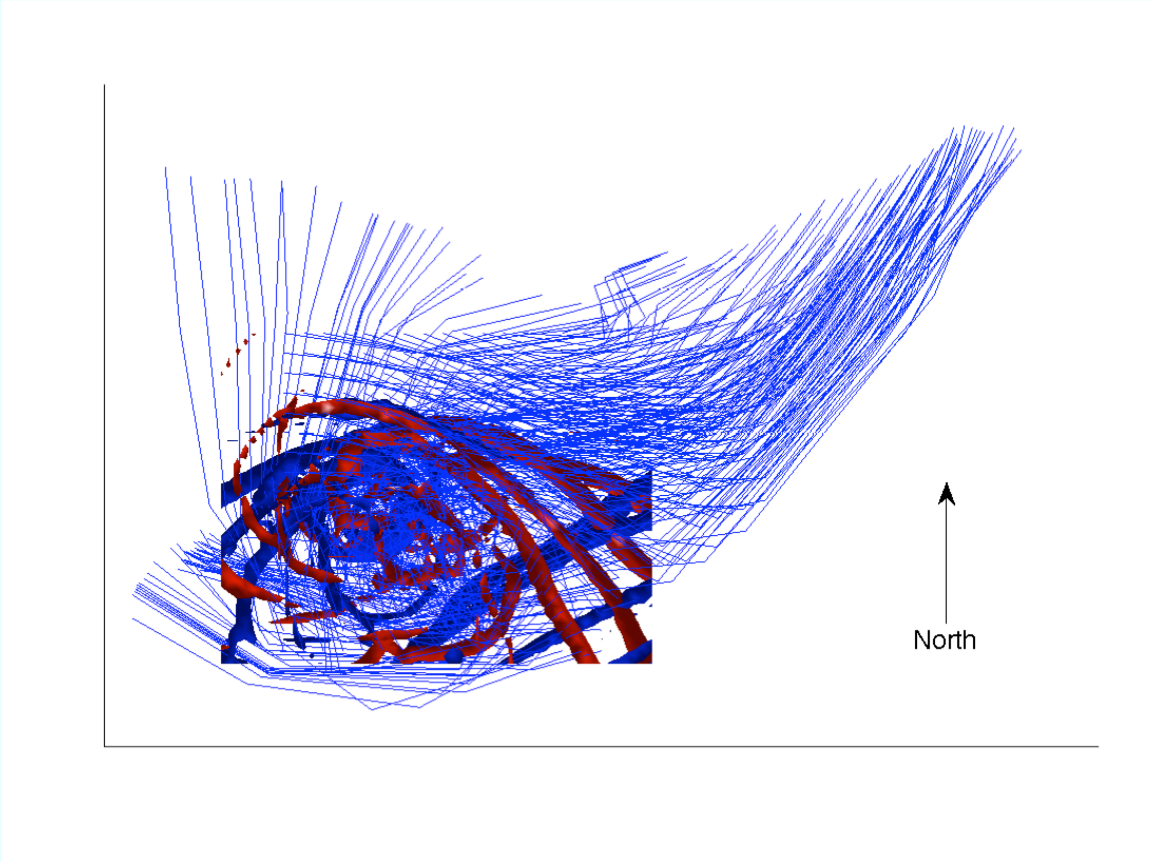
Gaston 1 Sept, 0 UTC, 500 hPa



RH tracer field at 500 hPa with LCSs overlaid. Dry air enters the pouch through the opening in the LCS. Red and blue contours mark repelling and attracting LCSs, respectively.

Gaston trajectories and LCSs at 700 hPa

- Time



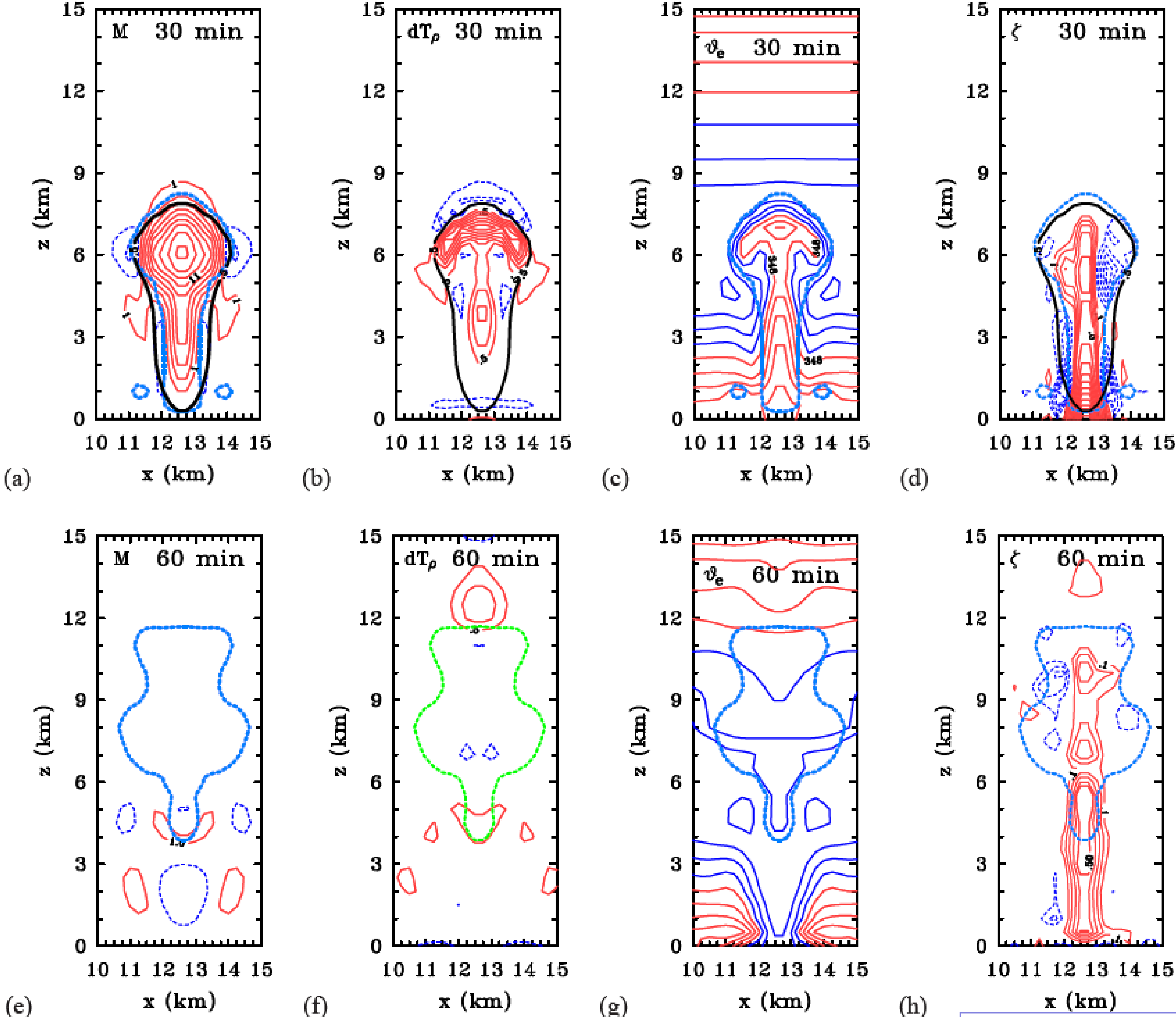
Trajectory paths in blue wrapping around the LCS structure and entering the circulation center of Gaston at 700 hPa. The red structures show the time evolution of an attracting LCS boundary, as time evolves forward from bottom to top

RMetS
Royal Meteorological Society

A numerical study of rotating convection during tropical cyclogenesis

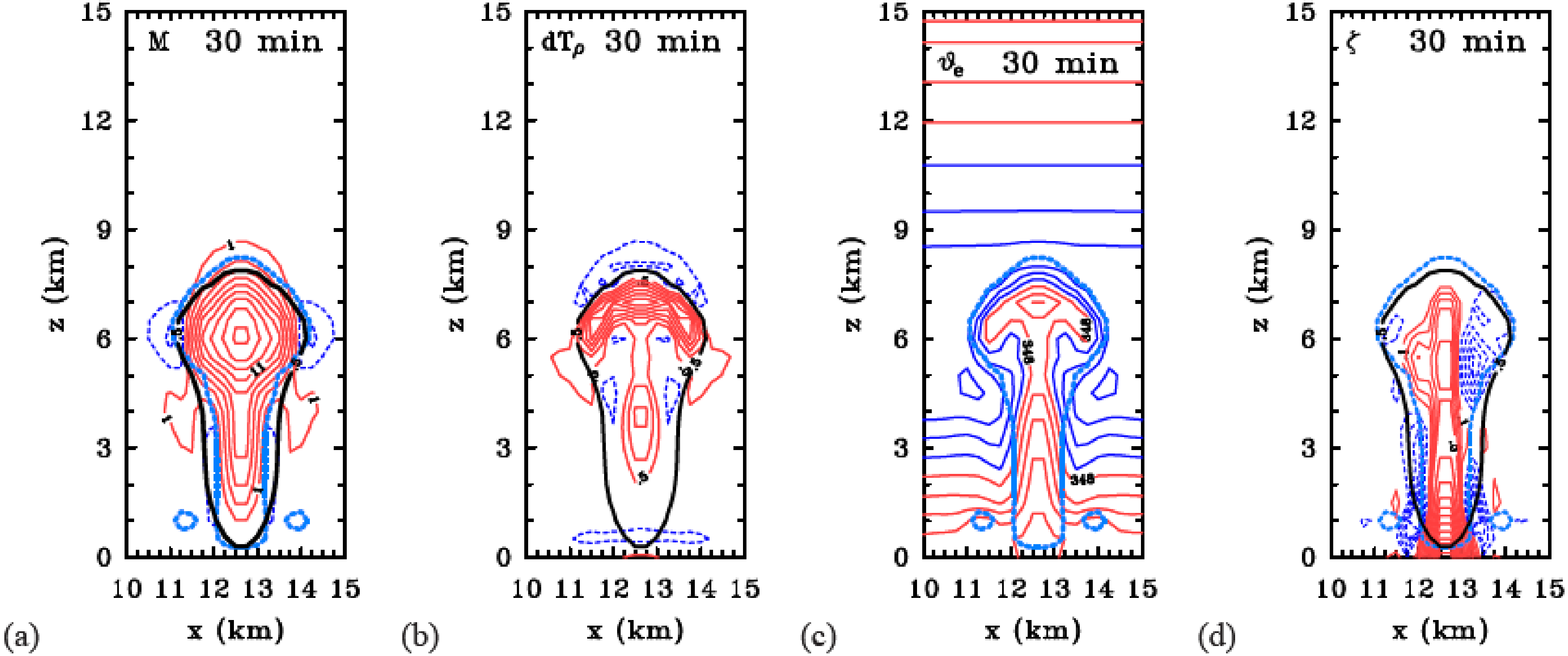
Gerard Kilroy and Roger K. Smith *
Meteorological Institute, University of Munich, Munich, Germany
*Correspondence to: Roger K. Smith, Meteorological Institute, University of Munich, Theresienstr. 37, 80333 Munich, Germany, Email: roger.smith@lmu.de

As in recent calculations of Wissmeier and Smith, the growing convective cells amplify locally the ambient rotation at low levels by more than an order of magnitude and this vorticity, which is produced by the stretching of existing ambient vorticity, persists long after the initial updraught has decayed. Moreover, significant amplification of vorticity occurs even for clouds of only moderate vertical extent. The maximum amplification of vorticity is relatively insensitive to the maximum updraught strength, or the height at which it occurs, and it is not unduly affected by the presence of dry air aloft. Thus the presence of dry air is not detrimental to the amplification of low-level vorticity, although it reduces the depth through which ambient vorticity is enhanced.



blue is cloud water + ice, black is rain water, green is ice

From Kilroy and Smith 2012



From Kilroy and Smith 2012

Figure 4. Vertical cross sections through the domain centre of (a,d) vertical mass flux, M, (b,e) density temperature difference, dT_ρ, between the cloud and its environment, and (c,f) pseudo-equivalent potential temperature, θ_e, and (d,h) the vertical component of relative vorticity ζ in Experiment 1 at 30 min (upper row) and 60 min (lower row). Shown also are the cloud boundaries, characterized by the 0.1 g kg^{-1} contour of cloud water + ice (thick dashed light blue curve), and the rain shaft, characterized by the 0.5 g kg^{-1} contour of rain water (thick black curve). In panels (d) and (e), the region of ice is delineated by the 0.1 g kg^{-1} contour of ice (thick dashed green curve). Contour interval: for M 1 kg s^{-1} m^{-2}; for dt_ρ 0.5 K; for θ_e 3 K; for ζ, thin contours $5 \times 10^{-4)}$ s^{-1}. Contours of θ_e change colour from blue at 345 K to red at and above 348 K.

Preliminary Conclusions

1. New cyclogenesis model helps synthesize multi-scale observations and predicts new properties of the formation process.

2. Data and analyses confirm predicted convective organization at the sweet of the parent wave-pouch disturbance.

3. Pouch-averaged view offers a picture of the basic thermodynamic environment within which cyclogenesis takes place. Pouch-averaged view does not support prior hypotheses on thermodynamic environment.

4. Data and analyses suggest alternative view on role of dry air in limiting vorticity amplification on convective scale over pouch depth.

5. Research with PREDICT data ongoing …

FIRST PREDICT WORKSHOP
June 8-10, 2011, NPS, USA

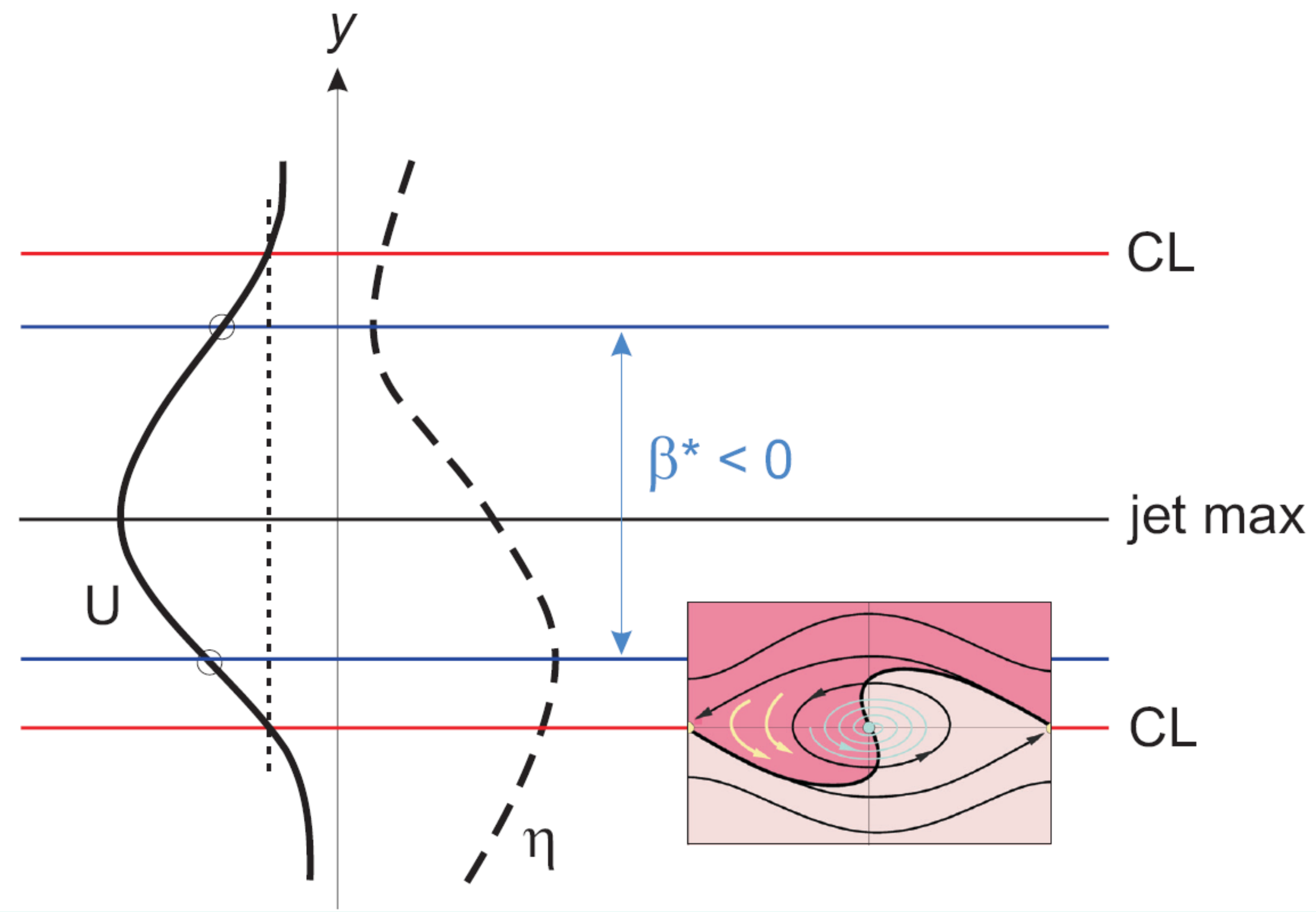
End of Presentation

Thank you!

HS3 2011 Dry Run
Pouch-tracking

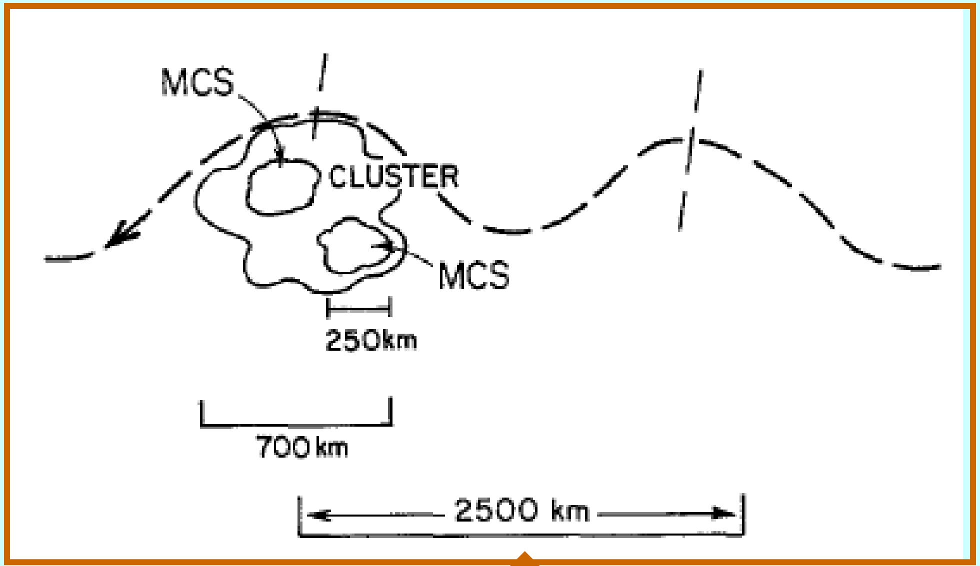
- 5 July – 18 October
- 41 pouches
  - 20 official invests +
    - 12 Tropical Depressions +
    - 1st Pouch forecast lead time before 1st NHC warning: Average 5 days

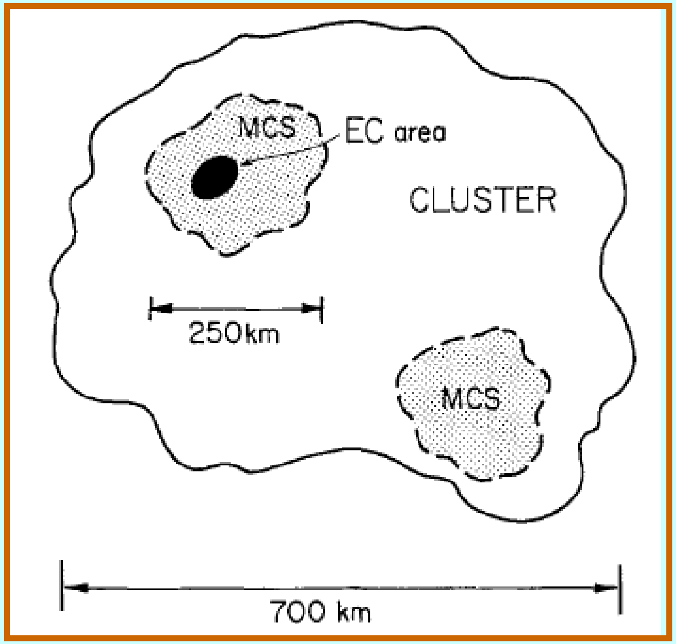
Hydrodynamically stable configuration



Dunkerton et al., 2008 ACP

Multi-scale nature of tropical cyclogenesis within tropical waves





Schematic of synoptic-scale flow through an easterly wave (dashed) with an embedded cluster of convection in the wave trough.

The cluster contains mesoscale convective systems (MCSs) and extreme convection (EC, black oval) within one of the MCSs.

From Gray (1998).

The marsupial paradigm for tropical cyclogenesis

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Atmospheric Chemistry and Physics

Tropical cyclogenesis in a tropical wave critical layer: easterly waves

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