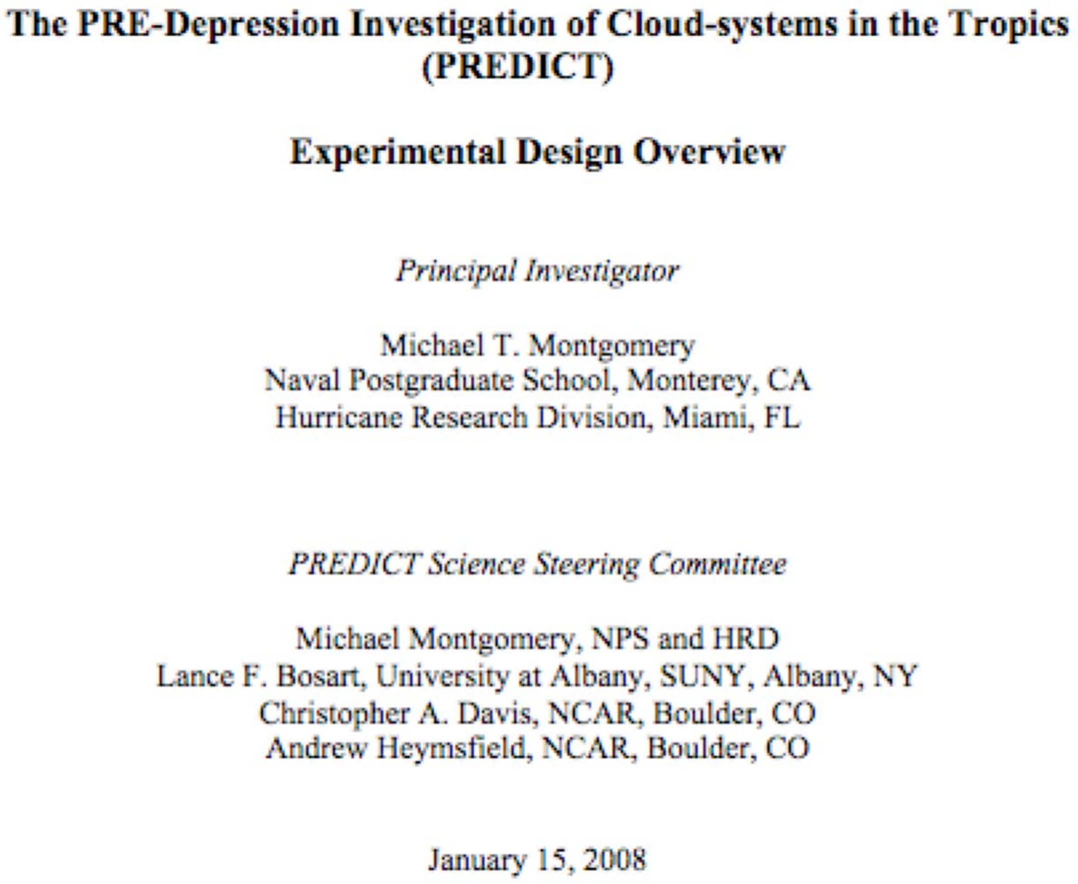

The PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT)

Experimental Design Overview

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January 15, 2008

Maximum Simplification of the Dynamic Equations

By EDWARD N. LORENZ, Massachusetts Institute of Technology[1]

(Manuscript received February 1, 1960)

Abstract

When the dynamic equations are to be used to further our understanding of atmospheric phenomena, it is permissible to simplify them beyond the point where they can yield acceptable weather predictions. Through the use of double Fourier series, and with the omission of all but the largest scales of motion, the barotropic vorticity equation may be reduced to a system of three ordinary nonlinear differential equations. The analytic solutions of these equations are elliptic functions of time. The equations may also be solved rapidly by numerical integration.

Particular solutions of the equations picture the motion of finite disturbances on a zonal flow, with exchanges of kinetic energy between the zonal flow and the disturbances accompanying the meridional transport of zonal momentum by the disturbances. Other solutions picture the initial growth and eventual cessation of growth of small disturbances on an unstable zonal current. Still further solutions picture the destruction of a stable zonal flow by large disturbances, and lead to a plausible hypothesis concerning index cycles in the atmosphere.

Less extreme simplifications of the dynamic equations may be used when more complicated atmospheric phenomena are to be studied.

1. Simplification of the dynamic equations and the initial conditions

The various phenomena which are observed in our atmosphere, and the changes in the state of the atmosphere from one time to another, are supposedly governed by a set of physical laws. The dynamic meteorologist does not usually regard the discovery of these laws as one of his tasks, being willing to concede that the laws have already been established, at least in approximate form, by workers in other fields. Instead, he includes among his problems the prediction of future states of the atmosphere by means of these laws, and the explanation of typical observable phenomena in terms of these laws. He ordinarily finds it convenient to express the laws as a set of mathematical equations.

In order to make the best attainable forecast of the future weather, it would be desirable to express the physical laws as exactly as possible, and determine the initial conditions as precisely as possible. Yet the ultimate achievement of producing perfect forecasts, by applying equations already known to be exact to initial conditions already known to be precise, if such a feat were possible, would not by itself increase our understanding of the atmosphere, no matter how important it might be from other considerations. For example, if we should observe a hurricane, we might ask ourselves, "Why did this hurricane form?" If we could determine the exact conditions at an earlier time, and if we should feed these conditions, together with a program for integrating the exact equations, into an electronic computer, we should in due time receive a forecast from the computer, which would show the presence of a hurricane. We then might still be justified in asking why

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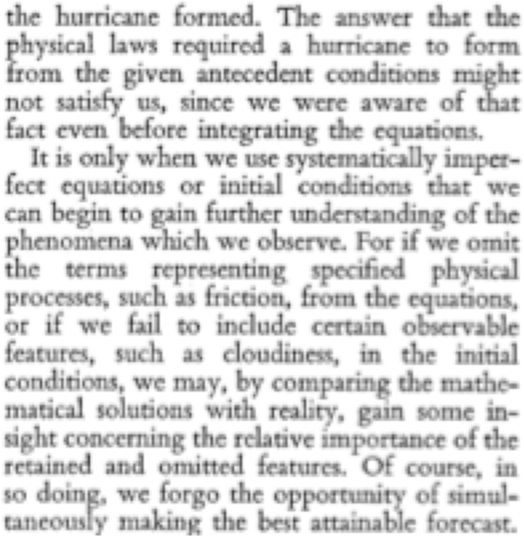
[1] The research resulting in this work has been sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, under Contract No. No. AF 19 (604)-1000.

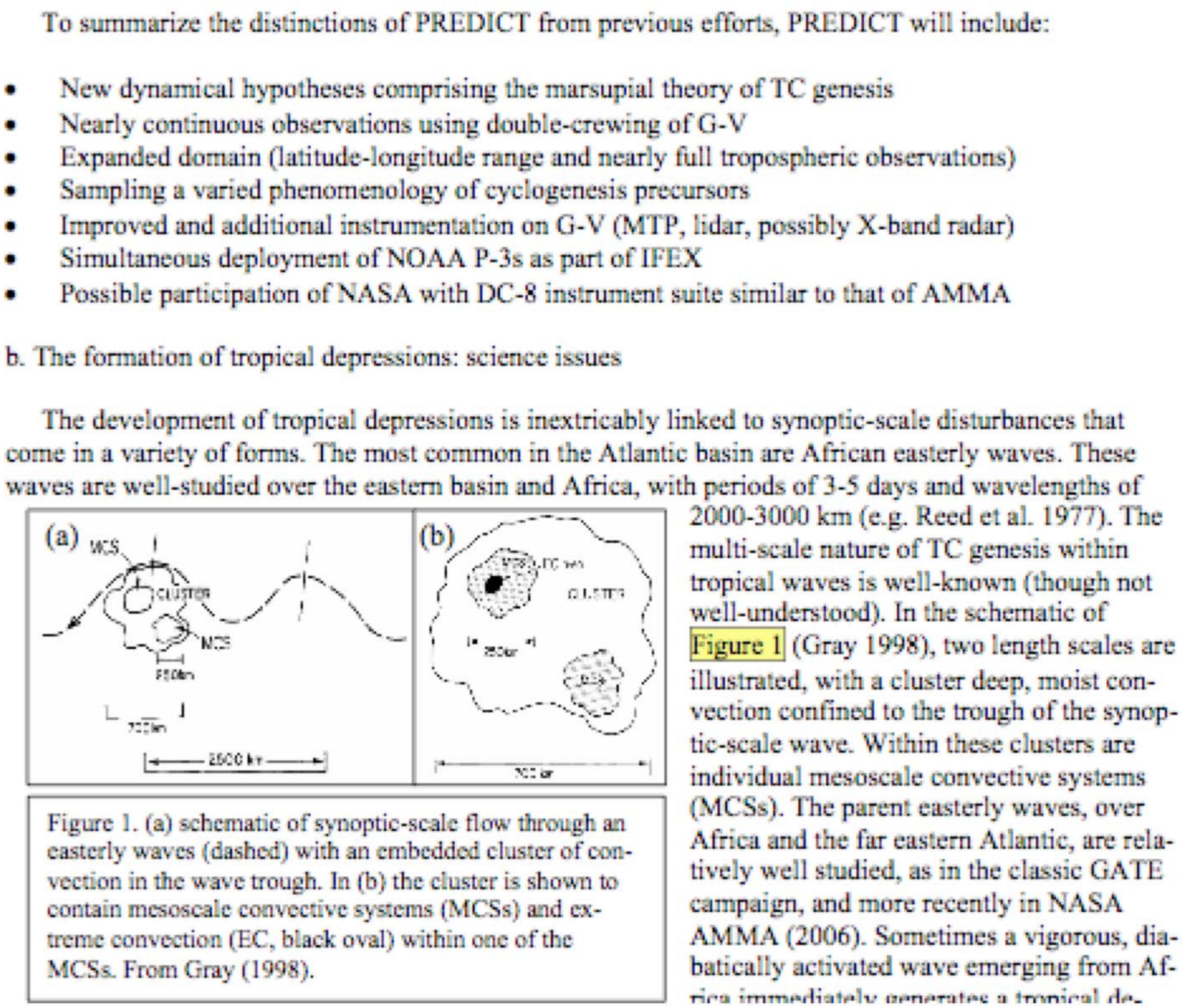


the hurricane formed. The answer that the physical laws required a hurricane to form from the given antecedent conditions might not satisfy us, since we were aware of that fact even before integrating the equations.

It is only when we use systematically imperfect equations or initial conditions that we can begin to gain further understanding of the phenomena which we observe. For if we omit the terms representing specified physical processes, such as friction, from the equations, or if we fail to include certain observable features, such as cloudiness, in the initial conditions, we may, by comparing the mathematical solutions with reality, gain some insight concerning the relative importance of the retained and omitted features. Of course, in so doing, we forgo the opportunity of simultaneously making the best attainable forecast.

Tropical Cyclogenesis - a Mystery of the Tropical Atmosphere

> *“Although some aspects of the transformation of atmospheric disturbances into tropical cyclones are relatively well understood, the general problem of tropical cyclogenesis remains, in large measure, one of the great mysteries of the tropical atmosphere.”*
>
> Kerry Emanuel, *Divine Wind*
>
> *2005*



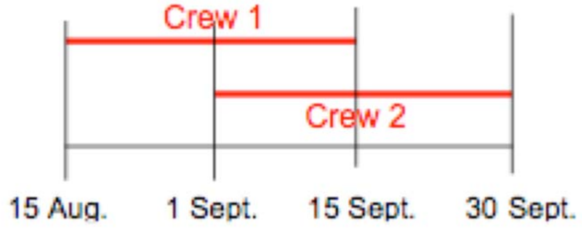
To summarize the distinctions of PREDICT from previous efforts, PREDICT will include:

- New dynamical hypotheses comprising the marsupial theory of TC genesis
- Nearly continuous observations using double-crewing of G-V
- Expanded domain (latitude-longitude range and nearly full tropospheric observations)
- Sampling a varied phenomenology of cyclogenesis precursors
- Improved and additional instrumentation on G-V (MTP, lidar, possibly X-band radar)
- Simultaneous deployment of NOAA P-3s as part of IFEX
- Possible participation of NASA with DC-8 instrument suite similar to that of AMMA

b. The formation of tropical depressions: science issues

The development of tropical depressions is inextricably linked to synoptic-scale disturbances that come in a variety of forms. The most common in the Atlantic basin are African easterly waves. These waves are well-studied over the eastern basin and Africa, with periods of 3-5 days and wavelengths of 2000-3000 km (e.g. Reed et al. 1977). The multi-scale nature of TC genesis within tropical waves is well-known (though not well-understood). In the schematic of Figure 1 (Gray 1998), two length scales are illustrated, with a cluster deep, moist convection confined to the trough of the synoptic-scale wave. Within these clusters are individual mesoscale convective systems (MCSs). The parent easterly waves, over Africa and the far eastern Atlantic, are relatively well studied, as in the classic GATE campaign, and more recently in NASA AMMA (2006). Sometimes a vigorous, diabatically activated wave emerging from Africa immediately generates a tropical de-

Figure 1. (a) schematic of synoptic-scale flow through an easterly waves (dashed) with an embedded cluster of convection in the wave trough. In (b) the cluster is shown to contain mesoscale convective systems (MCSs) and extreme convection (EC, black oval) within one of the MCSs. From Gray (1998).



Double-crewed G-V, 1-15 Sept.

Figure 4. Schematic time-line for PREDICT.

2. PREDICT Hypotheses

In the Introduction, descriptions of genesis from the synoptic-scale, mesoscale and convective-scale perspectives were presented. Genesis is believed to be inherently a multi-scale process, but it is likely that the roles of different scales can be evaluated and the following hypotheses can be tested to elucidate their relative importance in genesis over the western Atlantic, with strong implications for genesis elsewhere. The main hypothesis (H1) is the following:

H1: Tropical depression formation is greatly favored in the critical-layer region of the synoptic-scale, pre-depression wave or subtropical disturbance.

This hypothesis is the underlying tenet of the *marsupial paradigm*, or "marsupial/pouch theory" of tropical cyclogenesis. The *critical layer* of the parent wave is a region of cyclonic rotation and weak deformation that provides a set of closed material contours inside of which air is repeatedly moistened by convection, protected from lateral intrusion of dry air and deformation by horizontal or vertical shear, and (thanks to its location near the critical level) able to keep pace with the parent wave until the dominant vortex (a.k.a. proto-vortex) has strengthened into a self-maintaining entity. During this time the parent wave is maintained and possibly enhanced by diabatically amplified eddies within the wave (proto-vortices on the mesoscale), a process favored in regions of small intrinsic phase speed. In regard to wave maintenance it is important to note that we regard diabatic amplification as a key element of a feedback loop, but logically as an effect, not cause, of the parent wave. In other words, the critical layer giving birth to the proto-vortex is not simply an illusion caused by merger of such vortices that would have formed anyway, but an essential element of the incipient wave which governs the particular location(s) of proto-vortex development. Key to the marsupial paradigm is the existence of a *hybrid diabatic Rossby wave/vortex structure*; a configuration that may be uniquely instrumental in TC genesis.

Hypothesis H1 naturally motivates four sub-hypotheses (H2-H5) that we also propose for testing:

H2: Despite the variety of pre-cursor disturbances, tropical cyclone formation proceeds through essentially the same mesoscale and cloud processes.

H3: Genesis is a bottom-up process.

H4: The primary effect of Saharan Air Layers is to inject dry air into the marsupial pouch of candidate tropical disturbances.

H5: Despite potentially significant model errors, poor initial conditions are the key factor in poor predictions of genesis.

Outline

- The problem
- New observational insights
- New perspectives on meso-α, β and γ using idealized and real-case WRF simulations
- Upcoming Atlantic field experiment:

  PREDICT 2010

Tropical Cyclogenesis from Easterly Waves

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TC Genesis

2-Stage Genesis: (Karyamudi and Pierce 2002)

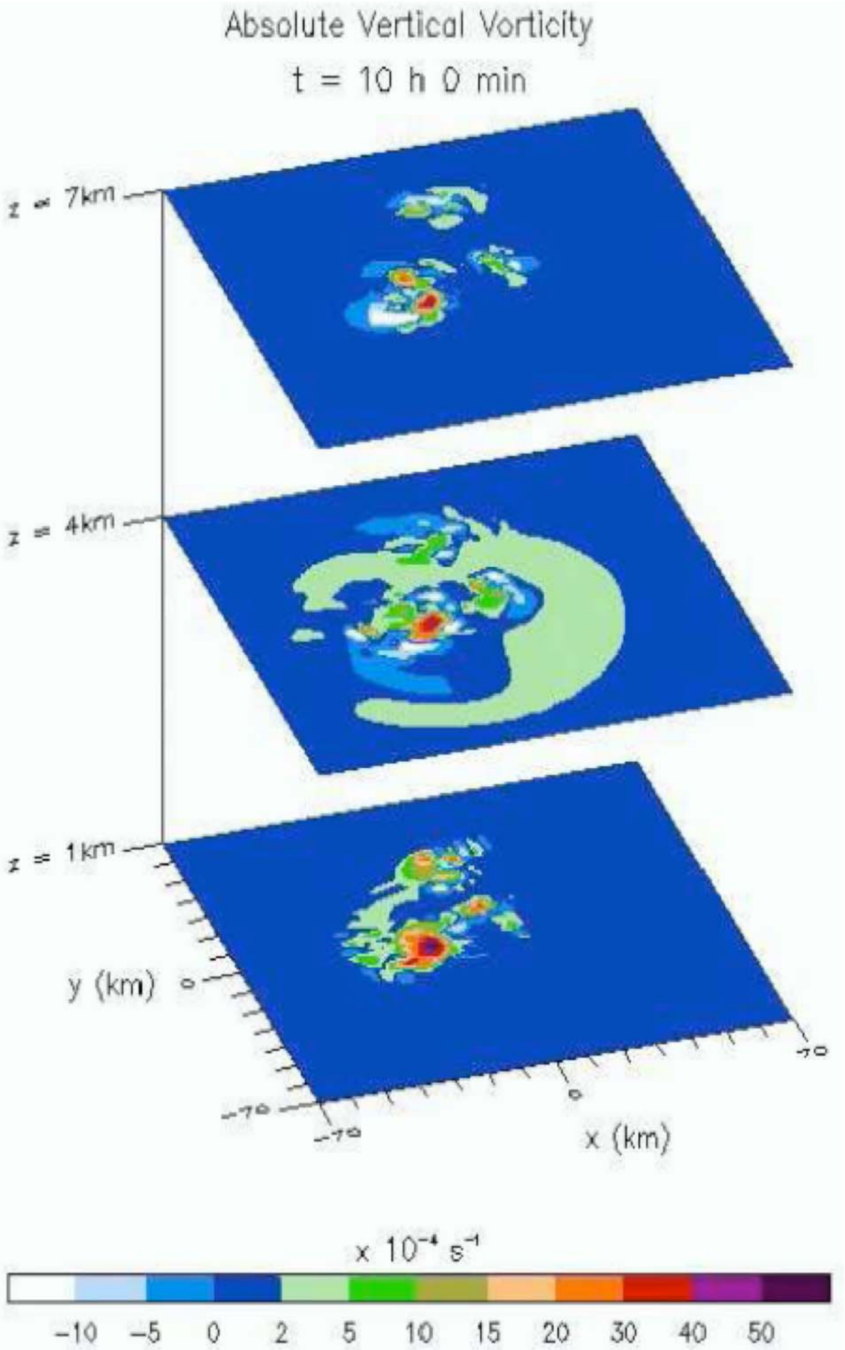
Stage 1: preconditioning of the synoptic scale environment

Necessary conditions for genesis

1. Cyclonic absolute vorticity in the lower troposphere
2. Weak vertical wind shear
3. Warm SST
4. Moist unstable air

It is not well understood how a TC-scale vortex is transformed from such an environment.

Stage 2: mesoscale organization and construction of the TC-scale PV monolith (Vortical hot towers)

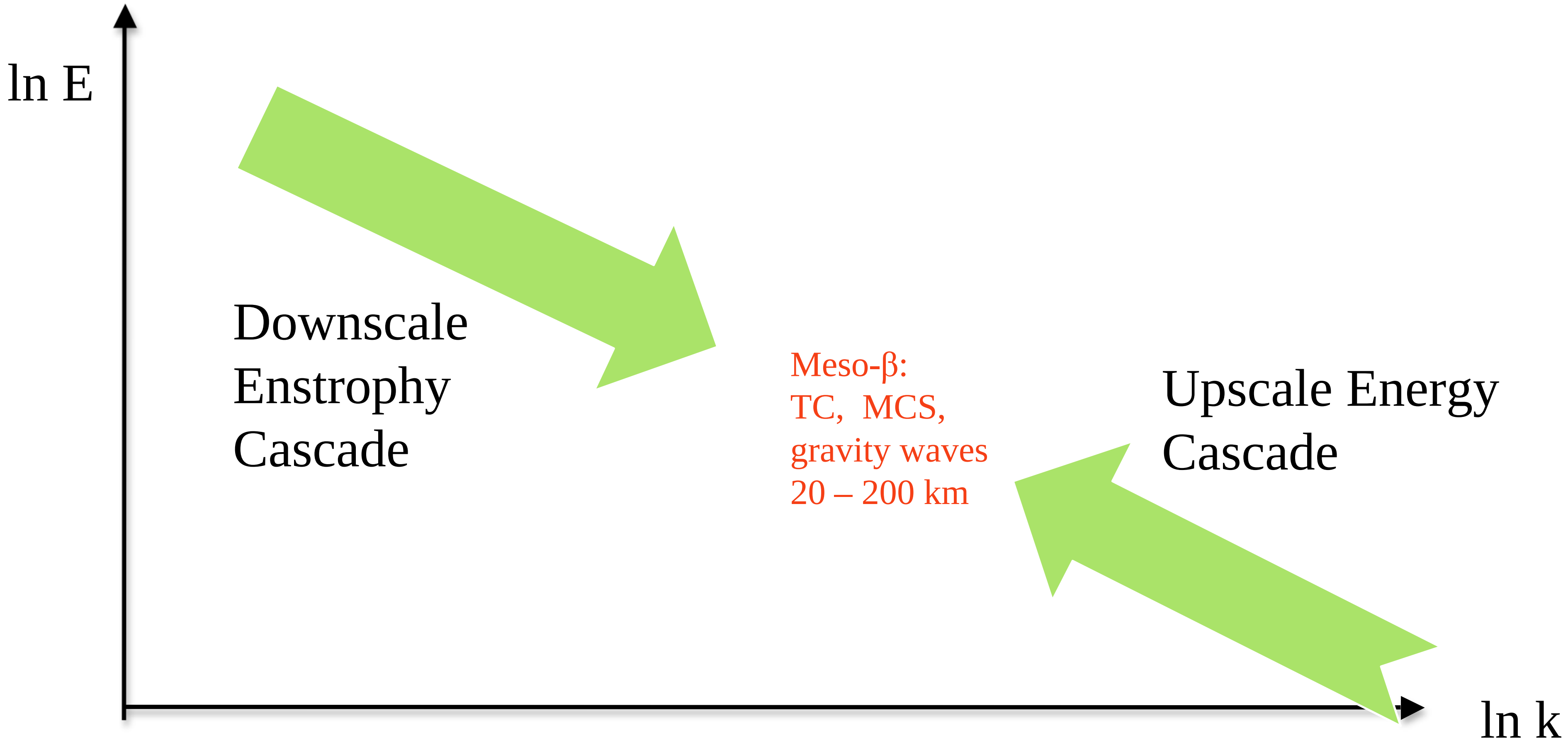


Vortical Hot Tower Route

in vorticity-rich environment

2006, JAS. Expt. A1, "A vortical hot tower route …"

Consideration of horizontal scales exposes the challenging nature of the problem



Downscale
Enstrophy
Cascade

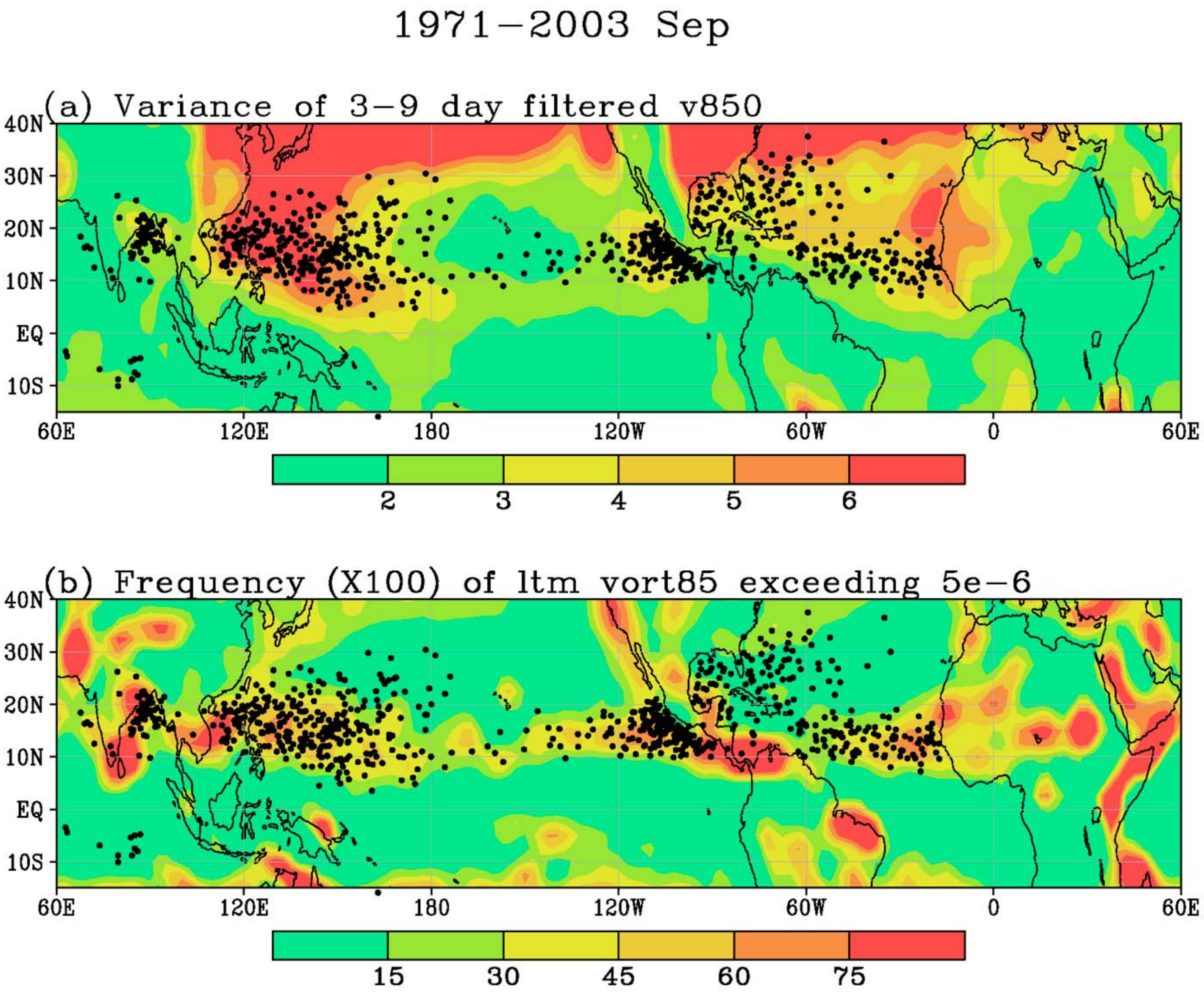
Meso-β:
TC, MCS,
gravity waves
20 – 200 km

Upscale Energy
Cascade

Synoptic
Easterly Waves
Hydro instability of ITCZ
Subtropical intrusions
2,000 – 8,000 km

Meso-α:
Easterly wave critical layer
Isolated recirculation regions
Inertia gravity waves
200 – 2,000 km

Meso-γ:
VHTs, Congestus, Precip.
Driven downdrafts, Gust
fronts
2 – 20 km

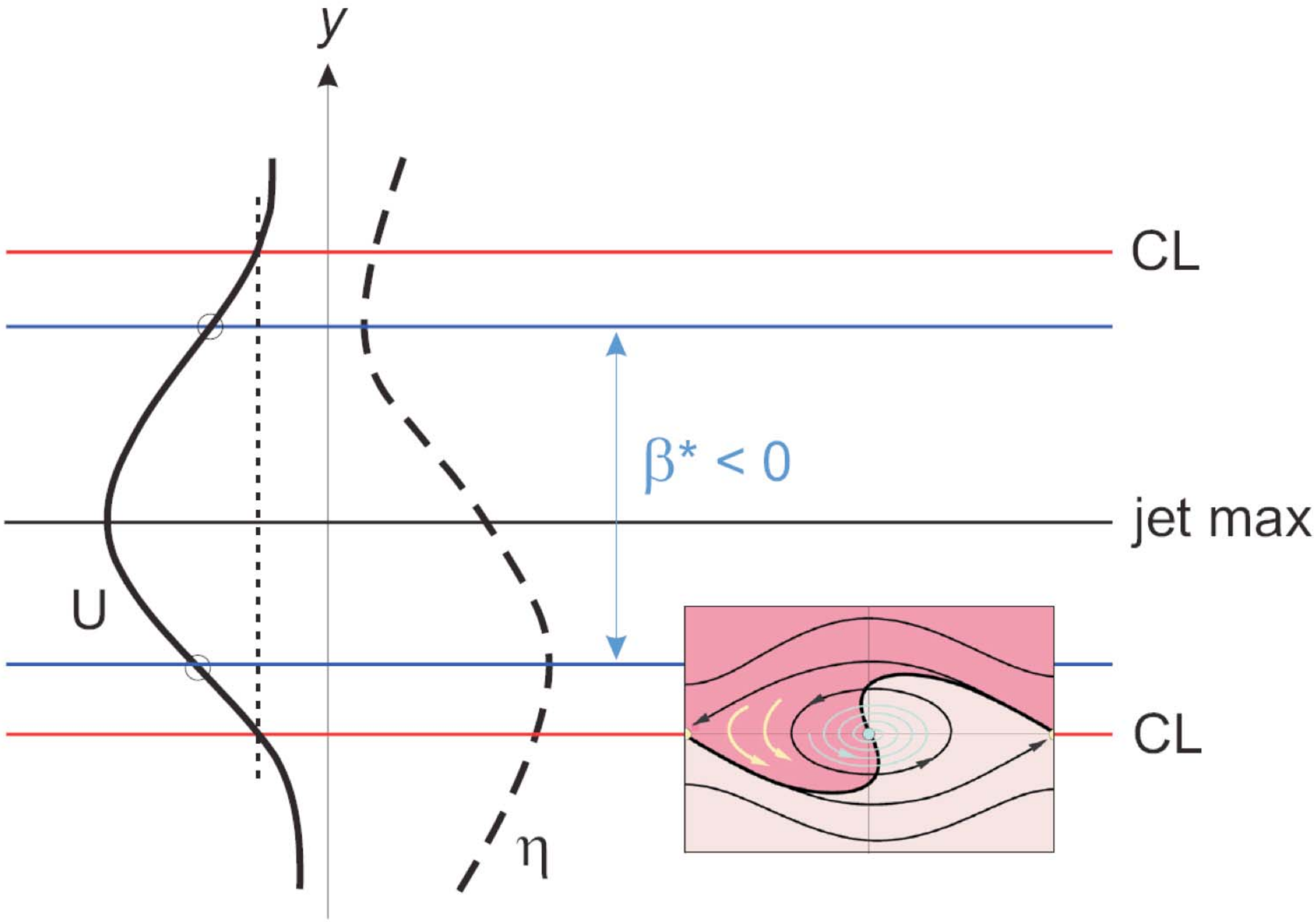


(a) Variance of 3-9 day band-pass filtered 850 hPa meridional velocity field (m^2s^{-2}) in September between 1971-2003; (b) Frequency of sum of band-pass filtered vorticity and long-term mean (ltm) vorticity exceeding $5x10^{-6}$ s^{-1} between 1971-2003. Dots represent the TC genesis locations as declared in the best track data

- **Marsupials** are mammals in which the female typically has a pouch (called the *marsupium*, from which the name 'Marsupial' derives) in which it rears its young through early infancy.

- 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.

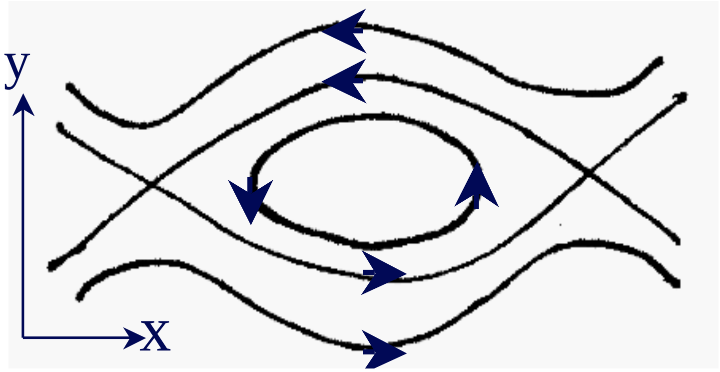
Hydrodynamically stable configuration



Dunkerton et al., 2008 ACP

Moist Critical Layer

- Critical latitude/surface: locus where c=U or equivalently where wave intrinsic frequency = 0
- Critical layer: A layer of finite width due to the nonlinear interaction of the wave with its own critical surface
- Kelvin's Cat's eye: Recirculating flow within CL wherein air parcels are trapped and the fluid is isolated from its surroundings

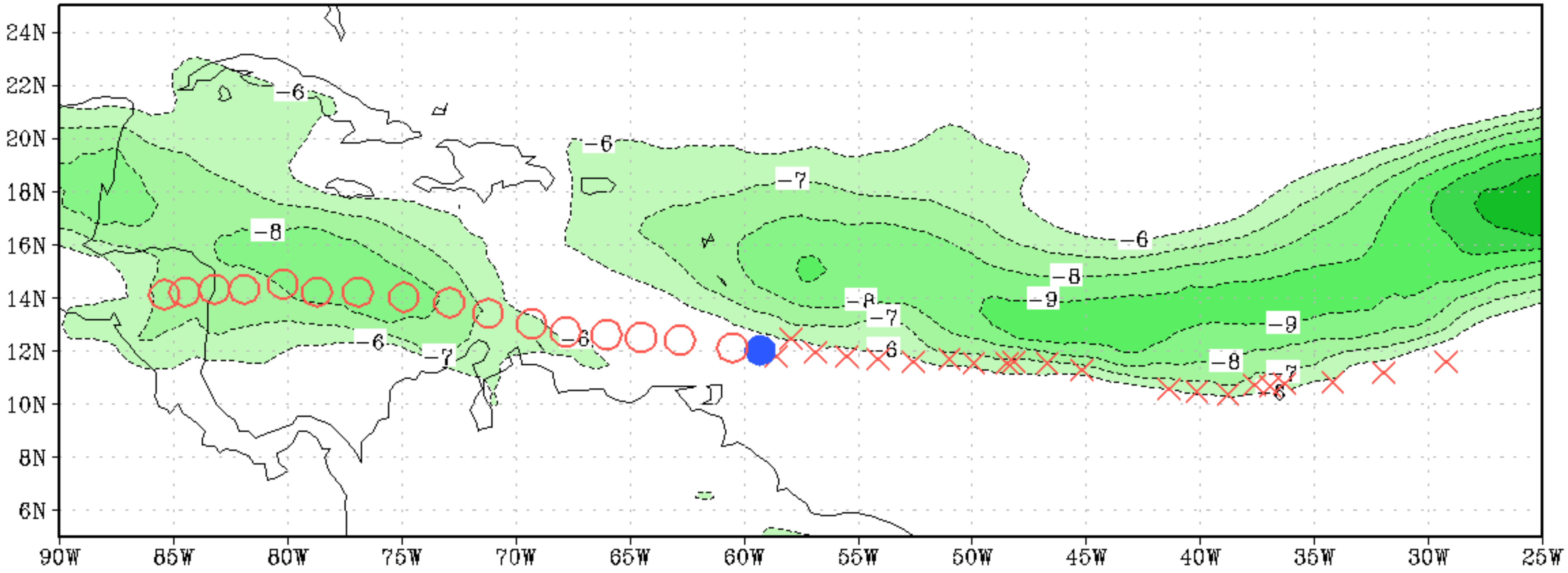


Marsupial Paradigm: 3 New Hypotheses

- H1: Wave breaking or roll-up of cyclonic vorticity near the critical surface in the lower troposphere provides favorable environment for aggregation of vorticity seedlings for TC formation.
- 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.

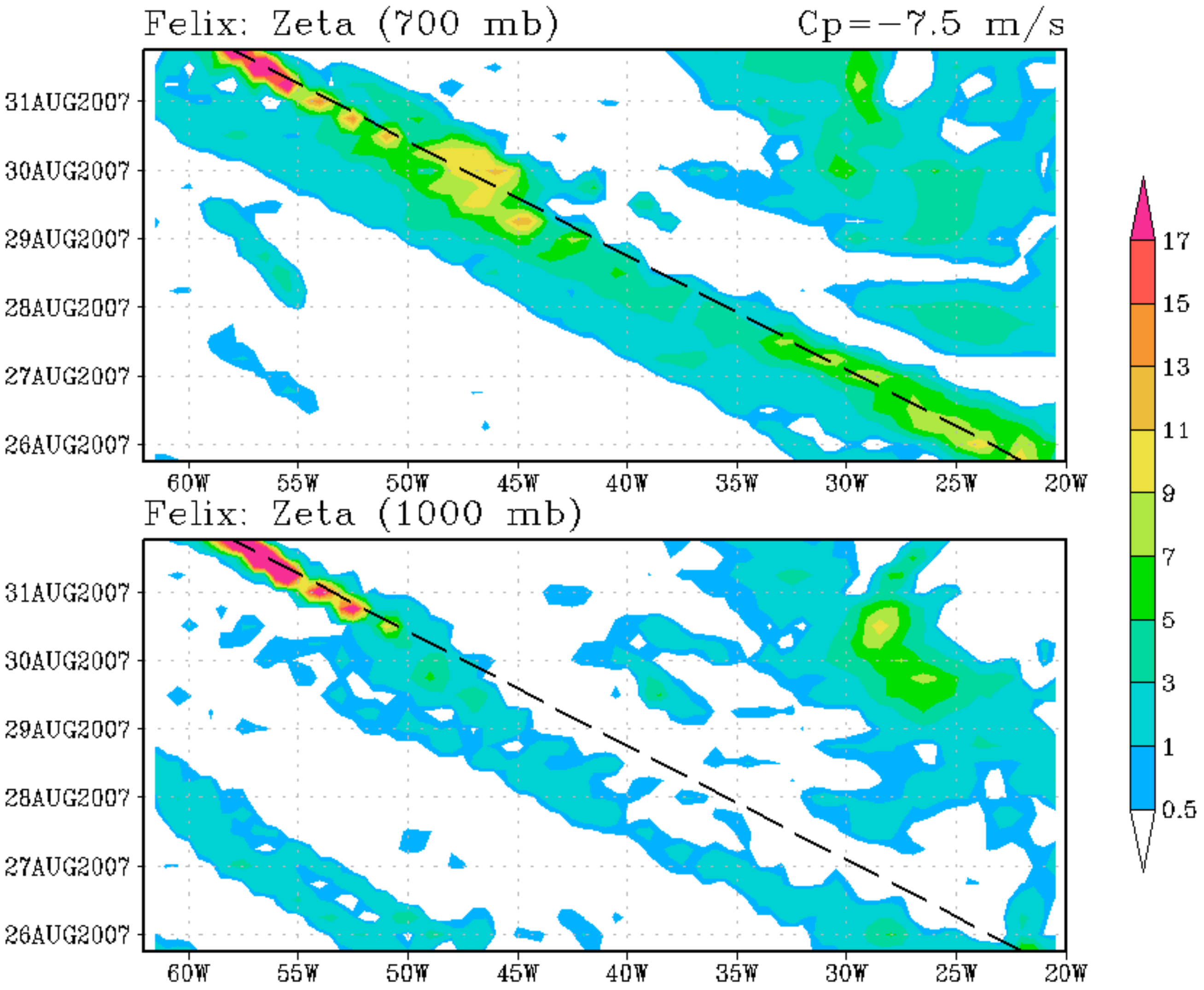
A Real World Example: Formation of Felix (2007)



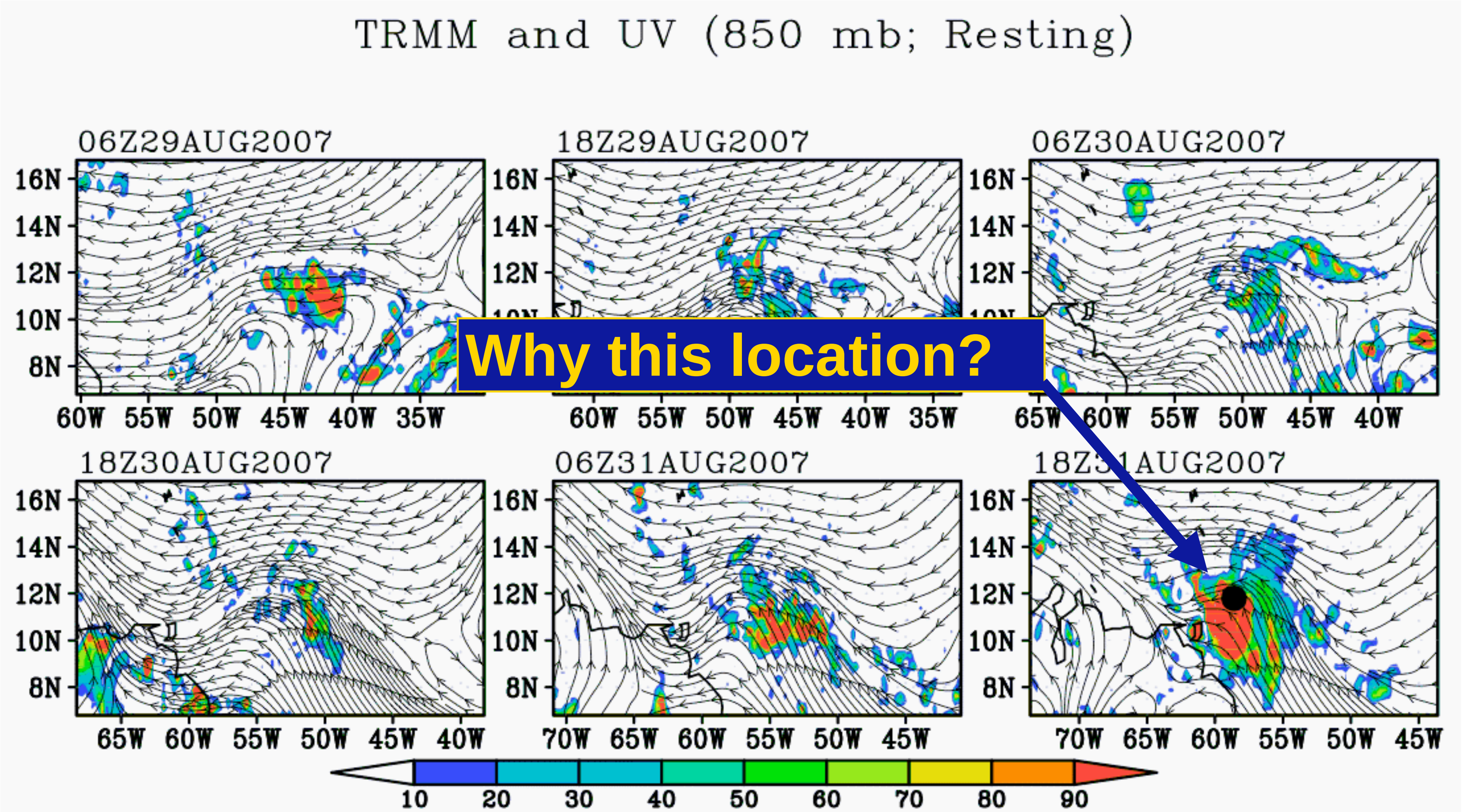
ECMWF 700 hPa U (Day -5 to 0)

NHC declared TS on Aug. 31, 21Z

Hovmoller Diagrams of Relative Vorticity (Day -6 to Day 0)

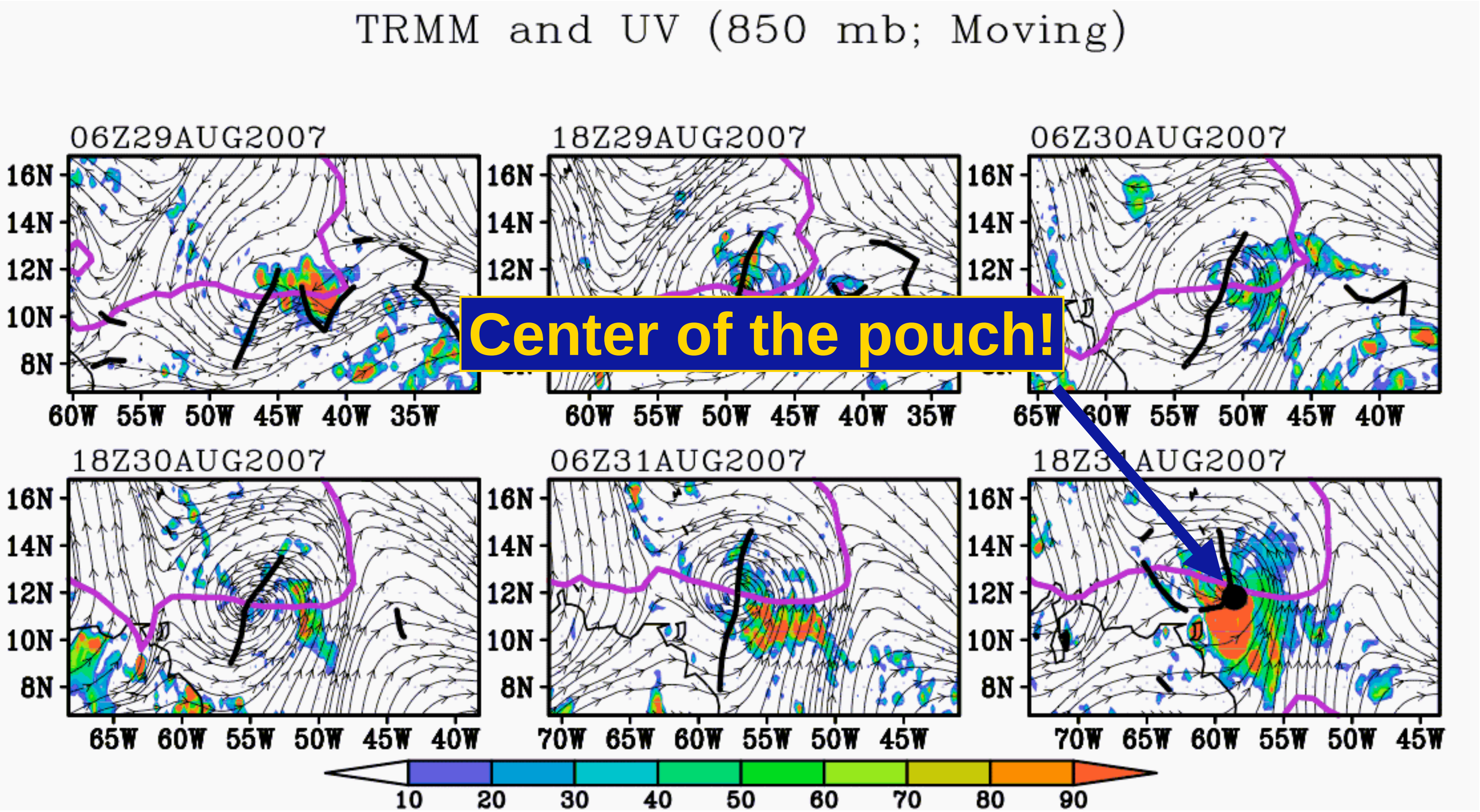


TRMM and Ground-based 850 hPa streamlines for pre-Felix

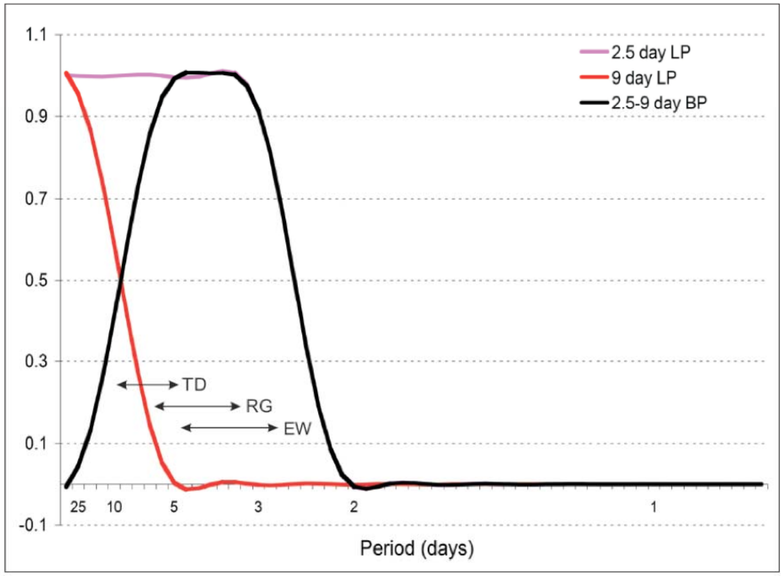


Why this location?

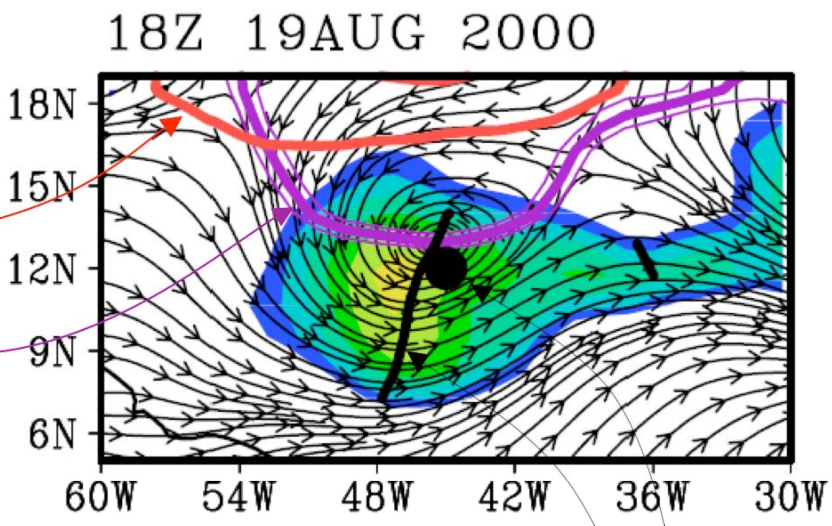
Felix: TRMM and Translated 850 hPa Streamlines~Lagrangian Flow



Center of the pouch!



Low-frequency filter for (linear) wave critical latitude

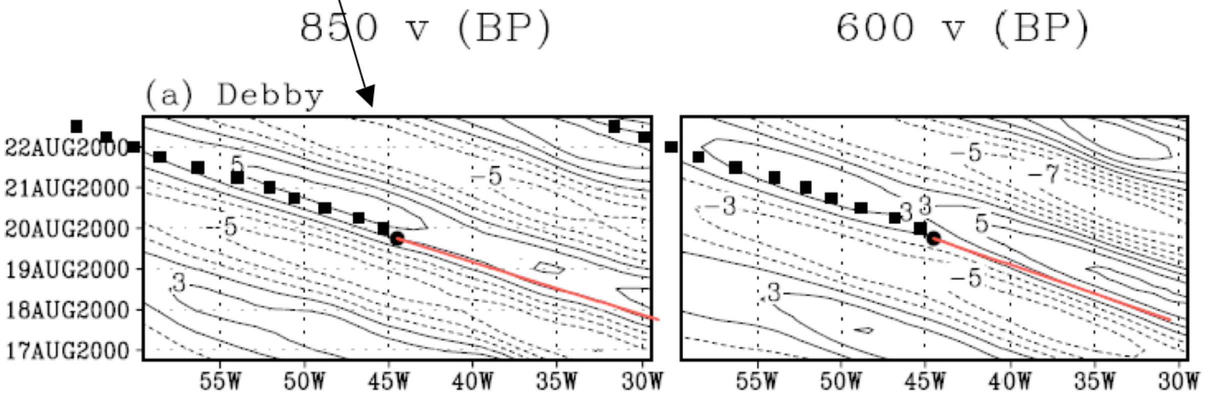


Low-pass filter for kinematic & dynamical fields

Best-track
genesis

Trough axis

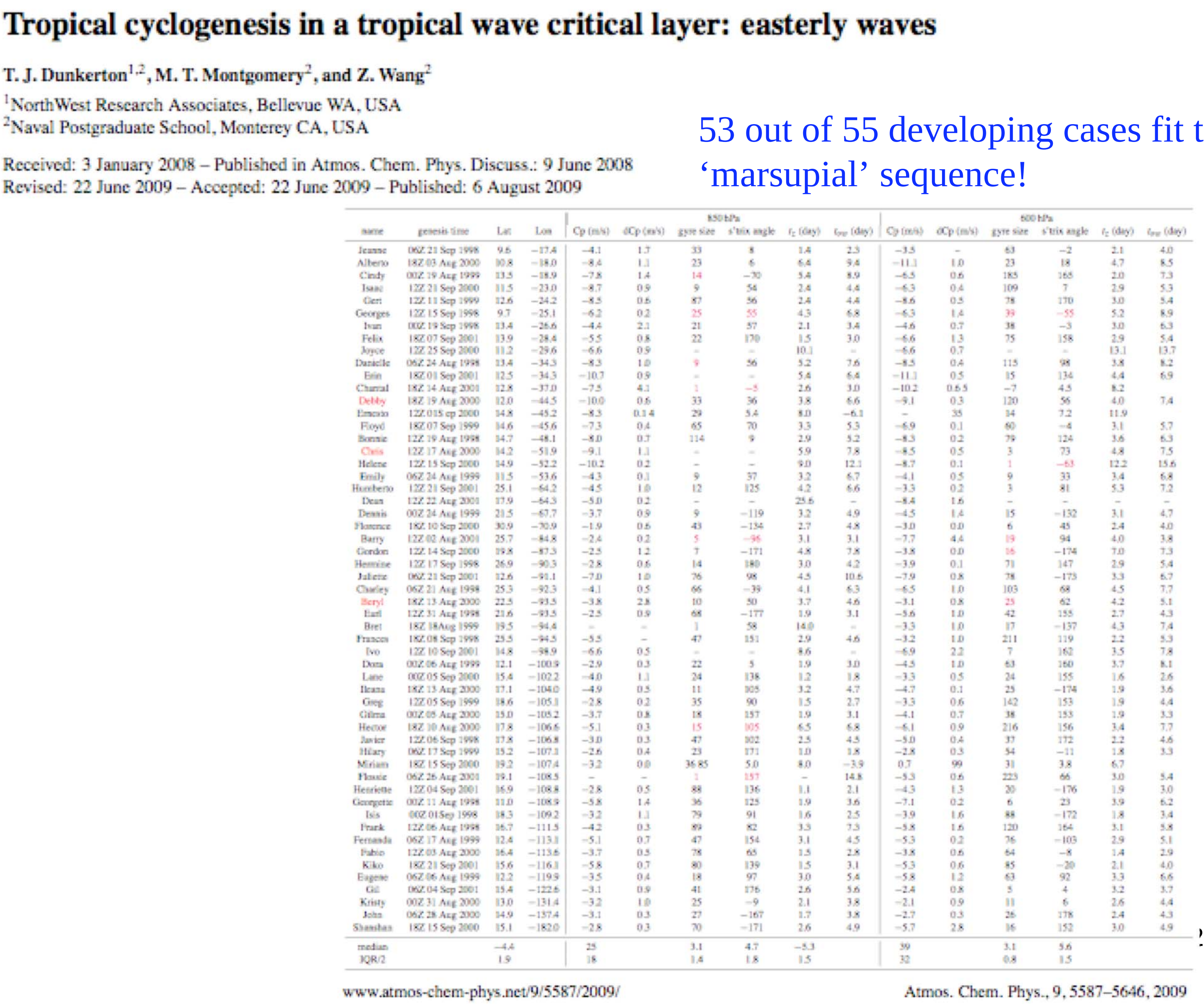
Band-pass
filter for anomaly
propagation



ERA-40
TRMM 3B42
NHC best-track
Aug-Sep 1998-2001

Dunkerton et al., 2008 ACP

53 out of 55 developing cases fit the ‘marsupial’ sequence!



Tropical cyclogenesis in a tropical wave critical layer: easterly waves

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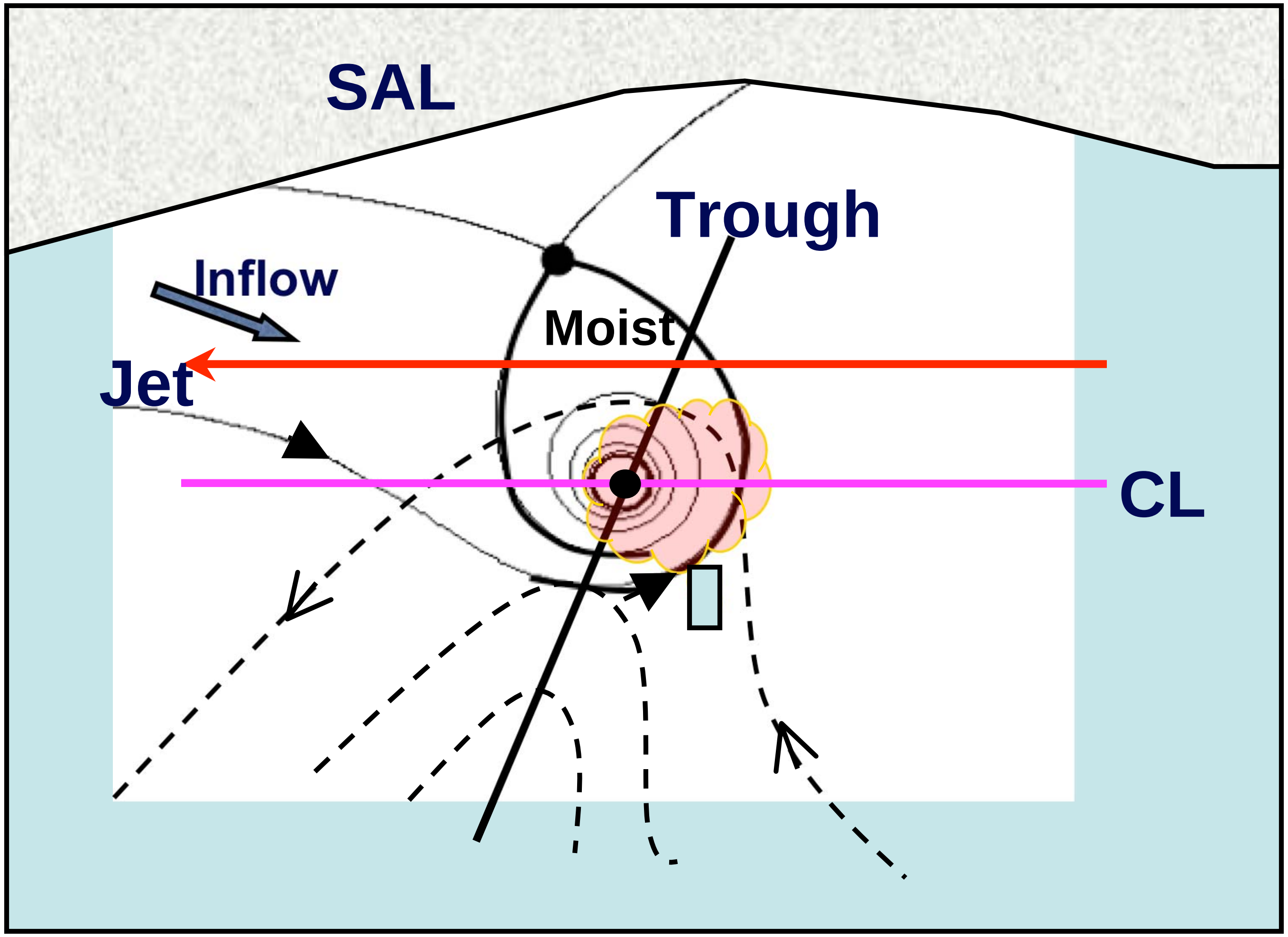
				850 hPa						600 hPa					
name	genesis time	Lat	Lon	Cp (m/s)	dCp (m/s)	gyre size	s'trix angle	t_z (day)	t_{sw} (day)	Cp (m/s)	dCp (m/s)	gyre size	s'trix angle	t_z (day)	t_{sw} (day)
Jeanne	06Z 21 Sep 1998	9.6	−17.4	−4.1	1.7	33	8	1.4	2.3	−3.5	–	63	−2	2.1	4.0
Alberto	18Z 03 Aug 2000	10.8	−18.0	−8.4	1.1	23	6	6.4	9.4	−11.1	1.0	23	18	4.7	8.5
Cindy	00Z 19 Aug 1999	13.5	−18.9	−7.8	1.4	14	−70	5.4	8.9	−6.5	0.6	185	165	2.0	7.3
Isaac	12Z 21 Sep 2000	11.5	−23.0	−8.7	0.9	9	54	2.4	4.4	−6.3	0.4	109	7	2.9	5.3
Gert	12Z 11 Sep 1999	12.6	−24.2	−8.5	0.6	87	56	2.4	4.4	−8.6	0.5	78	170	3.0	5.4
Georges	12Z 15 Sep 1998	9.7	−25.1	−6.2	0.2	25	55	4.3	6.8	−6.3	1.4	39	−55	5.2	8.9
Ivan	00Z 19 Sep 1998	13.4	−26.6	−4.4	2.1	21	57	2.1	3.4	−4.6	0.7	38	−3	3.0	6.3
Felix	18Z 07 Sep 2001	13.9	−28.4	−5.5	0.8	22	170	1.5	3.0	−6.6	1.3	75	158	2.9	5.4
Joyce	12Z 25 Sep 2000	11.2	−29.6	−6.6	0.9	–	–	10.1	–	−6.6	0.7	–	–	13.1	13.7
Danielle	06Z 24 Aug 1998	13.4	−34.3	−8.3	1.0	9	56	5.2	7.6	−8.5	0.4	115	98	3.8	8.2
Erin	18Z 01 Sep 2001	12.5	−34.3	−10.7	0.9	–	–	5.4	6.4	−11.1	0.5	15	134	4.4	6.9
Chantal	18Z 14 Aug 2001	12.8	−37.0	−7.5	4.1	1	−5	2.6	3.0	−10.2	0.6 5	−7	4.5	8.2	
Debby	18Z 19 Aug 2000	12.0	−44.5	−10.0	0.6	33	36	3.8	6.6	−9.1	0.3	120	56	4.0	7.4
Ernesto	12Z 01S ep 2000	14.8	−45.2	−8.3	0.1 4	29	5.4	8.0	−6.1	–	35	14	7.2	11.9	
Floyd	18Z 07 Sep 1999	14.6	−45.6	−7.3	0.4	65	70	3.3	5.3	−6.9	0.1	60	−4	3.1	5.7
Bonnie	12Z 19 Aug 1998	14.7	−48.1	−8.0	0.7	114	9	2.9	5.2	−8.3	0.2	79	124	3.6	6.3
Chris	12Z 17 Aug 2000	14.2	−51.9	−9.1	1.1	–	–	5.9	7.8	−8.5	0.5	3	73	4.8	7.5
Helene	12Z 15 Sep 2000	14.9	−52.2	−10.2	0.2	–	–	9.0	12.1	−8.7	0.1	1	−63	12.2	15.6
Emily	06Z 24 Aug 1999	11.5	−53.6	−4.3	0.1	9	37	3.2	6.7	−4.1	0.5	9	33	3.4	6.8
Humberto	12Z 21 Sep 2001	25.1	−64.2	−4.5	1.0	12	125	4.2	6.6	−3.3	0.2	3	81	5.3	7.2
Dean	12Z 22 Aug 2001	17.9	−64.3	−5.0	0.2	–	–	25.6	–	−8.4	1.6	–	–	–	–
Dennis	00Z 24 Aug 1999	21.5	−67.7	−3.7	0.9	9	−119	3.2	4.9	−4.5	1.4	15	−132	3.1	4.7
Florence	18Z 10 Sep 2000	30.9	−70.9	−1.9	0.6	43	−134	2.7	4.8	−3.0	0.0	6	45	2.4	4.0
Barry	12Z 02 Aug 2001	25.7	−84.8	−2.4	0.2	5	−96	3.1	3.1	−7.7	4.4	19	94	4.0	3.8
Gordon	12Z 14 Sep 2000	19.8	−87.3	−2.5	1.2	7	−171	4.8	7.8	−3.8	0.0	16	−174	7.0	7.3
Hermine	12Z 17 Sep 1998	26.9	−90.3	−2.8	0.6	14	180	3.0	4.2	−3.9	0.1	71	147	2.9	5.4
Juliette	06Z 21 Sep 2001	12.6	−91.1	−7.0	1.0	76	98	4.5	10.6	−7.9	0.8	78	−173	3.3	6.7
Charley	06Z 21 Aug 1998	25.3	−92.3	−4.1	0.5	66	−39	4.1	6.3	−6.5	1.0	103	68	4.5	7.7
Beryl	18Z 13 Aug 2000	22.5	−93.5	−3.8	2.8	10	50	3.7	4.6	−3.1	0.8	25	62	4.2	5.1
Earl	12Z 31 Aug 1998	21.6	−93.5	−2.5	0.9	68	−177	1.9	3.1	−5.6	1.0	42	155	2.7	4.3
Bret	18Z 18Aug 1999	19.5	−94.4	–	–	1	58	14.0	–	−3.3	1.0	17	−137	4.3	7.4
Frances	18Z 08 Sep 1998	25.5	−94.5	−5.5	–	47	151	2.9	4.6	−3.2	1.0	211	119	2.2	5.3
Ivo	12Z 10 Sep 2001	14.8	−98.9	−6.6	0.5	–	–	8.6	–	−6.9	2.2	7	162	3.5	7.8
Dora	00Z 06 Aug 1999	12.1	−100.9	−2.9	0.3	22	5	1.9	3.0	−4.5	1.0	63	160	3.7	8.1
Lane	00Z 05 Sep 2000	15.4	−102.2	−4.0	1.1	24	138	1.2	1.8	−3.3	0.5	24	155	1.6	2.6
Ileana	18Z 13 Aug 2000	17.1	−104.0	−4.9	0.5	11	105	3.2	4.7	−4.7	0.1	25	−174	1.9	3.6
Greg	12Z 05 Sep 1999	18.6	−105.1	−2.8	0.2	35	90	1.5	2.7	−3.3	0.6	142	153	1.9	4.4
Gilma	00Z 05 Aug 2000	15.0	−105.2	−3.7	0.8	18	157	1.9	3.1	−4.1	0.7	38	153	1.9	3.3
Hector	18Z 10 Aug 2000	17.8	−106.6	−5.1	0.3	15	105	6.5	6.8	−6.1	0.9	216	156	3.4	7.7
Javier	12Z 06 Sep 1998	17.8	−106.8	−3.0	0.3	47	102	2.5	4.5	−5.0	0.4	37	172	2.2	4.6
Hilary	06Z 17 Sep 1999	15.2	−107.1	−2.6	0.4	23	171	1.0	1.8	−2.8	0.3	54	−11	1.8	3.3
Miriam	18Z 15 Sep 2000	19.2	−107.4	−3.2	0.0	36 85	5.0	8.0	−3.9	0.7	99	31	3.8	6.7	
Flossie	06Z 26 Aug 2001	19.1	−108.5	–	–	1	157	–	14.8	−5.3	0.6	223	66	3.0	5.4
Henriette	12Z 04 Sep 2001	16.9	−108.8	−2.8	0.5	88	136	1.1	2.1	−4.3	1.3	20	−176	1.9	3.0
Georgette	00Z 11 Aug 1998	11.0	−108.9	−5.8	1.4	36	125	1.9	3.6	−7.1	0.2	6	23	3.9	6.2
Isis	00Z 01Sep 1998	18.3	−109.2	−3.2	1.1	79	91	1.6	2.5	−3.9	1.6	88	−172	1.8	3.4
Frank	12Z 06 Aug 1998	16.7	−111.5	−4.2	0.3	89	82	3.3	7.3	−5.8	1.6	120	164	3.1	5.8
Fernanda	06Z 17 Aug 1999	12.4	−113.1	−5.1	0.7	47	154	3.1	4.5	−5.3	0.2	76	−103	2.9	5.1
Fabio	12Z 03 Aug 2000	16.4	−113.6	−3.7	0.5	78	65	1.5	2.8	−3.8	0.6	64	−8	1.4	2.9
Kiko	18Z 21 Sep 2001	15.6	−116.1	−5.8	0.7	80	139	1.5	3.1	−5.3	0.6	85	−20	2.1	4.0
Eugene	06Z 06 Aug 1999	12.2	−119.9	−3.5	0.4	18	97	3.0	5.4	−5.8	1.2	63	92	3.3	6.6
Gil	06Z 04 Sep 2001	15.4	−122.6	−3.1	0.9	41	176	2.6	5.6	−2.4	0.8	5	4	3.2	3.7
Kristy	00Z 31 Aug 2000	13.0	−131.4	−3.2	1.0	25	−9	2.1	3.8	−2.1	0.9	11	6	2.6	4.4
John	06Z 28 Aug 2000	14.9	−137.4	−3.1	0.3	27	−167	1.7	3.8	−2.7	0.3	26	178	2.4	4.3
Shanshan	18Z 15 Sep 2000	15.1	−182.0	−2.8	0.3	70	−171	2.6	4.9	−5.7	2.8	16	152	3.0	4.9
median		−4.4		25		3.1	4.7	−5.3		39		3.1	5.6		
IQR/2		1.9		18		1.4	1.8	1.5		32		0.8	1.5		

www.atmos-chem-phys.net/9/5587/2009/

Atmos. Chem. Phys., 9, 5587–5646, 2009

Schematic of the “Pouch”



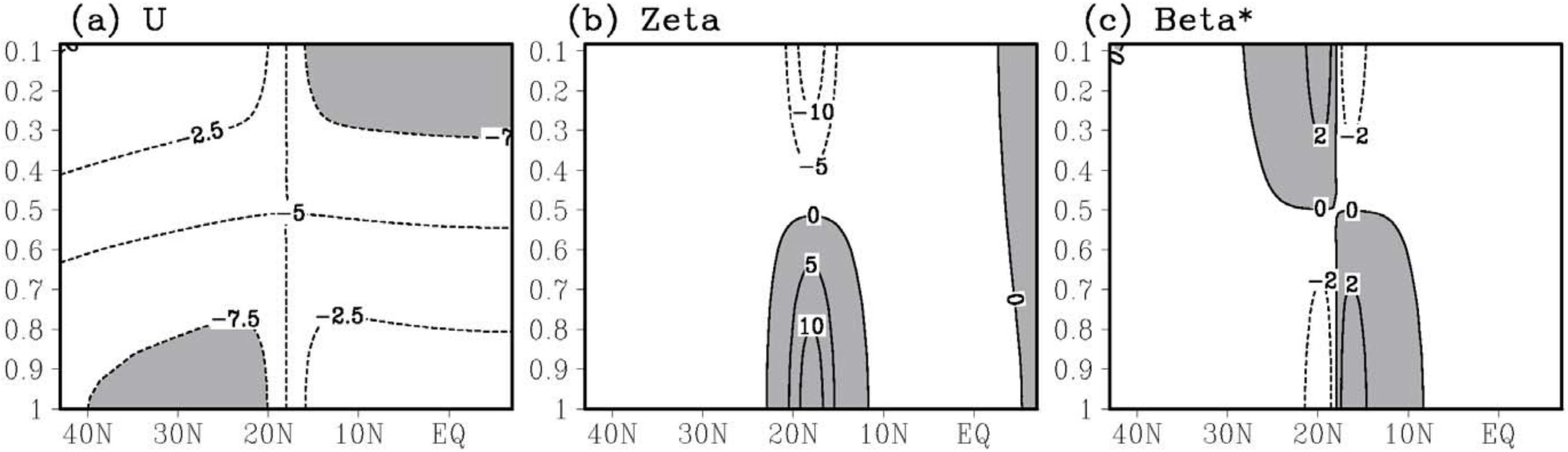
Open Questions: What are the dynamics at meso-α, meso-β and meso-γ?

Seek preliminary answers by revisiting
Kurihara and Tuleya (1981, NOAA/GFDL)

- f-plane approximation (~18N)
- 3-grid nested run: 28 km-9 km- 3km
- Physics: Betts-Miller-Janjic scheme for the outer grid, and cumulus convection is calculated explicitly at the grid scale for the inner two grids. YSU PBL scheme, Kessler (warm-rain) microphysics, RRTM longwave radiation scheme and Dudhia shortwave radiation scheme.

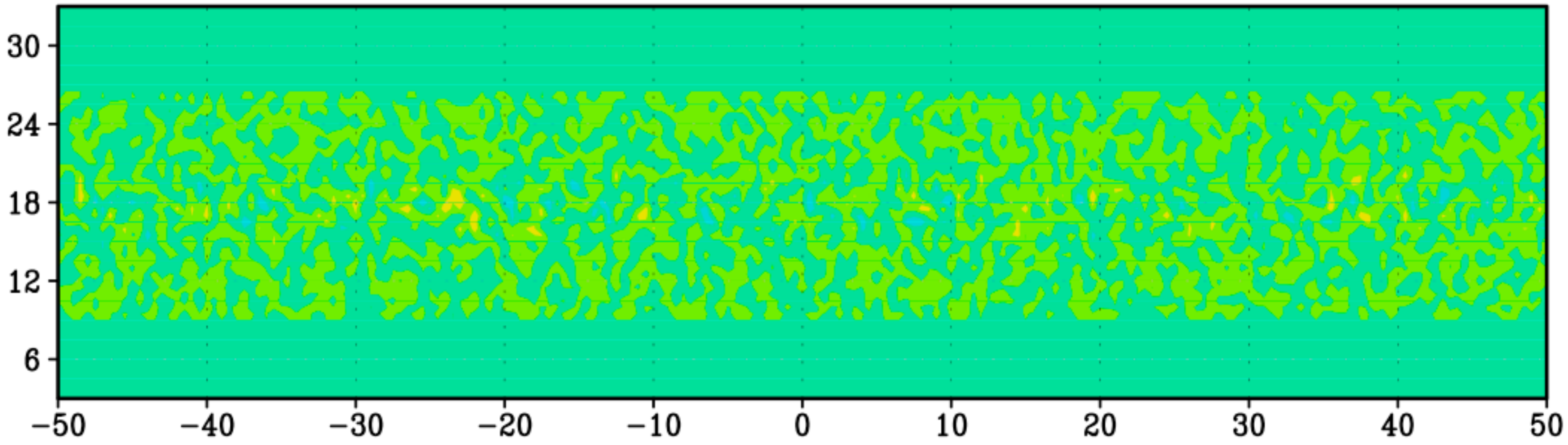
Basic Flow

Following Kurihara and Tuleya (1981); consistent with the observed zonal flow during Phase III of GATE over the west Atlantic region; weakly barotropically unstable.

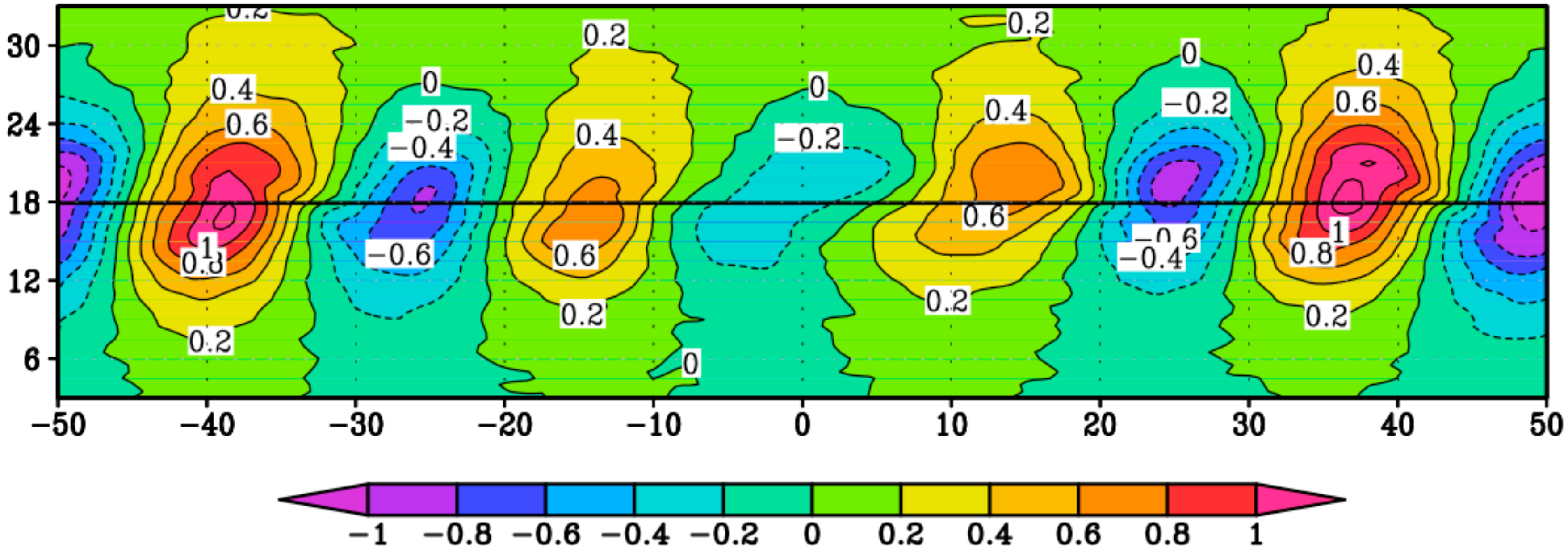


$$\begin{cases} \bar{u}(\phi,\sigma) = u_1 \cos(\sigma\pi)\tanh(\dfrac{\phi-\phi_0}{D}) + u_0 \dfrac{\cos\phi}{\cos\phi_0} \\ \bar{v} = 0 \end{cases}$$

(a) Day 1



(b) Day 30



Meridional wind disturbance from dry model simulation following KT81 at Day 1 and Day 30

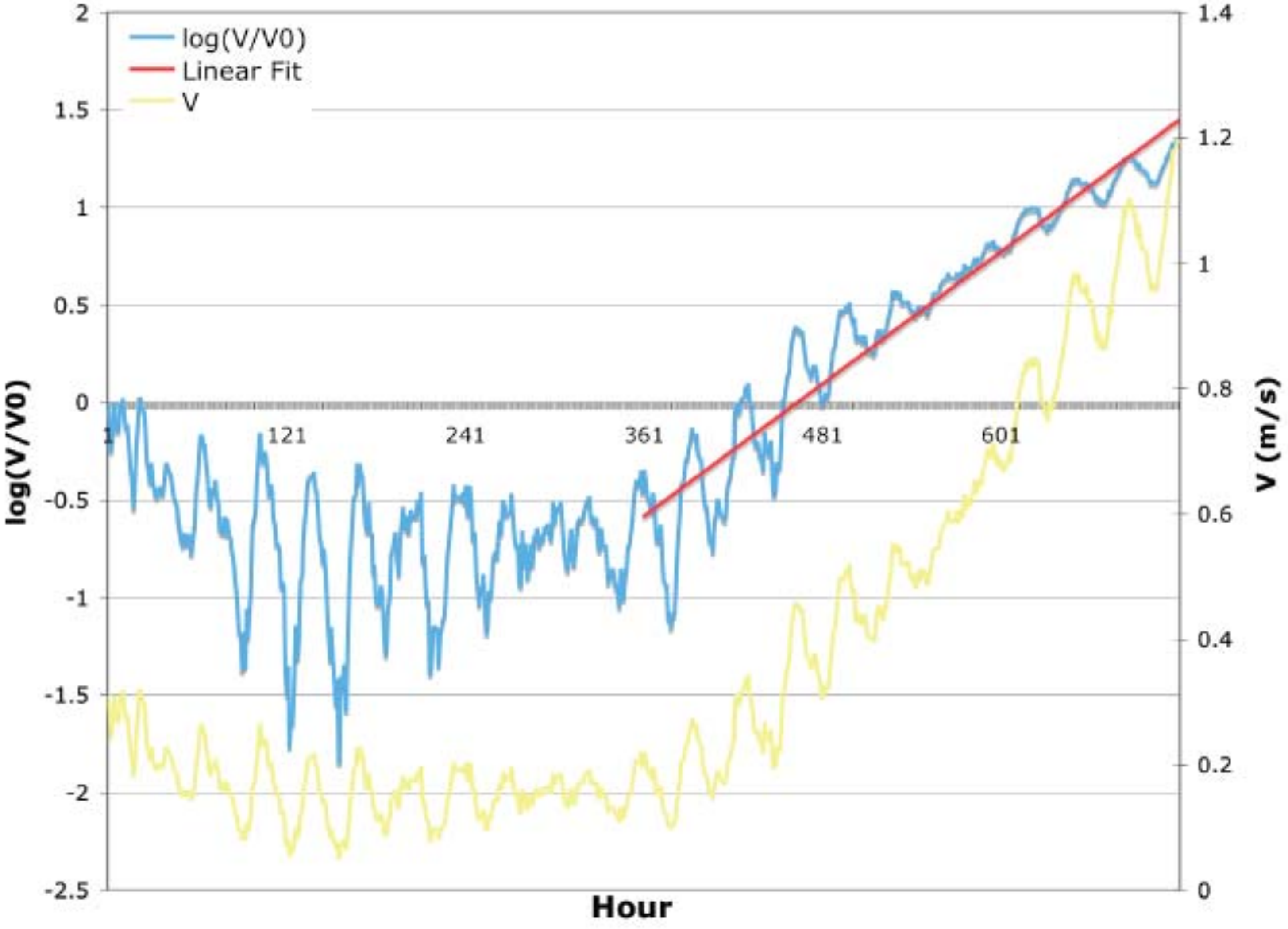
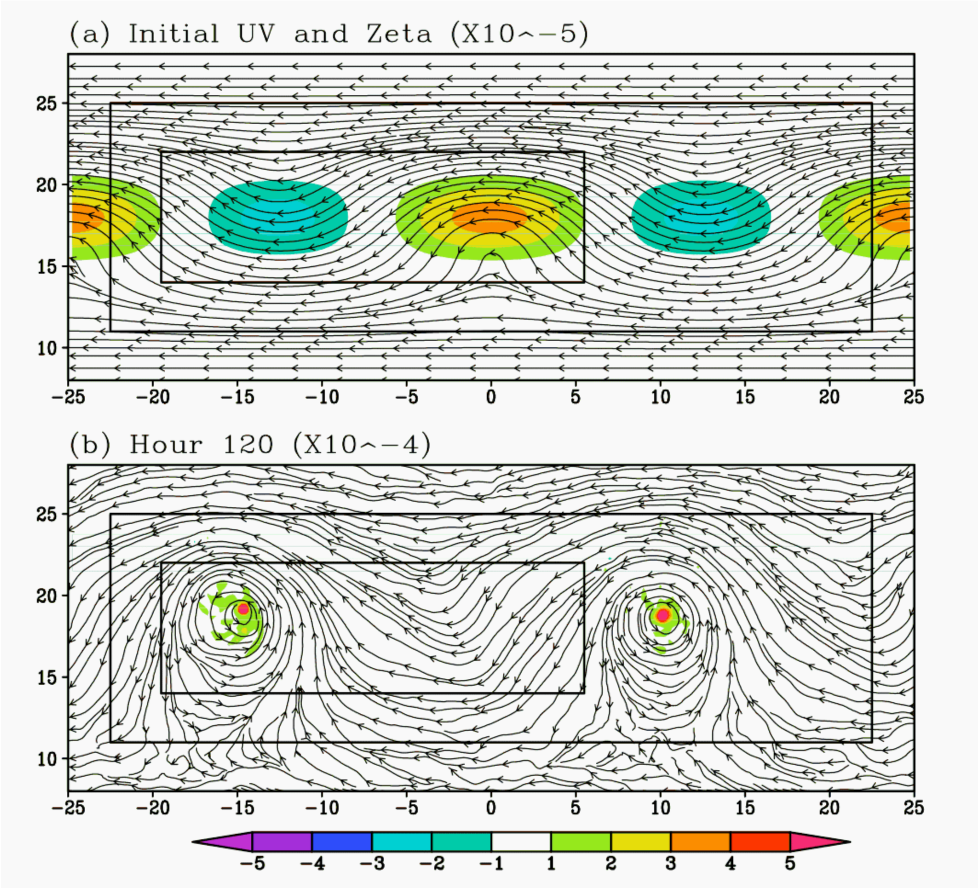


Figure 3 Time series of the surface maximum meridional wind (yellow; y-axis on the right) and its natural logarithm (blue; y-axis on the left) from the dry WRF simulation. The red straight line shows the linear growth rate.

(e-folding time scale =7.4d; 30d to attain finite amplitude coherent wave train from noise)

Initial Value Problem



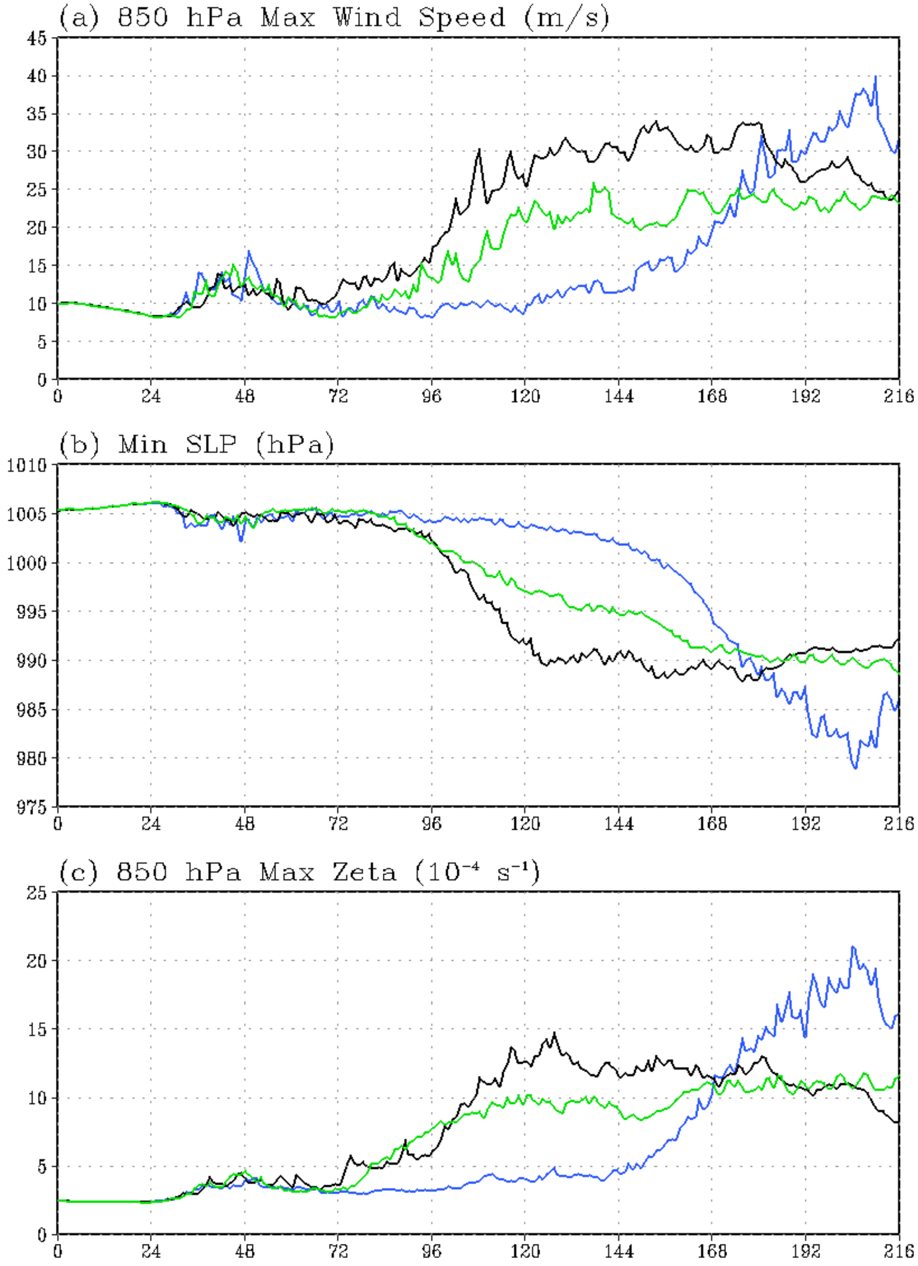
Resembles the most unstable mode

Wavelength=2800 km (2 waves within outer domain)

Amplitude confined primarily to middle and lower troposphere

Simulated Intensity

- Black: single-grid, coarse-resolution (28 km) simulation
- Green: high-resolution (3 km) warm-rain simulation (CTRL)
- Blue: high-resolution (3 km) simulation with ice microphysics (WRF single-moment, 6-class microphysics scheme)


(a) 850 hPa Max Wind Speed (m/s)

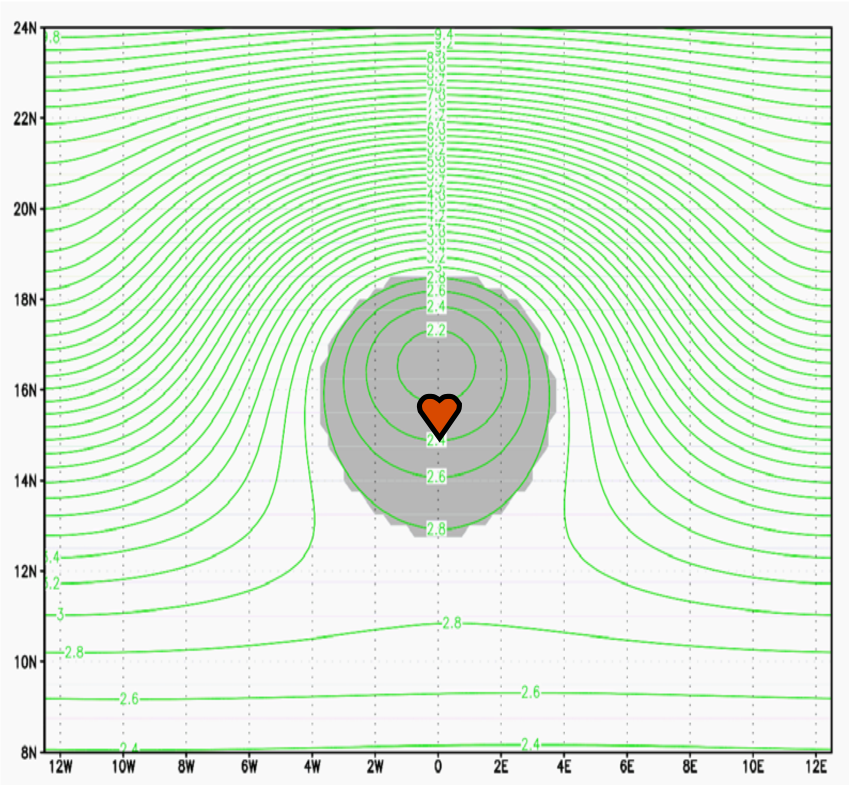
(b) Min SLP (hPa)

(c) 850 hPa Max Zeta (10^{-4} s^{-1})

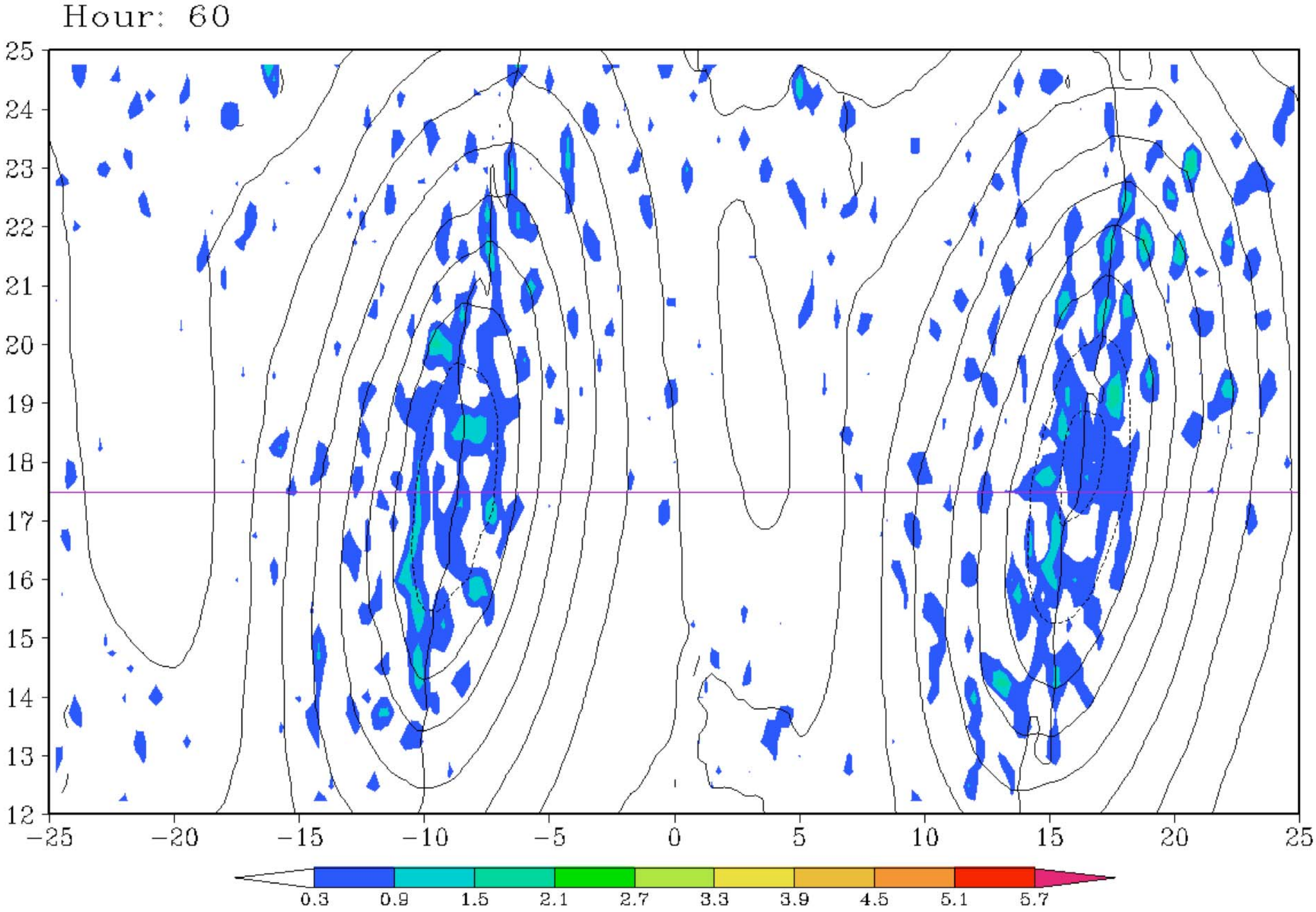
Tracking of Gyre Centroid

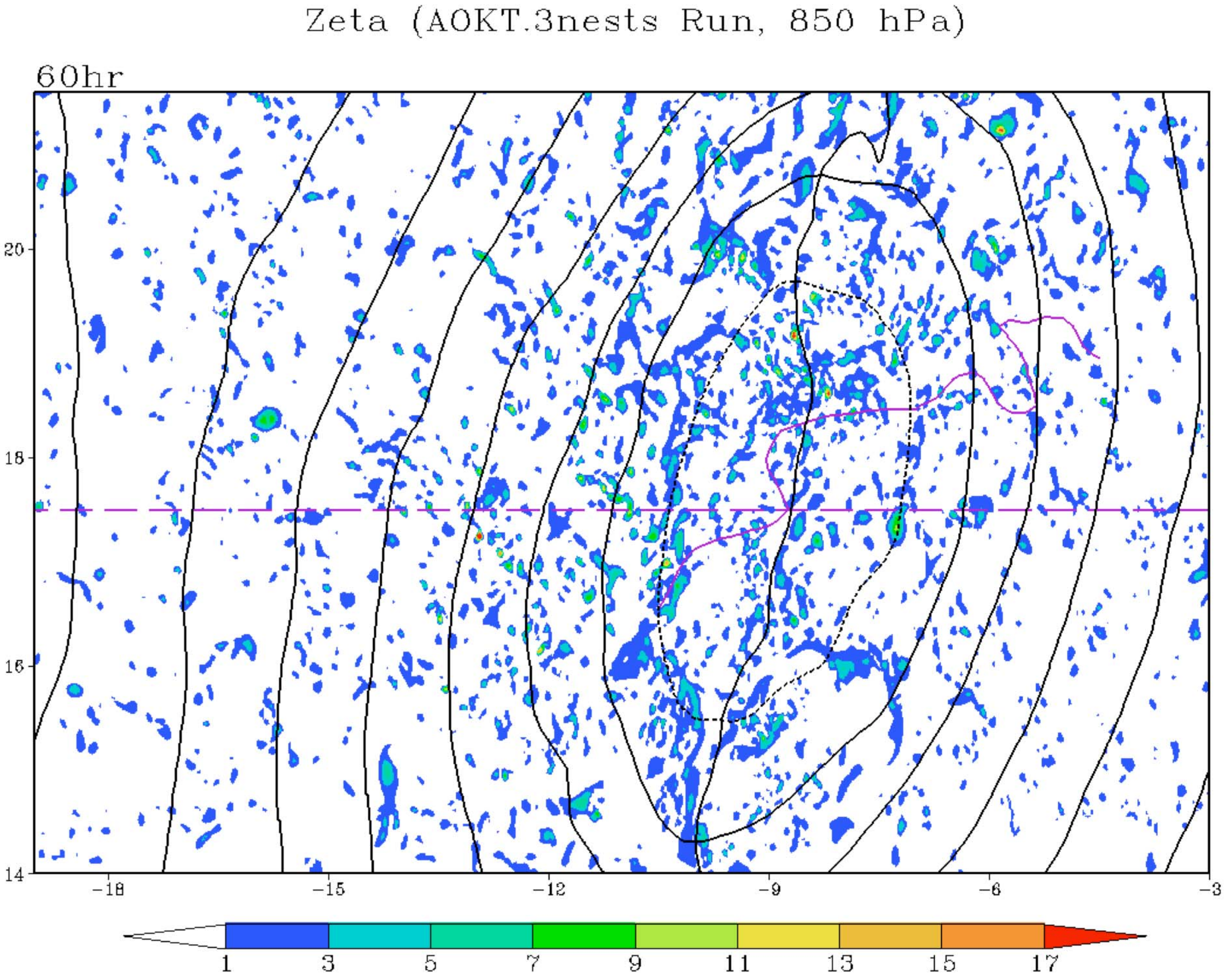
- It is difficult to track vorticity or meridional wind in the high-resolution model simulation
- Thus the propagation speed of the wave is defined based upon a tracking of the pouch centroid in the resting frame of reference:

$$\bar{x} = \frac{1}{n}\sum_{gyre} x_i \qquad \bar{y} = \frac{1}{n}\sum_{gyre} y_i$$

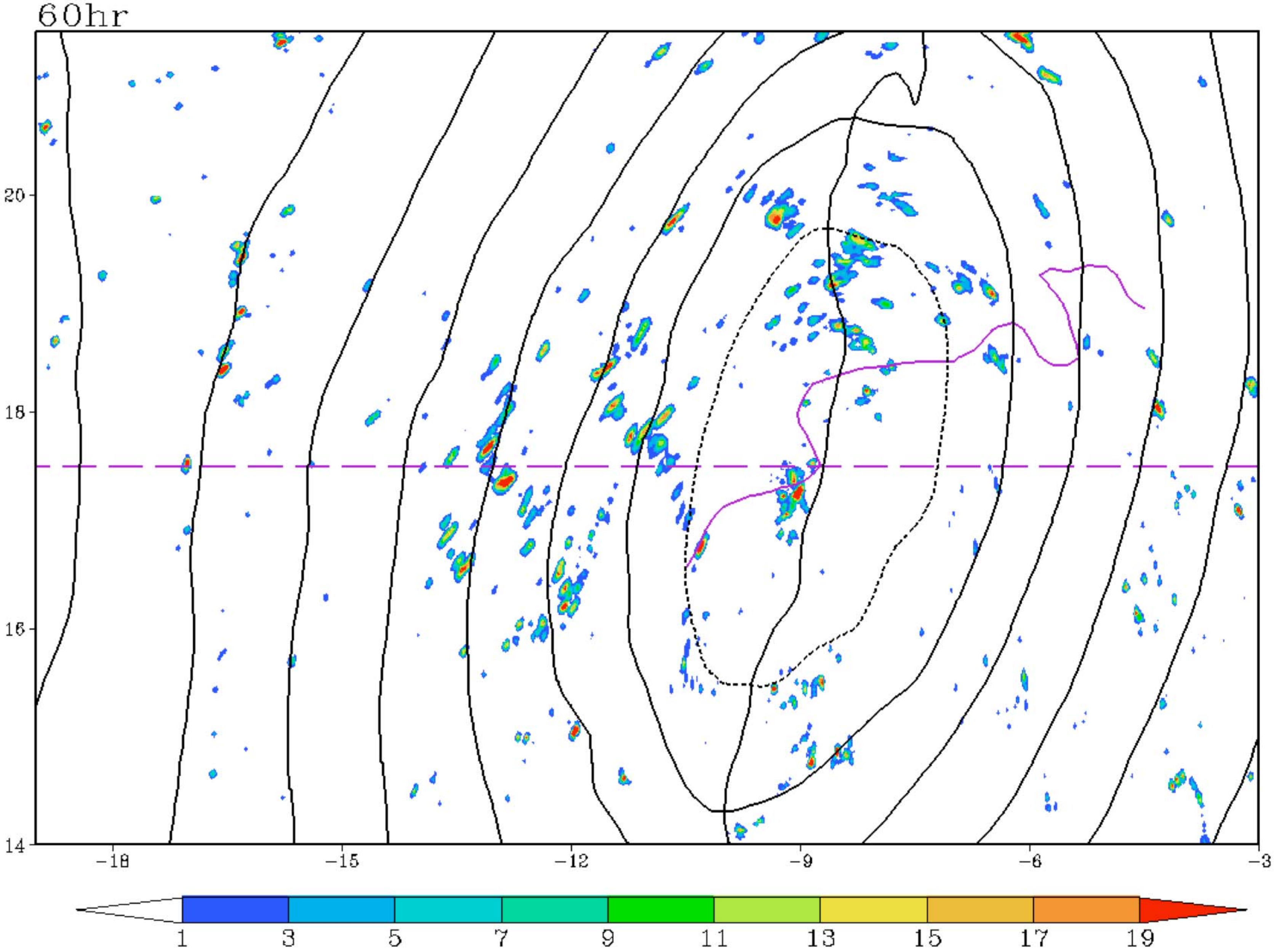


Evolution of the Pouch (d01)

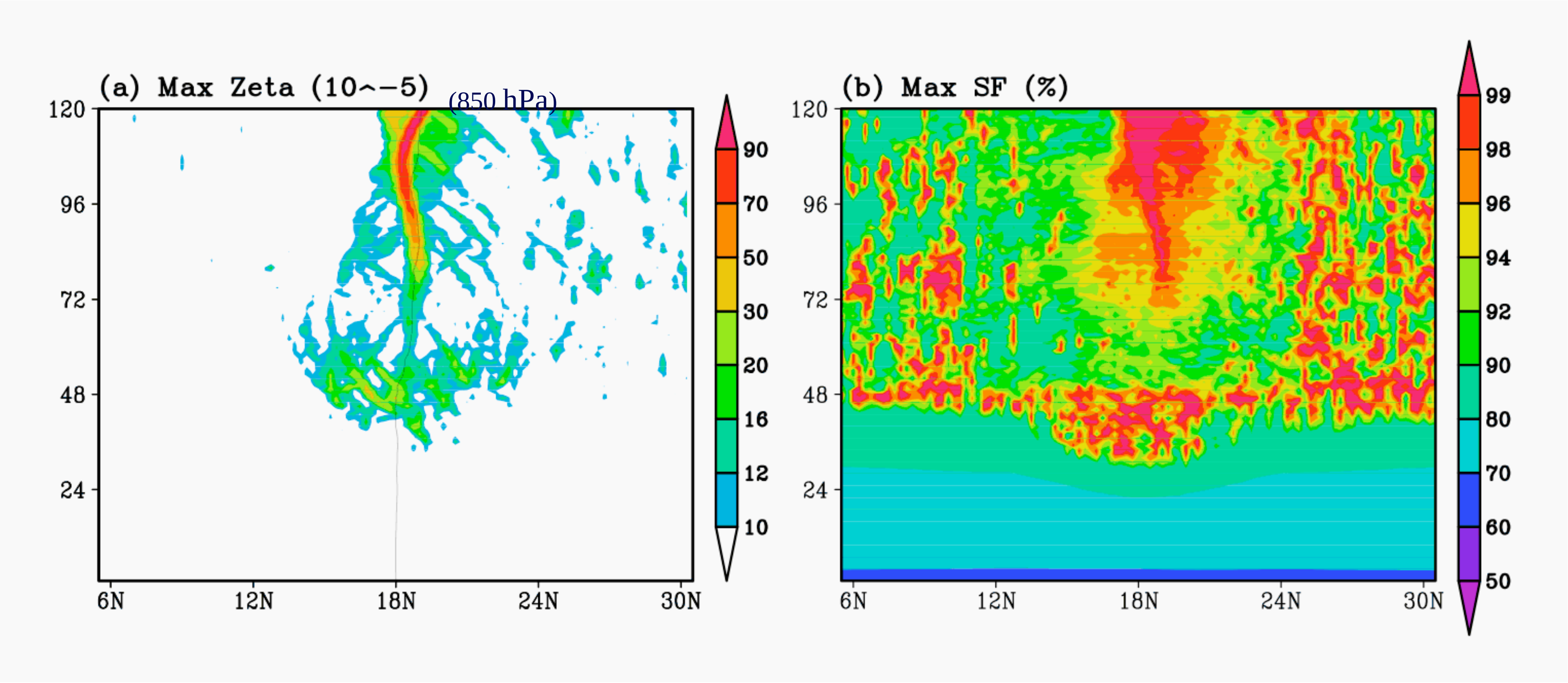



Zeta (AOKT.3nests Run, 850 hPa)
60hr
20
18
16
14
-18
-15
-12
-9
-6
-3
1
3
5
7
9
11
13
15
17

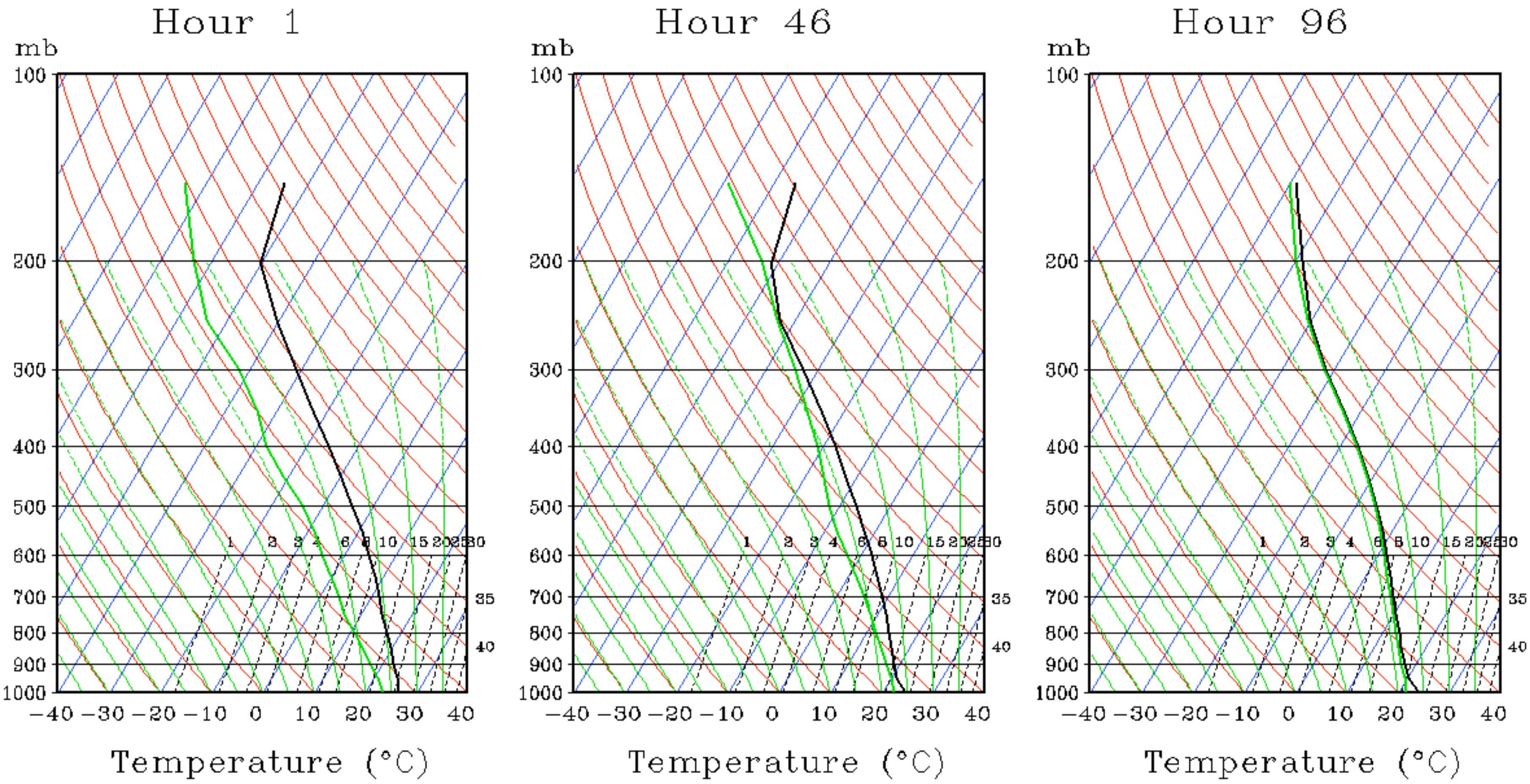
Precip (AOKT.3nests Run, 850 hPa)



“Fujita Diagram”

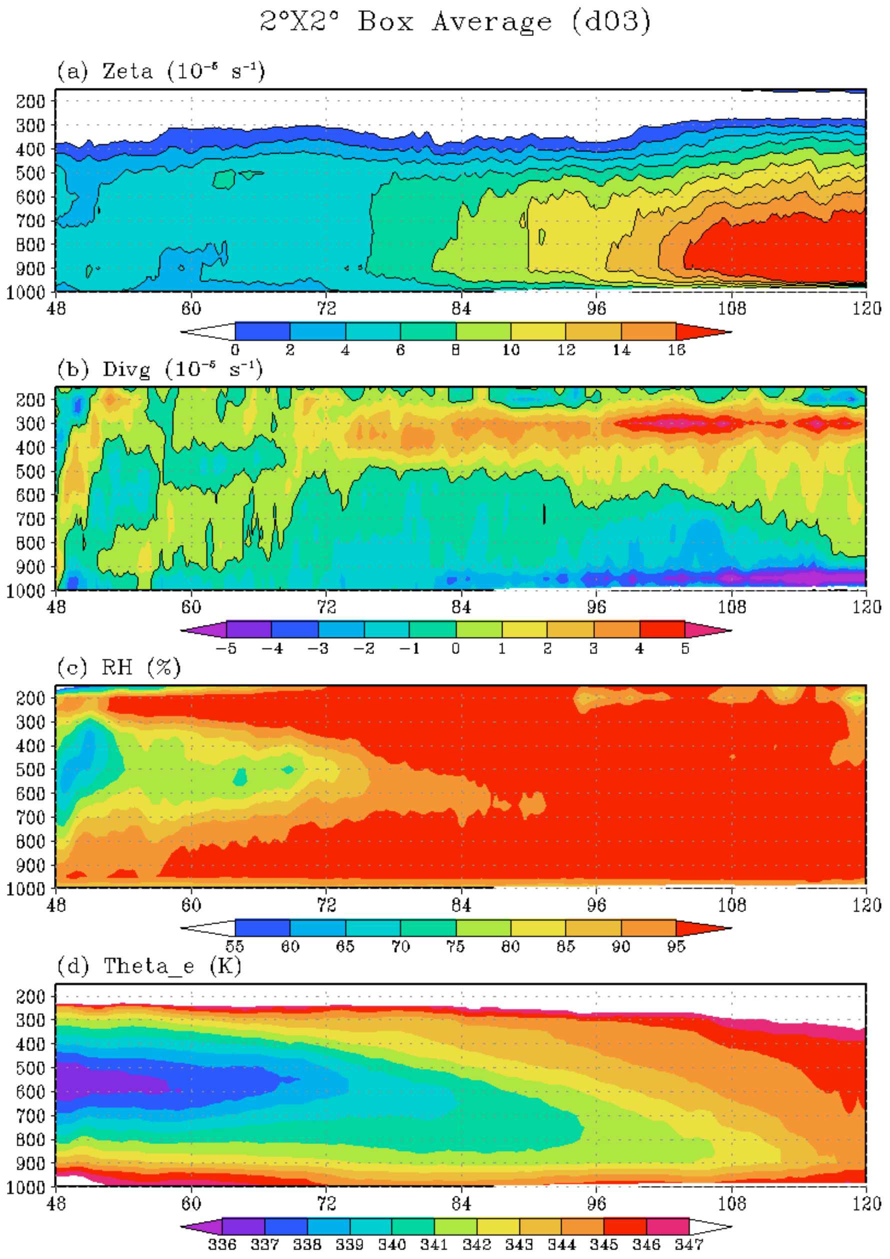


Skew T- Log P Diagrams

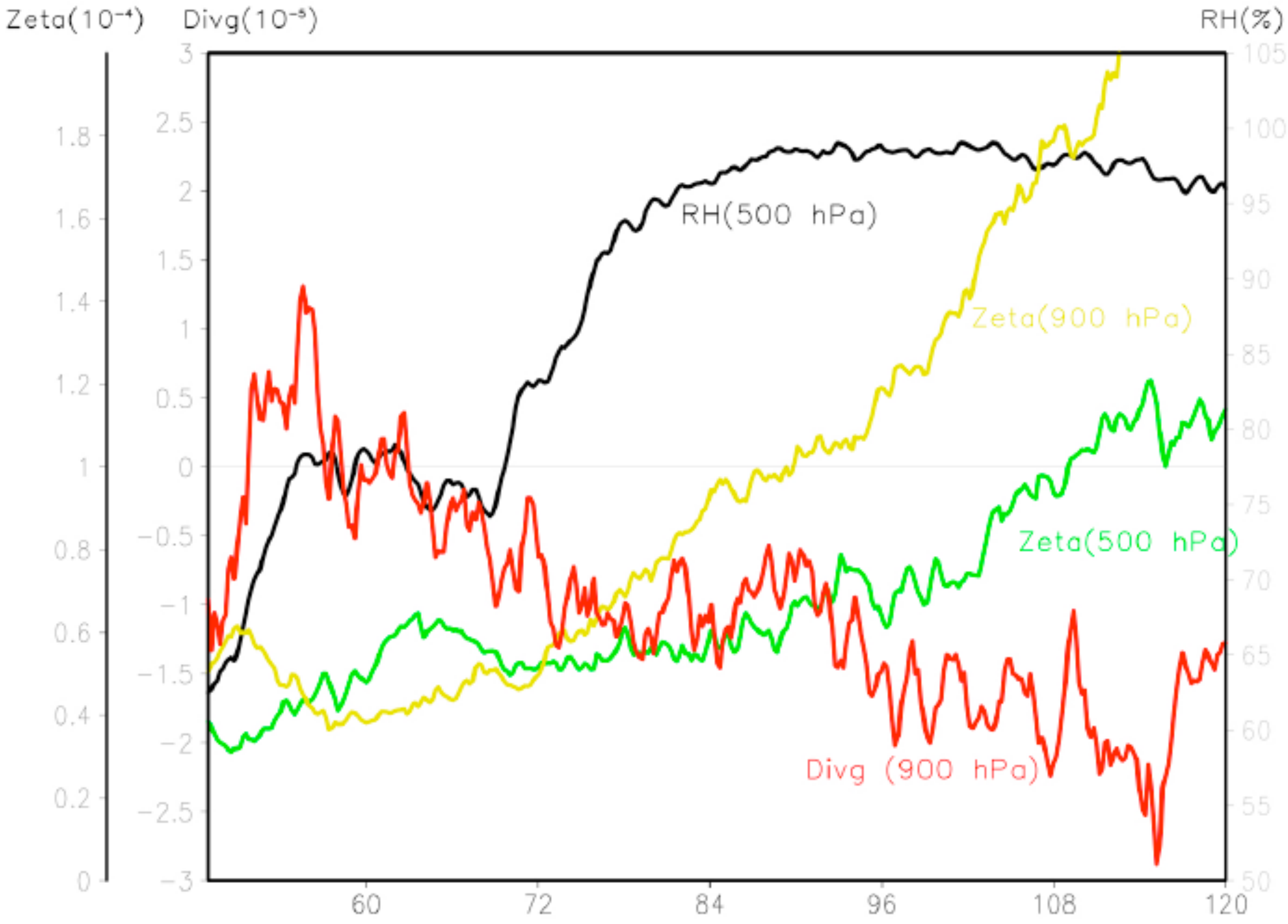


2ºX2º Box-average Following Pouch Center

Time-Height Evolution of <Zeta>, <Div>, <RH> & < θ_e>



<-->=2ºX2º Area-Avg.
Following
Pouch Center



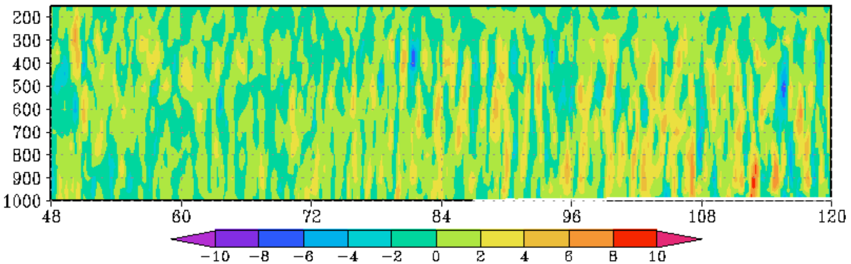
10^{-5}

Time evolution of 2x2 degree box-averaged 500 hPa RH, 900 hPa Divergence, 500 hPa and 900 hPa rel. vorticity from hour 0 to hour 120.

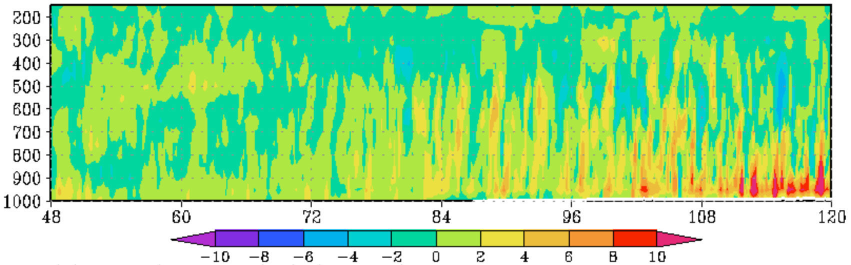
Vorticity Budget Following the Pouch Center

2°X2° Box Average (d03)

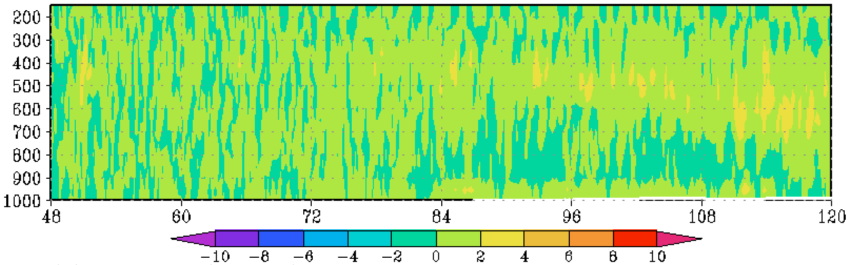
(a) $\partial\eta/\partial t$ (10^{-9} s^{-2})



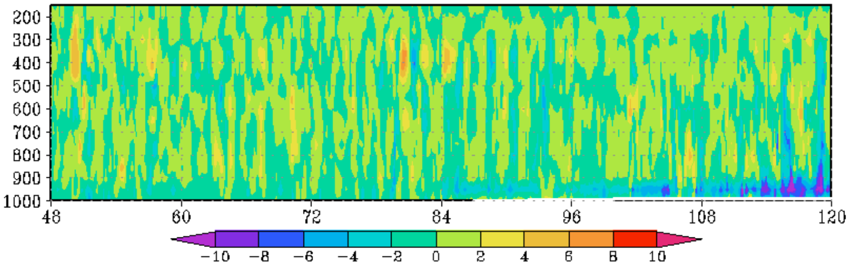
(b) $-\nabla\cdot(\eta V)$ (10^{-9} s^{-2})



(c) $-\nabla\cdot(-k\times\omega\partial V/\partial p)$ (10^{-9} s^{-2})



(d) Residual (10^{-9} s^{-2})



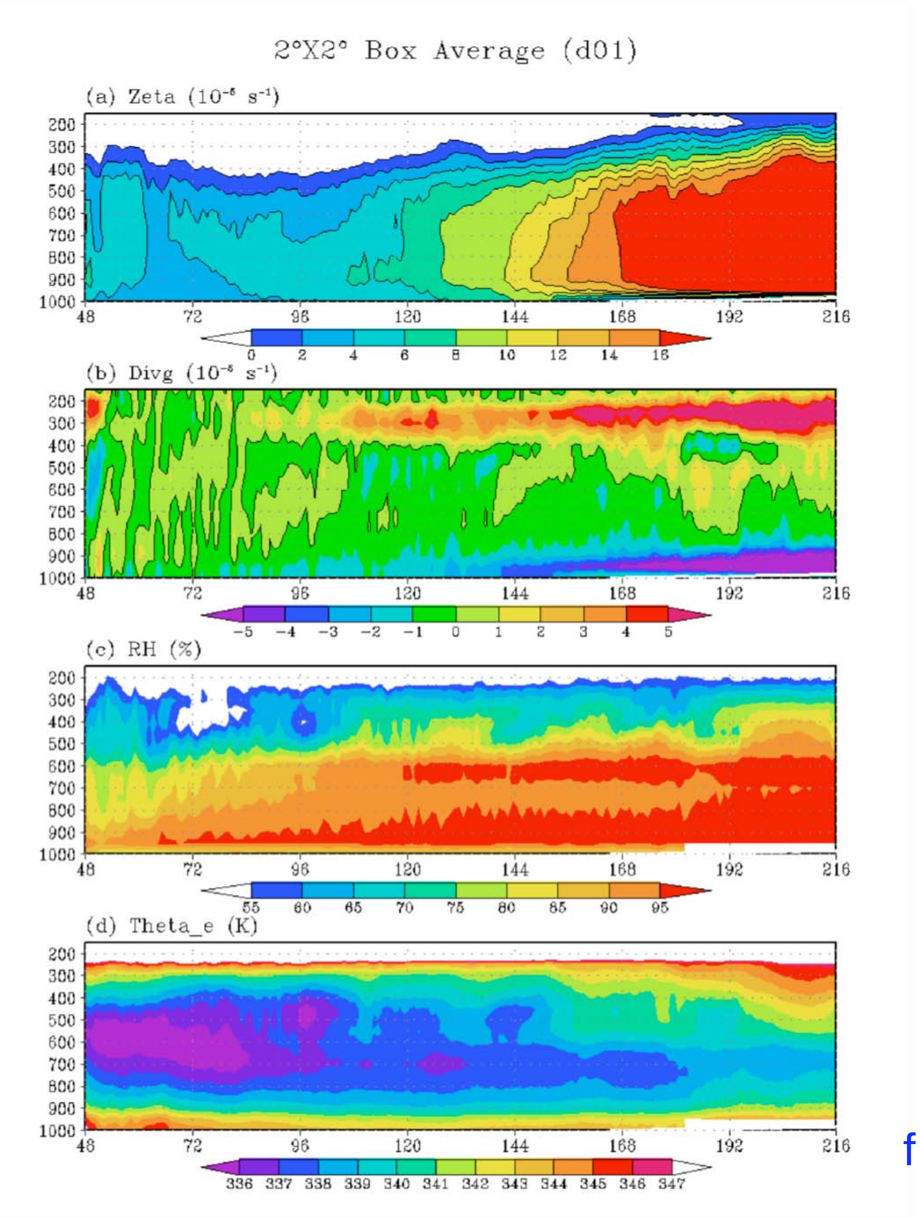
The vorticity budget equation in the isobaric coordinates can be written as

$$\frac{\partial\eta}{\partial t} = -\nabla\ (\vec{V}'\eta) - \nabla\ (\omega\vec{k}\times\frac{d\vec{V}'}{dp}) + R$$

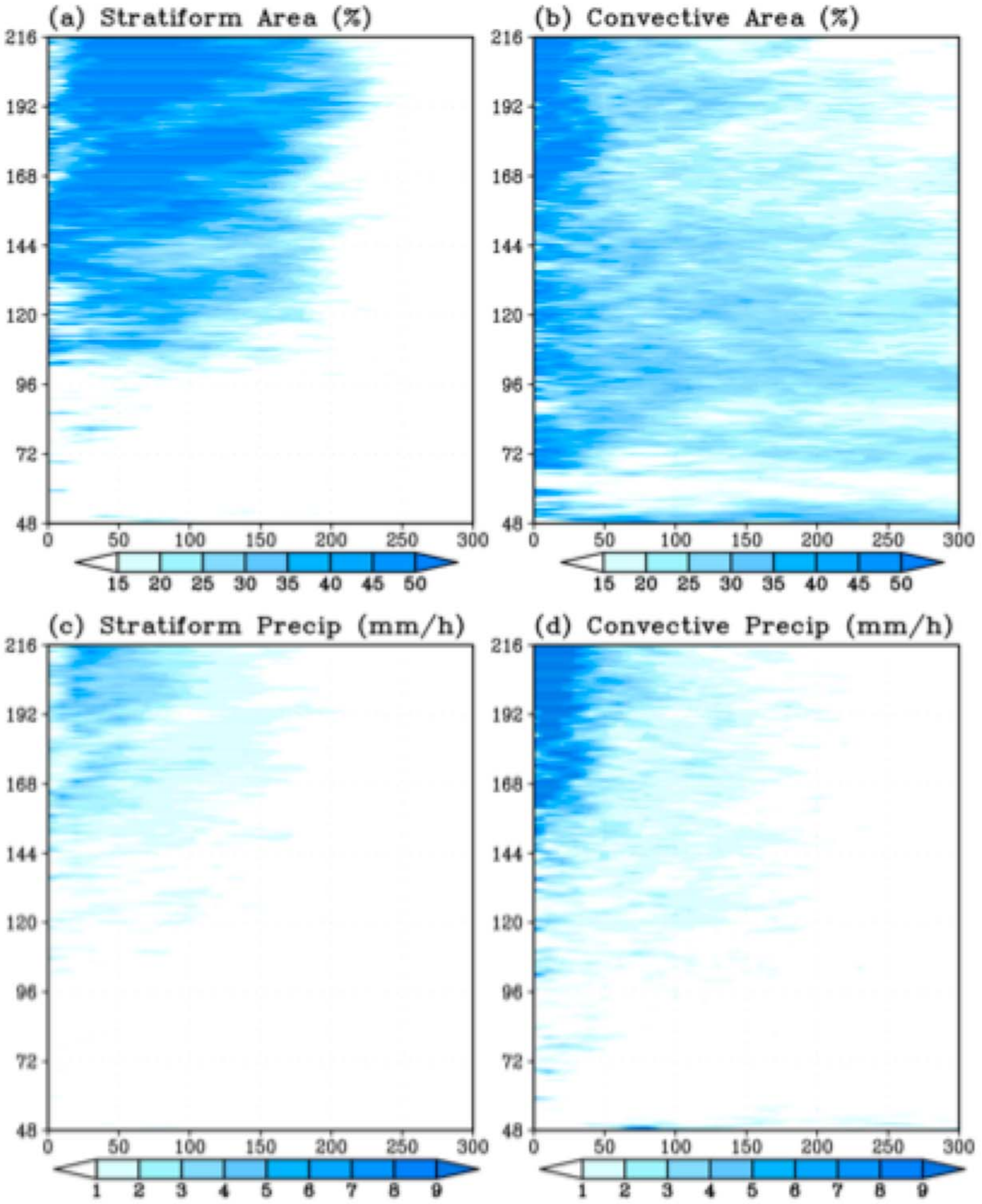
where V’ is the wave-relative flow, and the absolute vorticity is defined as

$$\eta = f + \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Time-Height Evolution of <Zeta>, <Div>, <RH> & < θ_e> with ice microphysics



<-->=2ºX2º area-avg. following pouch center


(a) Stratiform Area (%)
(b) Convective Area (%)
(c) Stratiform Precip (mm/h)
(d) Convective Precip (mm/h)
216
192
168
144
120
96
72
48
0
50
100
150
200
250
300
15
20
25
30
35
40
45
50
1
2
3
4
5
6
7
8
9

Conclusions

- VHTs need a favorable environment to build TC vortex, and genesis climatology suggests waves play important role in TC formation in deep tropics

- Diagnoses of observational data (ERA-40 and TRMM 1998-2001) and num. model simulation suggests the development of a critical layer in the lower troposphere is a *necessary* condition for genesis, and the intersection of the critical latitude and the trough axis provides sweet spot for genesis

Conclusions contd.

Intermediate and high-resolution simulations with Kurihara and Tuleya (1981) configuration support the "Marsupial Paradigm":

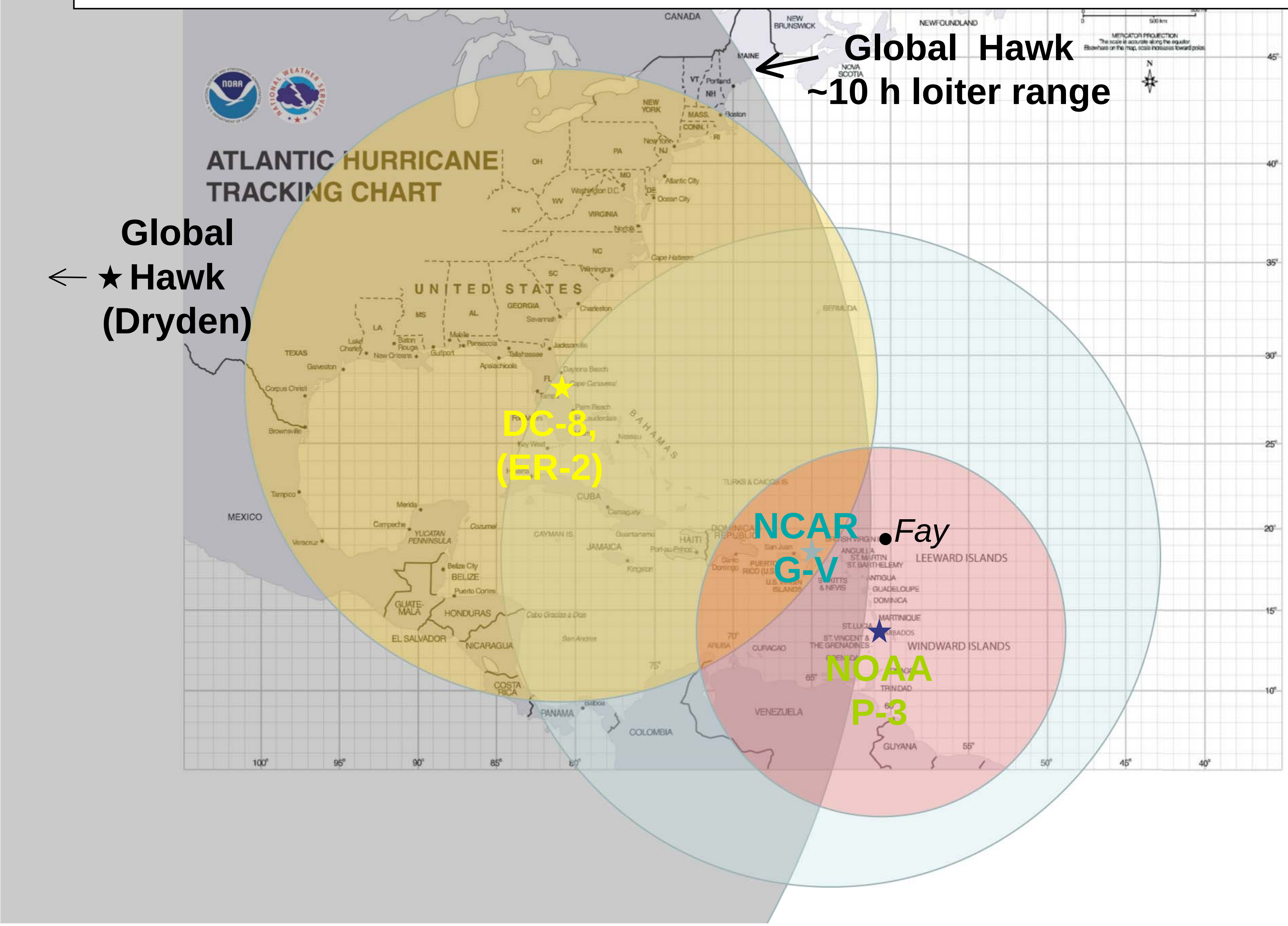
Genesis occurs near the intersection of the trough axis and the critical latitude (center of the pouch).

Air within the pouch is repeatedly moistened by deep convection and protected from dry air entrainment to some extent. Convective heating dominates stratiform heating.

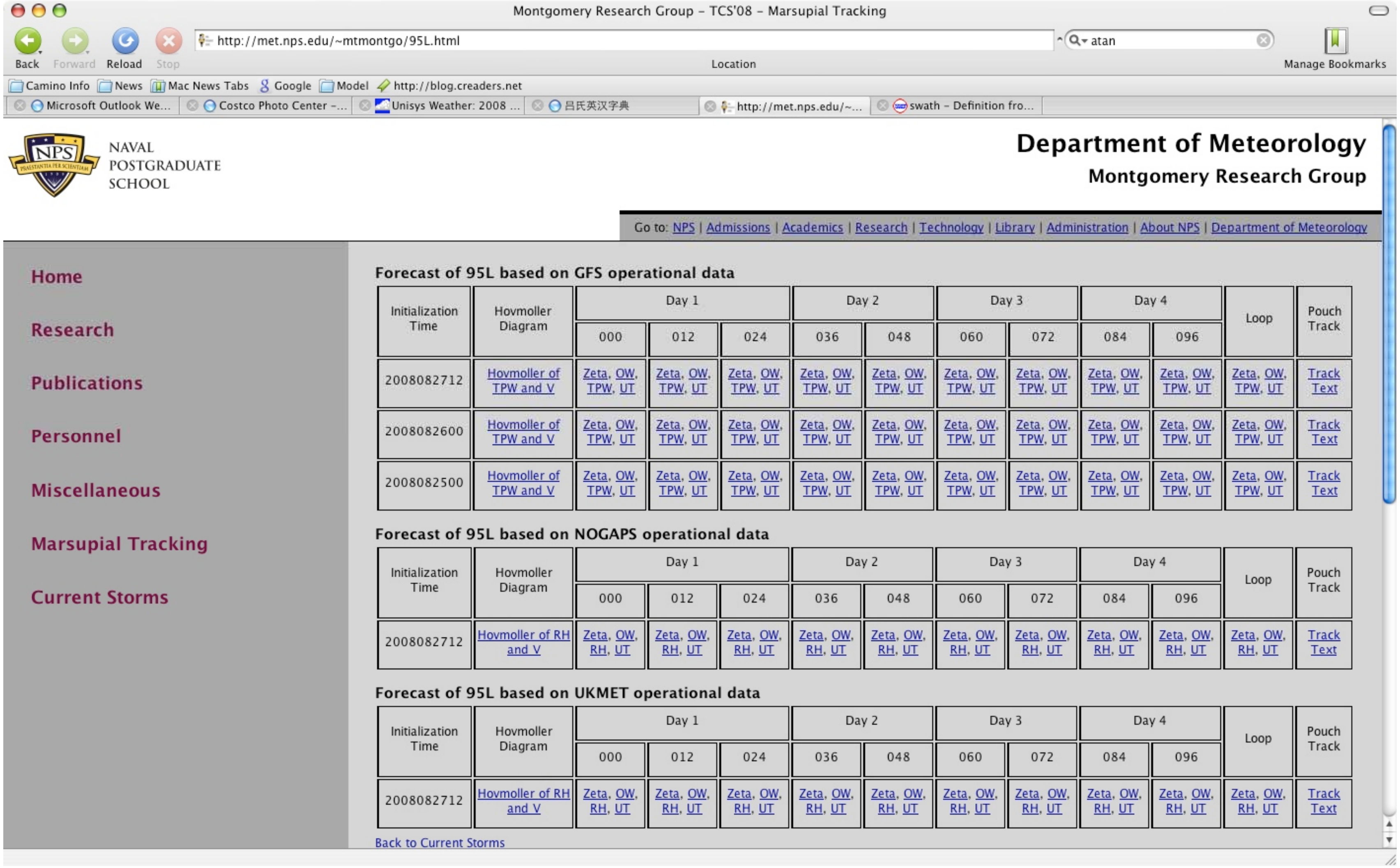
Middle level RH and near-surface vorticity increase concurrently. Middle level RH not a "trigger" to tropical cyclogenesis in wave-to- TC sequence.

- ***PREDICT*****:** PRE-Depression Investigation of Cloud-systems in the Tropics **(Aug. 15 - Sept 30, 2010)**
- ***NSF & NOAA supported***
- ***PREDICT Science Steering Committee*** *:*
  - Michael Montgomery (PI), NPS and HRD
  - Lance F. Bosart, University at Albany, SUNY, Albany, NY
  - Christopher A. Davis, NCAR, Boulder, CO
  - Andrew Heymsfield, NCAR, Boulder, CO

Fight Ranges



Website for the Real-time Forecast



Department of Meteorology

Montgomery Research Group

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Miscellaneous

Marsupial Tracking

Current Storms

Forecast of 95L based on GFS operational data

Initialization Time	Hovmoller Diagram	Day 1			Day 2		Day 3		Day 4		Loop	Pouch Track
		000	012	024	036	048	060	072	084	096		
2008082712	Hovmoller of TPW and V	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Track Text
2008082600	Hovmoller of TPW and V	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Track Text
2008082500	Hovmoller of TPW and V	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Zeta, OW, TPW, UT	Track Text

Forecast of 95L based on NOGAPS operational data

Initialization Time	Hovmoller Diagram	Day 1			Day 2		Day 3		Day 4		Loop	Pouch Track
		000	012	024	036	048	060	072	084	096		
2008082712	Hovmoller of RH and V	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Track Text

Forecast of 95L based on UKMET operational data

Initialization Time	Hovmoller Diagram	Day 1			Day 2		Day 3		Day 4		Loop	Pouch Track
		000	012	024	036	048	060	072	084	096		
2008082712	Hovmoller of RH and V	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Zeta, OW, RH, UT	Track Text

Back to Current Storms

- Website: http://www.met.nps.edu/~mtmontgo/storms.html

Marsupial slogans

- “Ride the wave”
  - A wave-centric point of view is preferred over the Earth frame for identification of Lagrangian boundaries.
- “Go with the flow”
  - Focus on critical surface / critical layer as locus of wave-mean flow interaction & TC genesis.
- “Divide and conquer”
  - Identify manifolds of 2D horizontal flow on stratification isosurfaces, critical points = separatrix, attracting & repelling node, center, etc.
- “Roadkill on the Rossby wave highway”
  - Vorticity debris is everywhere, but mostly irrelevant; focus instead on gyre-pouch recirculation that is deep, local, rapid & persistent.
- “It’s a nasty world out there”
  - Tropical atmosphere is generally hostile to tropical cyclogenesis.
  - Jule Charney / Jim Holton tropical “barotropic” scaling, independence of adjacent levels, Jim McWilliams “stratified turbulence”

Publications on the ‘Marsupial’ Paradigm

1. Dunkerton, T.J., M.T. Montgomery, and Z. Wang, 2008: Tropical cyclogenesis in a tropical wave critical layer: Easterly waves. *Atmos. Chem. & Phys. Discuss.*, 8(3), 11149-11292.
2. Wang, Z., M. T. Montgomery, and T. J. Dunkerton, 2009: A dynamically-based method for forecasting tropical cyclogenesis location in the Atlantic sector using global model products, *Geophys. Res. Lett.*, 36, L03801, doi:10.1029/2008GL035586.
3. Montgomery, M. T., Z. Wang, and T. J. Dunkerton, 2009: Intermediate and High Resolution Numerical Simulations of the Transition of a Tropical Wave Critical Layer to a Tropical Depression. Submitted to Atmos. Chem. & Phys. Discuss.
4. Wang, Z., M. T. Montgomery, and T. J. Dunkerton, 2009: Genesis of Pre-hurricane Felix (2007) and the Role of the Wave Critical Layer. J. Atmos. Sci/NASA-TCSP-NAMMA special issue, accepted with revision. .
5. Montgomery, M. T., L. L. Lussier III, R. W. Moore and, and Z. Wang, 2009: The Genesis of Typhoon Nuri as Observed During the Tropical Cyclone Structure 08 (TCS-08) Field Experiment. Part I: The Role of the Easterly Wave Critical Layer. Atmos. Chem. Phys. Discussion, In Review.
6. Lussier III, L. L., M. T. Montgomery, T. J. Dunkerton and Z. Wang, 2009: The Spatial and Temporal Evolution of Precipitation within the Critical Layer of Easterly Waves as Seen by the TRMM TMI and its Implications for Tropical Cyclogenesis. Soon to be submitted to Geophys. Res. Lett.

Website: http://www.met.nps.edu/~mtmontgo/publications

End of Presentation

Thank you!