Development of Double Warm Cores in Intense Tropical Cyclones in the HWRF Model

Chanh Kieu, and Vijay Tallapragada

Environmental Modeling Center,
NWS/NOAA/NCEP, College Park, MD 20740

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Outline

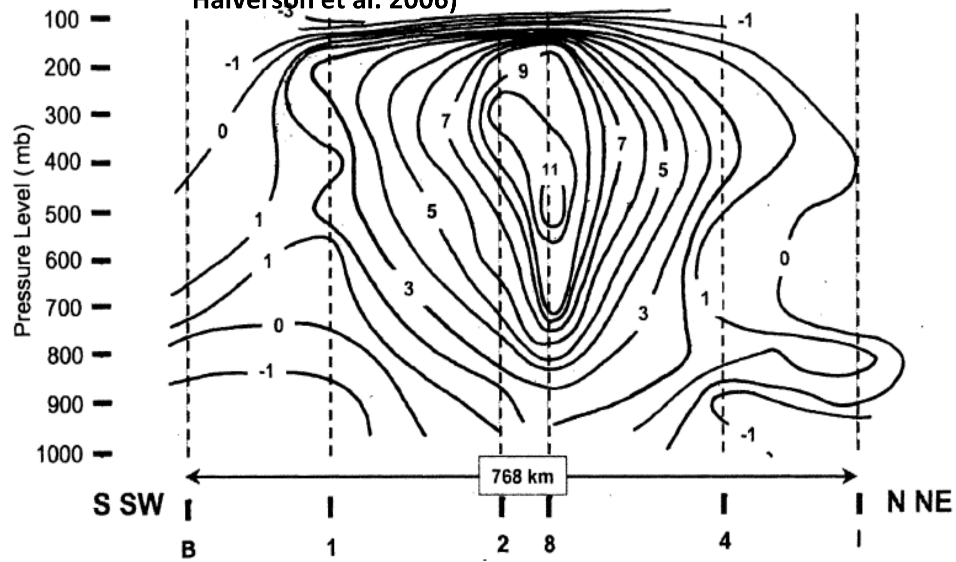
- Motivation
- High level inflow
- Double warm core
- Implications
- Concluding remarks

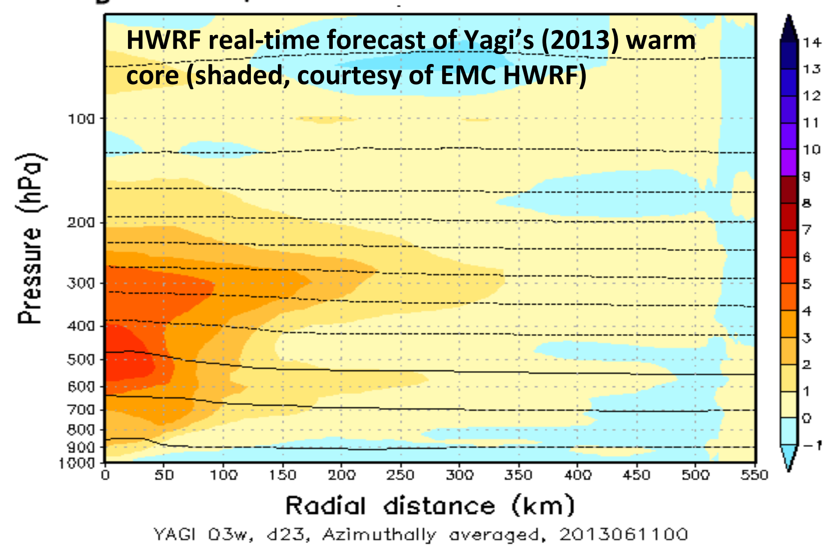
Motivation

- The tropical cyclone (TC) warm core is a characteristic of the TC balance dynamics to ensure the thermal wind balance;

- Location of TC warm core varies largely from 500 – 100 mb, but the thermal wind balance would imply that TC warm core should be around 500-400 hPa for a typical TC (Stern and Nolan 2011)

Observation of Erin's (2001) warm core (contours, Halverson et al. 2006)





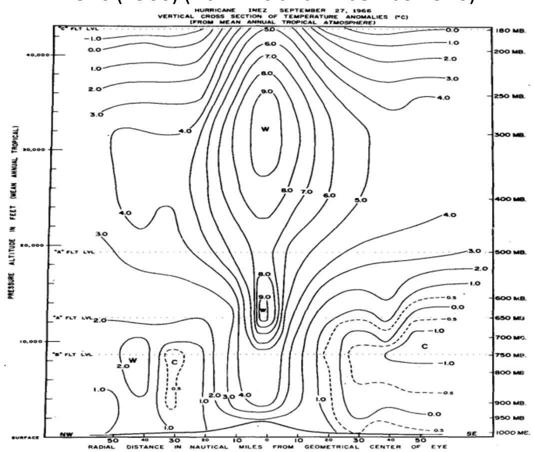
HWRF real-time forecast of Yagi's (2013) warm core (shaded, courtesy of EMC HWRF)

Motivation: warm core in intense TCs

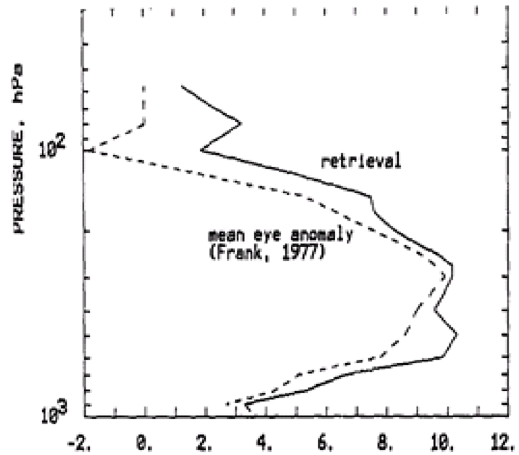
For TCs that approach Cat-3 (> 120 kt , or 61 m s^{-1}), observation and model simulations sometime capture a different picture…

Observation …

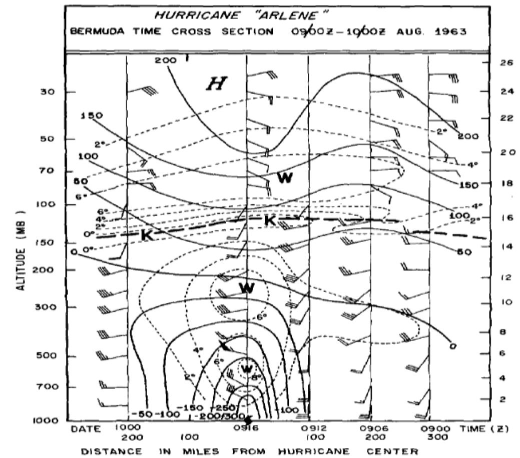
Inez's (1966) (Hawkins and Imbembo 1976)



Frank (1977) (Schwartz et al. 1996)

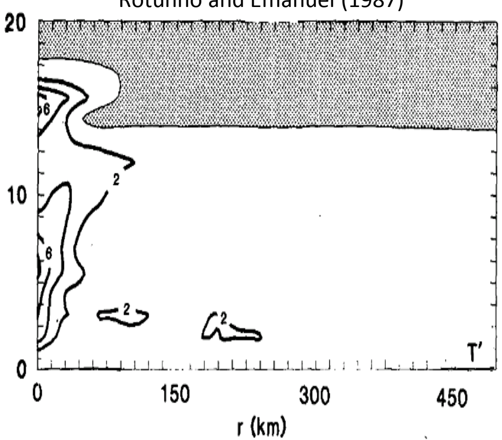


Arlene (1963) (Koteswaram 1967)

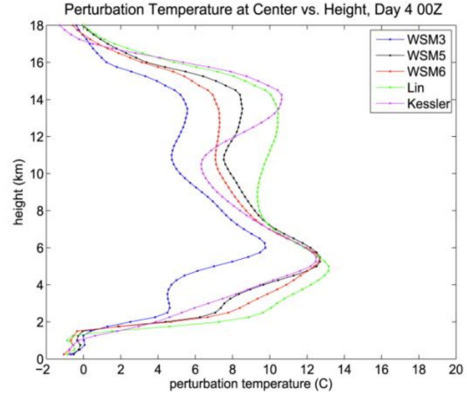


Modelling …

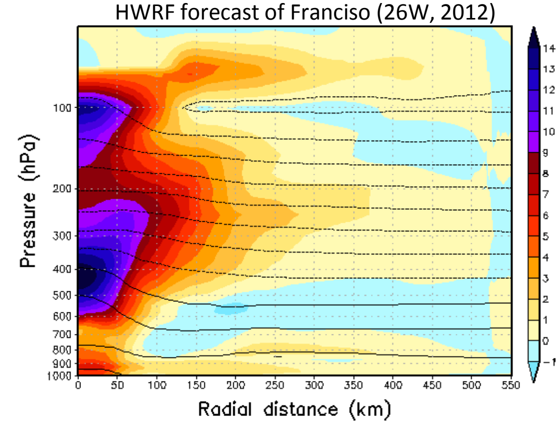
Rotunno and Emanuel (1987)



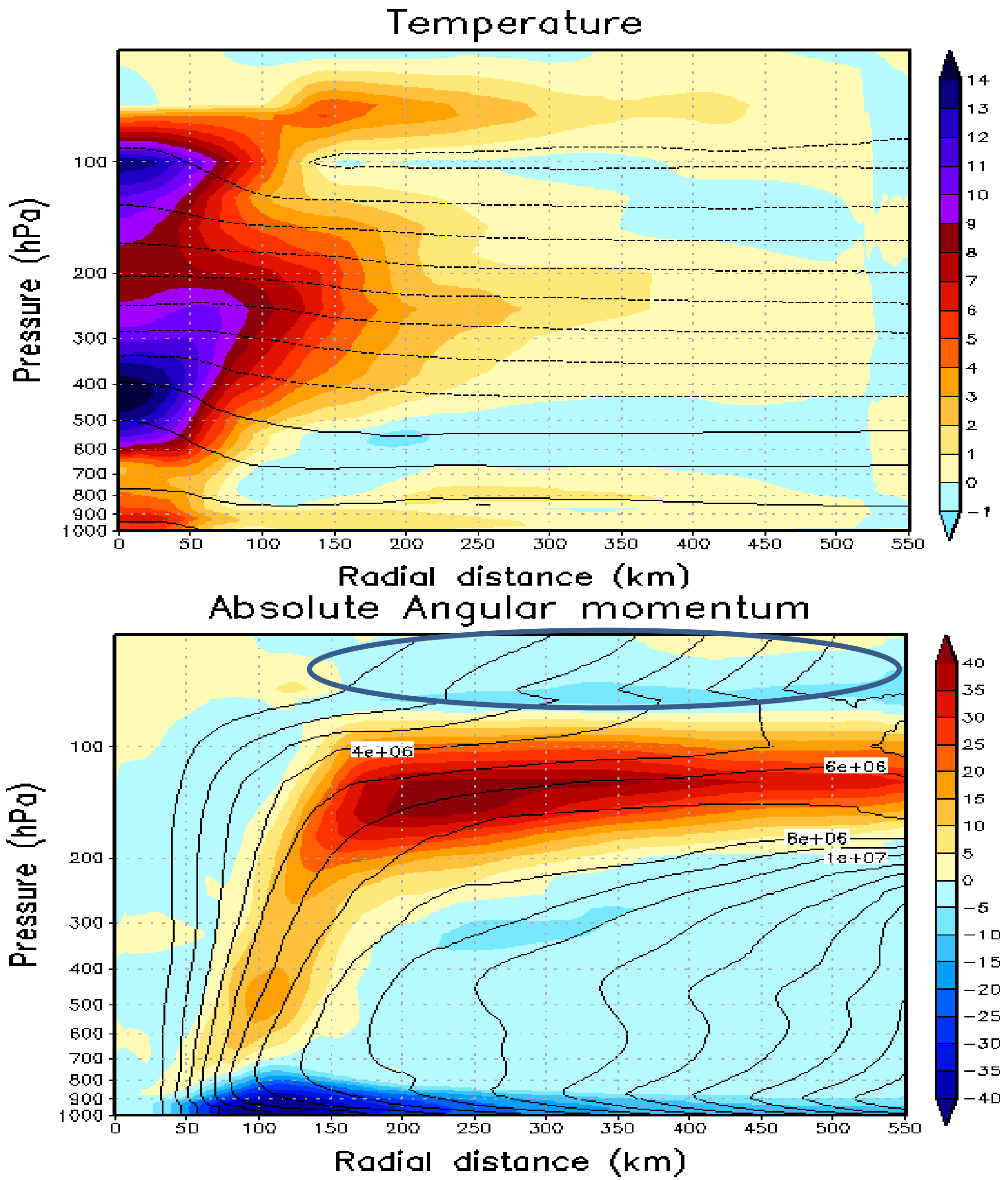
Stern and Zhang (2012)



HWRF forecast of Francisco (26W, 2012)

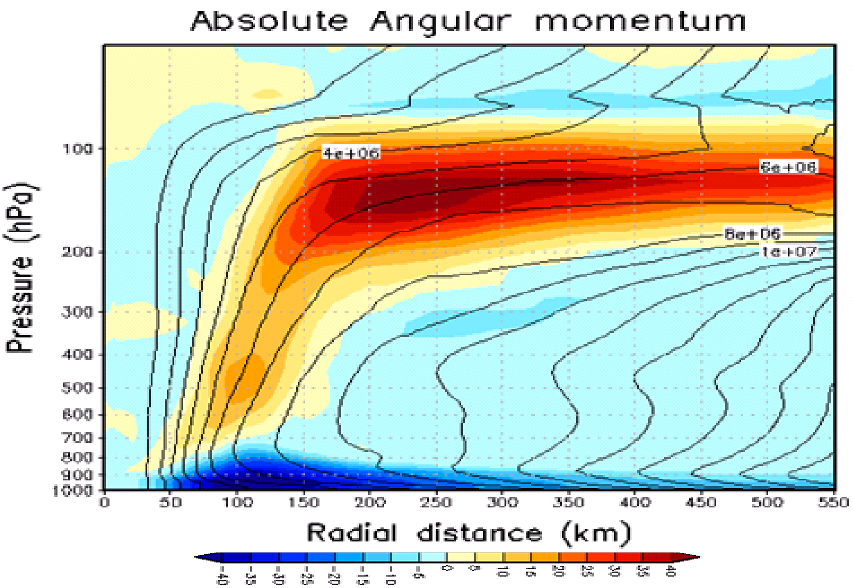


Questions?

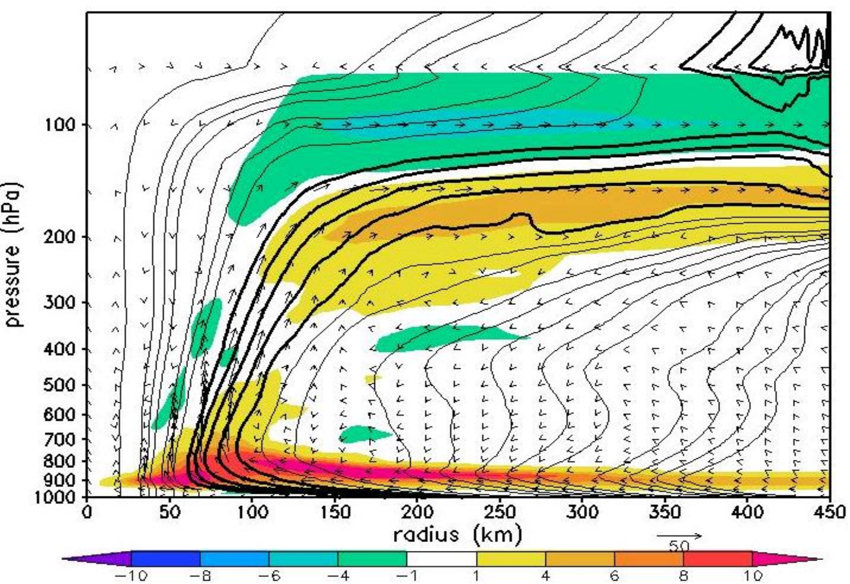


1. Are there any constrains or conditions for the development of the upper level warm core?
2. How is the upper level warm core formed and what are the roles of the high level inflow layer?
3. What are the implications of the upper warm core development?

High level inflow (HIL)



- Consistent development of HIL in all double warm core cases with intense TCs (120 kt +) during HWRF real-time exps in WPAC from 2012-2013;
- HIL appears to develop from outer region, confined within a thin layer above the outflow layer, extend from outside all the way to the eye;



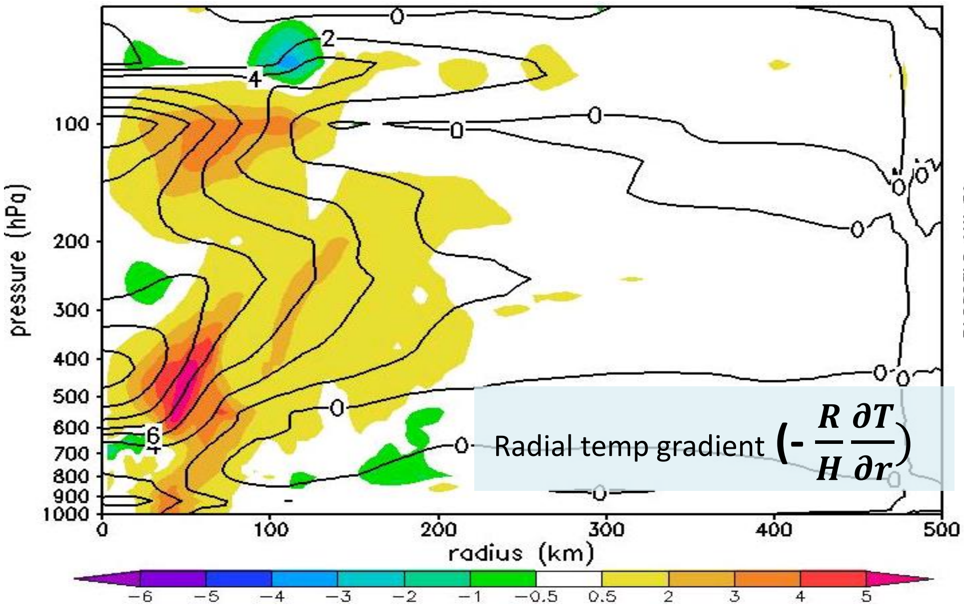
Introduce $\Gamma \equiv \partial u/\partial z$, a Lagrangian parcel along an M-surface will have

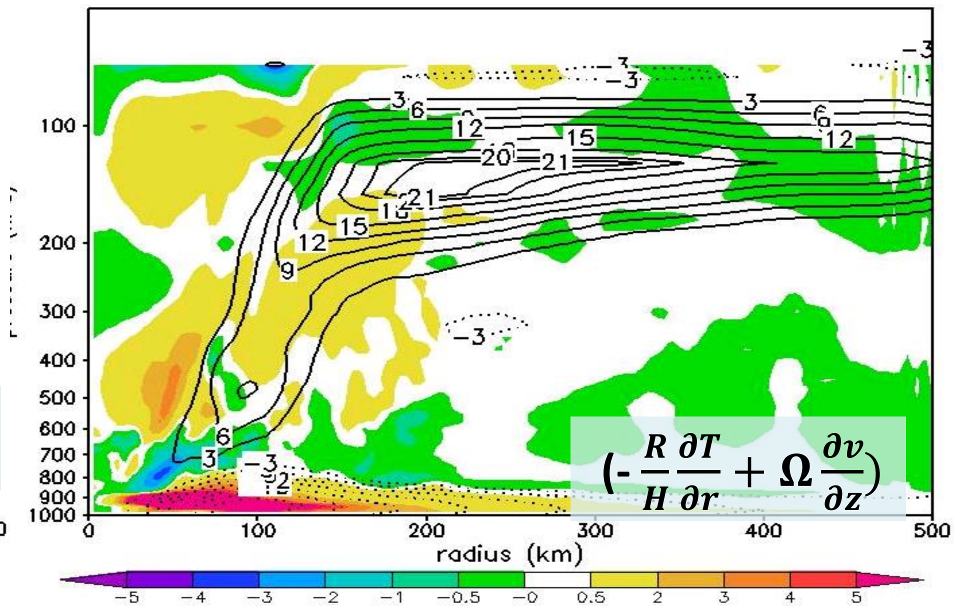
$$\Gamma_0(t) = \int \left[-\frac{R}{H}\frac{\partial T}{\partial r} + \Omega\frac{\partial v}{\partial z}\right] e^{\int_0^t\left(Sw-\frac{\partial w}{\partial z}\right)d\tau} dt$$

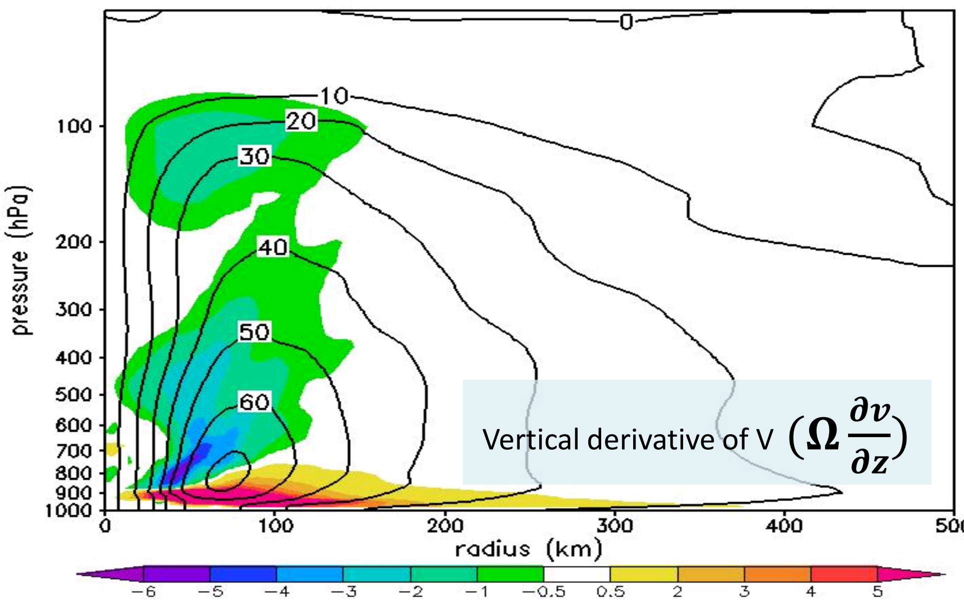
Result 1: A balance warm core must exist below the outflow level.

Proof: Because the outflow is where $\Gamma > 0$, A(t) needs to > 0. Since $\partial v/\partial z < 0$ along M surface, this requires $\partial T/\partial r < 0$ at some point along M surface such that A(t) > 0. Thus a TC warm core must exist below the outflow level such this condition is met

Conditions for high level inflow





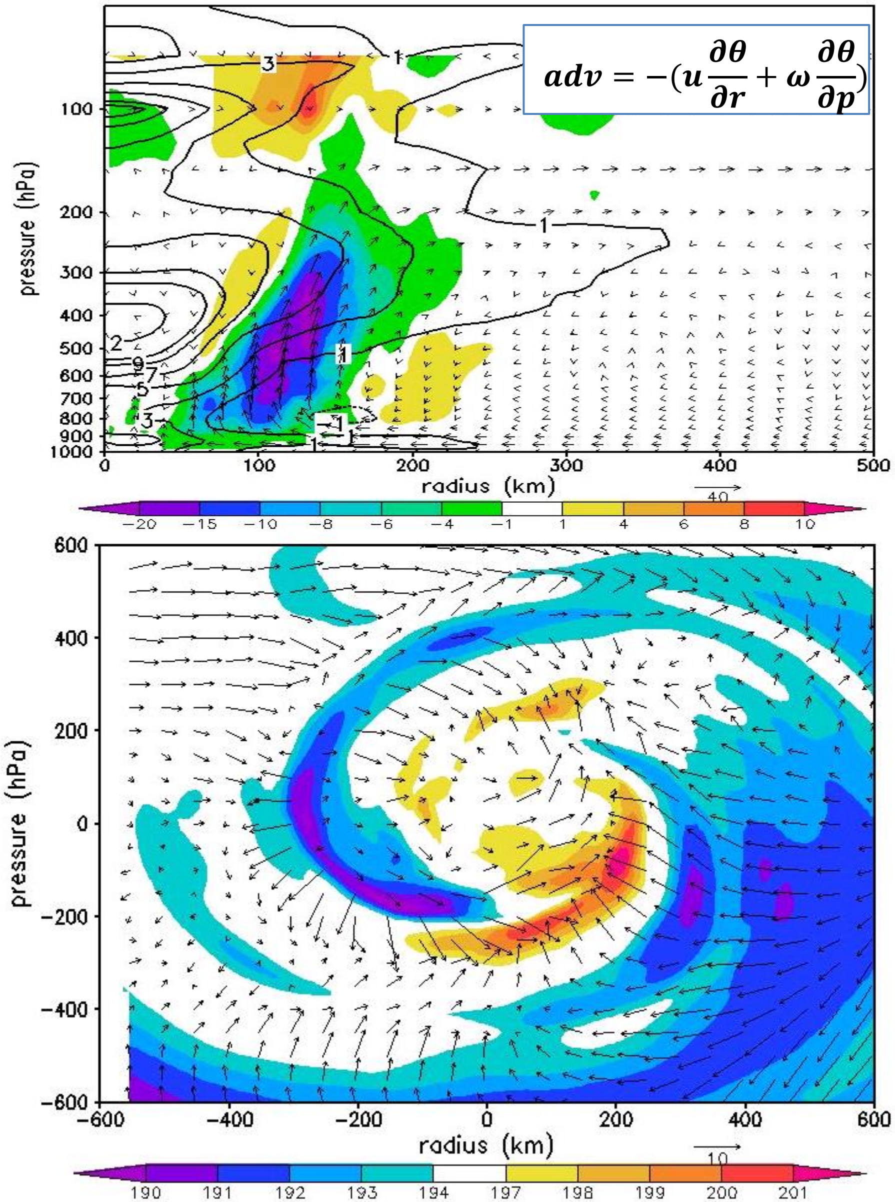


Result 2: A cold annulus (or a warm ring) must exist outside the eye at the upper level for HIL to develop.

Proof: Recall that $A(t) \equiv -\frac{R}{H}\frac{\partial T}{\partial r} + \Omega\frac{\partial v}{\partial z}$. Because $\partial v/\partial z < 0$ along M surface whim the storm central region, necessary condition for A(t) changes from positive to negative at upper level (i.e., the parcel turns from outflow to inflow along M surface) if $-\partial T/\partial r \leq 0$ above the outflow level. This amounts to a cold annulus formed within the storm central region such that radial gradient of T > 0.

Physically, this means $-\nabla \mathbf{p} < 0$ (i.e., pressure gradient points inward). E.g., upper level radiative cooling can cause cold layer to shrink, or overshooting deep convection in the eyewall

Upper warm core formation



- HIL could induce a substantial amount of warm advection from the lower stratosphere toward storm center;
- Consistent development of the double warm in all cycles with high intensity (> 120 kt).
- The upper warm core is not seen in weaker storms, indicating the external role of the upper troposphere

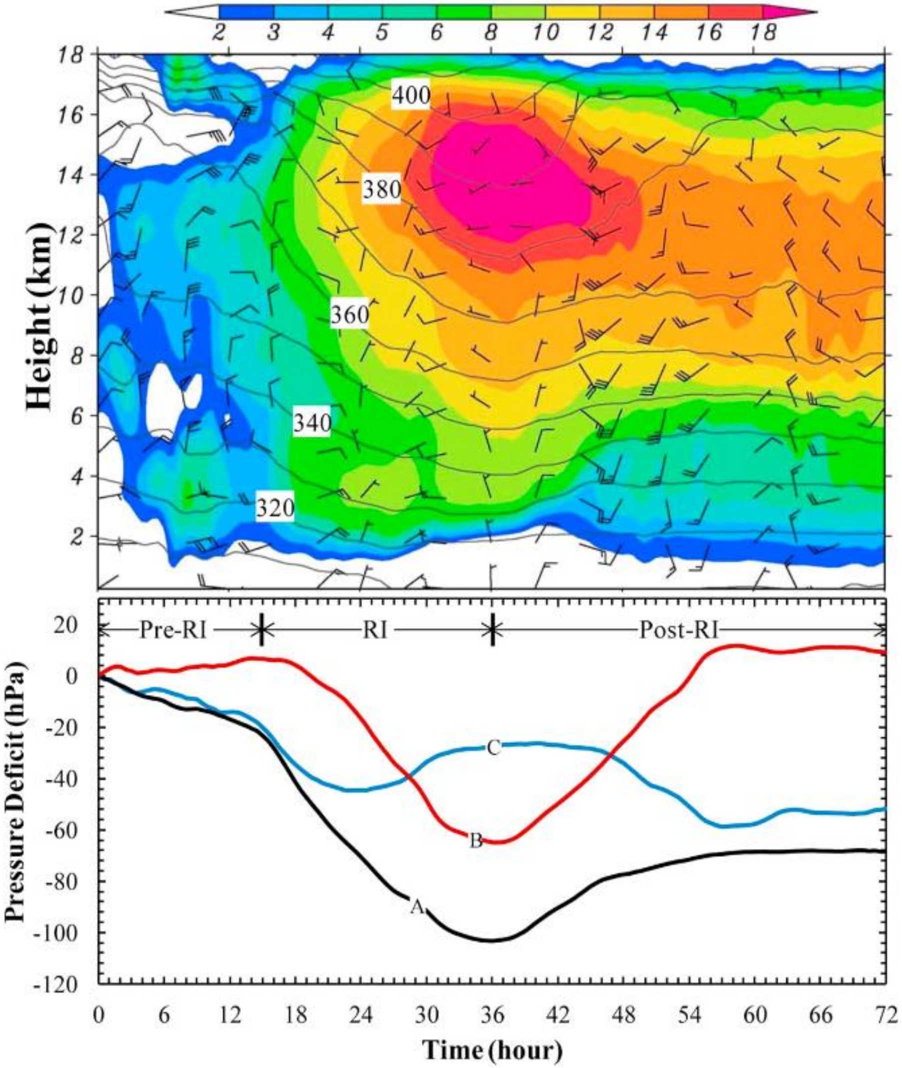
Upper warm core implication

- Chen and Zhang (2012) shows that the upper warm core could account more than 50% of the total pressure level.
- The effectiveness of upper warm core contribution to PMIN can be seen from the hydrostatic equation

$$\Phi(z=0) = \Phi\Big|_{\text{top}} - \int_0^{top} \frac{RT(z)}{H} dz$$
$$= \Phi\Big|_{\text{top}} - \int_0^{top} \frac{\bar{R}\bar{T}(z)}{H}\left(1 + \frac{T'}{\bar{T}(z)}\right) dz$$

As seen from the equation above, given the same T', the higher the warm core, the deeper the pressure drop at the surface.

No causal implication, unless there is a mechanism that could help build the upper warm core… stratosphere ???

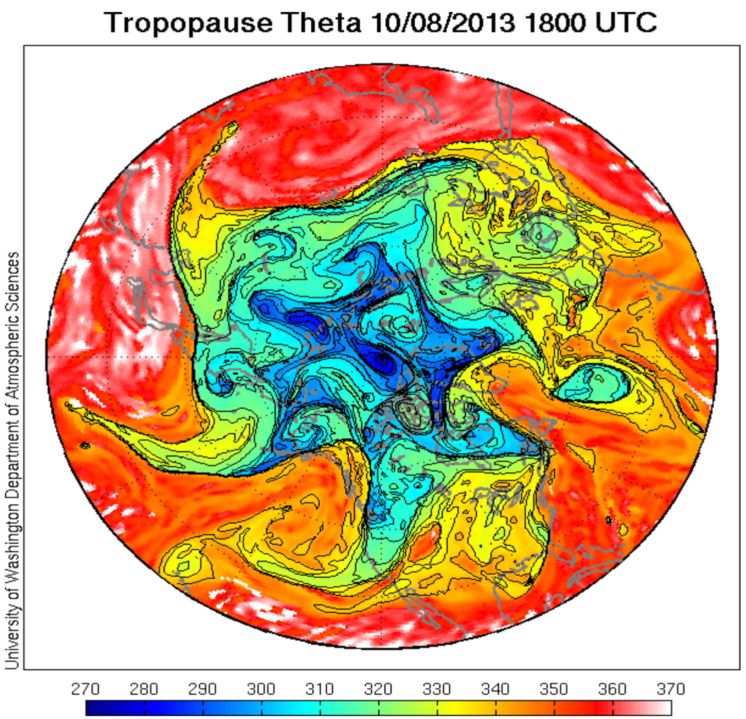


Upper warm core contribution o the pressure drop at the surface (red curve) from simulation of Hurricane Wilma (2005, courtesy of Chen and Zhang (GRL, 2012)

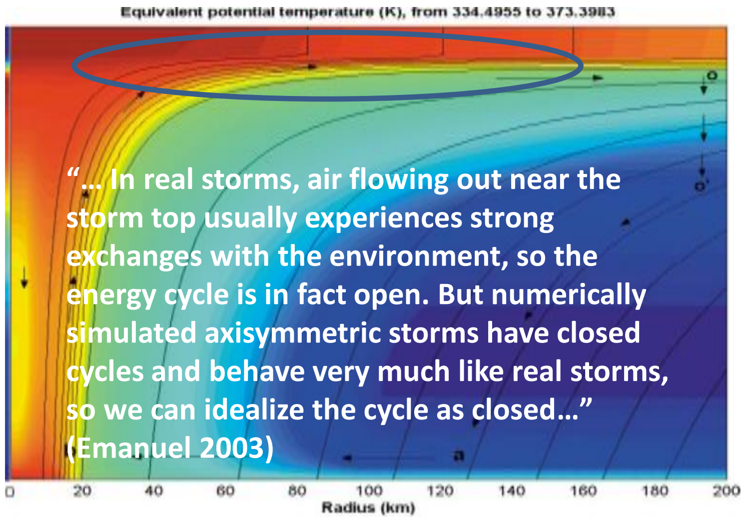
Double warm core implication

Condition for DWC configuration: Check in *a layer between 100-50 hPa* for the potential development of HIL:

i) Convergence flow with cyclonic circulation;
ii) An annulus of low pressure anomaly between 200 -500 km radius;
iii) A ring of deep vertical motion surrounding the eye;
iv) The tropopause locates at low altitude .



Interaction of TCs with the warm air in the lower stratosphere may have more significant impact to the TC climatology than our current understanding.

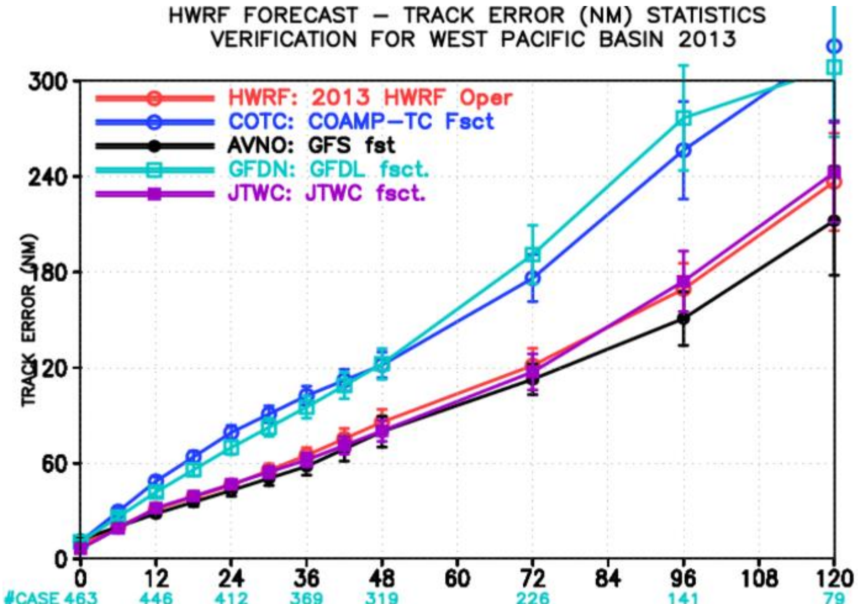


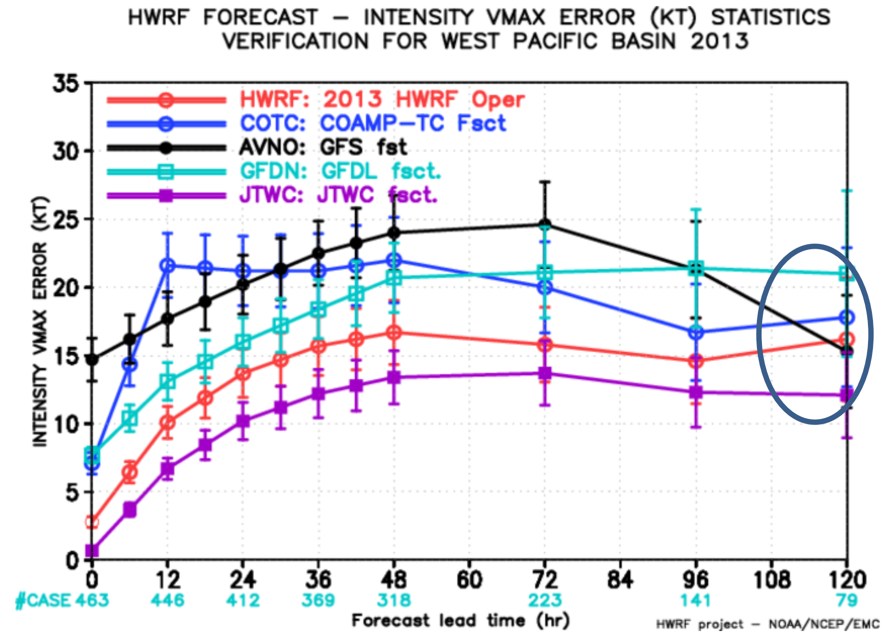
Concluding remarks

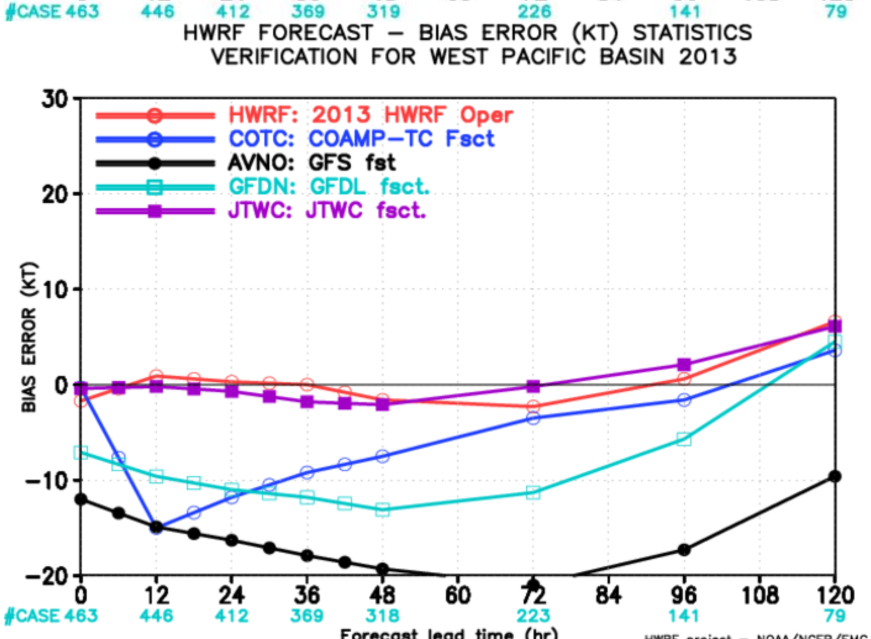
- Double warm core (DWC) in intense TCs was reported in observation and previous modelling but has never been addressed;
- HWRF captured very persistently DWC during the peak intensity for intense TCs (> 120 kt for longer than 12 h);
- HWRF real-time simulations show specific conditions for the DWC to take place;
- More observations/higher model resolution at upper level should be conducted to capture the existence of high level returning inflow.
- Lower stratosphere may have larger influence to the behaviors or distribution of the extreme TCs than our current understanding.

Thank you!

Verification of HWRF real-time forecasts for the 2013 WPAC







- HWRF track forecasts outperformed all regional models; very close to GFS forecasts in the 2013 season;
- Intensity forecast skill was superior than all other models during both 2012-2013 season;
- Still possessed some positive intensity bias near the end of 5-day forecast;

TABLE 4. Summary of anomaly profile results for all cases. MSLP is near time of sounding.

Storm	MSLP (hPa)	$\Delta\theta_e$ (K)	D200 (10^{-7} s^{-1})	V500 (m s^{-1})	Max anomaly (K)	Anomaly level (hPa)
Flo	891				17	380
Oliver 6	955				9	475
Oliver 8	965				9/9/8	355/470/550
Bonnie 23	955	17	41	7	10/10/10	250/345/455
Bonnie 24	963	15	53	9	10/9/8	270/405/550
Bonnie 26	964	14	64	12	11	340
Danielle	983	14	53	4	9/8	600/260
Georges	970	18	5	6	11/10	380/630
Erin	970	7	20	4	13	480
Humberto 23	983	13	16	3	10/10	630/550
Humberto 24	991	9	−17	0	7	670
Earl 29	978	15	22	8	7/6	350/540
Earl 30	940	15	42	10	13/12	350/560
Earl 01	935	13	60	11	15/13/10	260/460/590
Earl 02	948	10	26	11	12/12/12	640/350/250
Karl	976	7	20	6	6	680
Unnamed 1944	967				14	350
Unnamed 1946	987				5	650
Arlene	976				10/9	705/560
Inez	987				8	400
Shirley	965				12	275
Francelia	992				6	760
Gloria	942	6	100	10	13	350
Rusa	963	10	41	17	10	450
Etau	933	12	105	18	15/8	290/540

Durden (2013) has a list of warm core distribution within storm center. However, this sounding is mostly limited below 300 mb.