Secondary Eyewall Replacement and Associated Intensity Change

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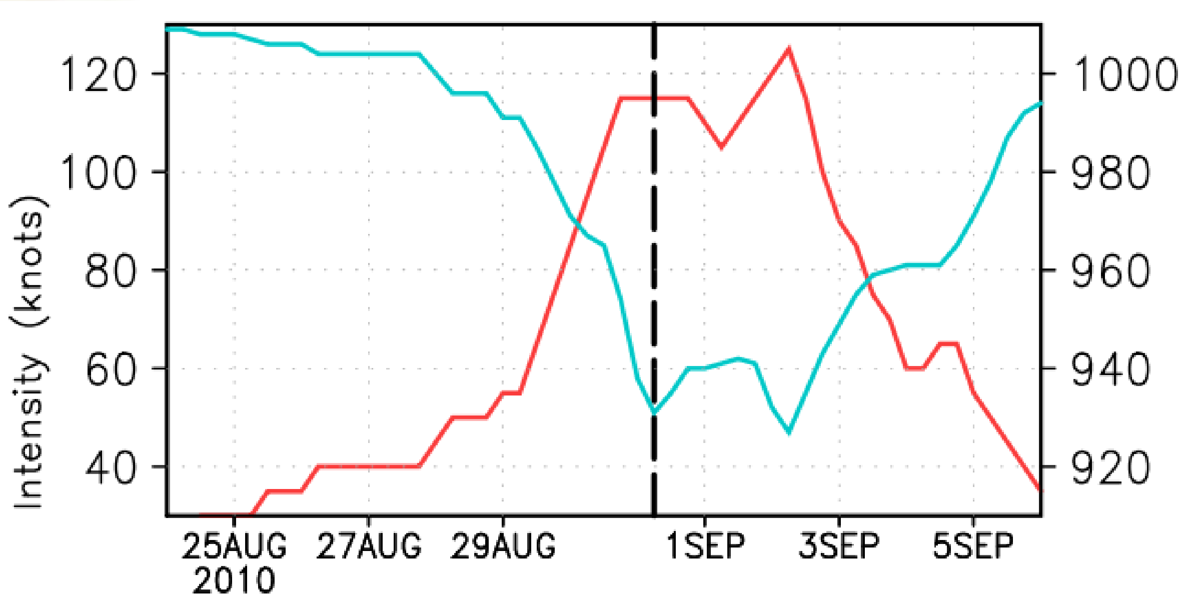
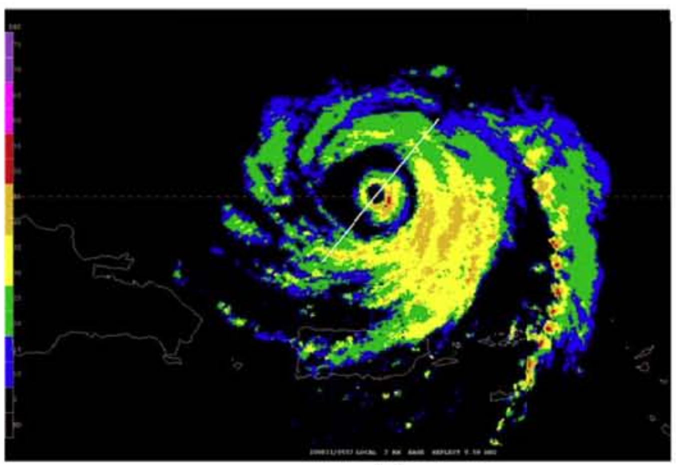
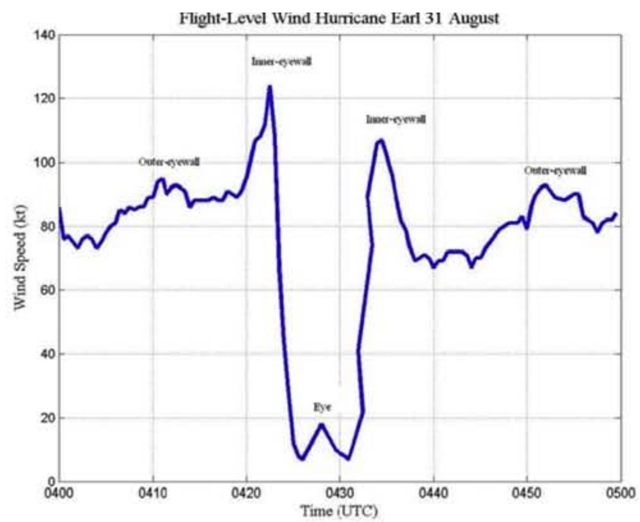
Secondary Eyewall in Hurricane Earl (2010)





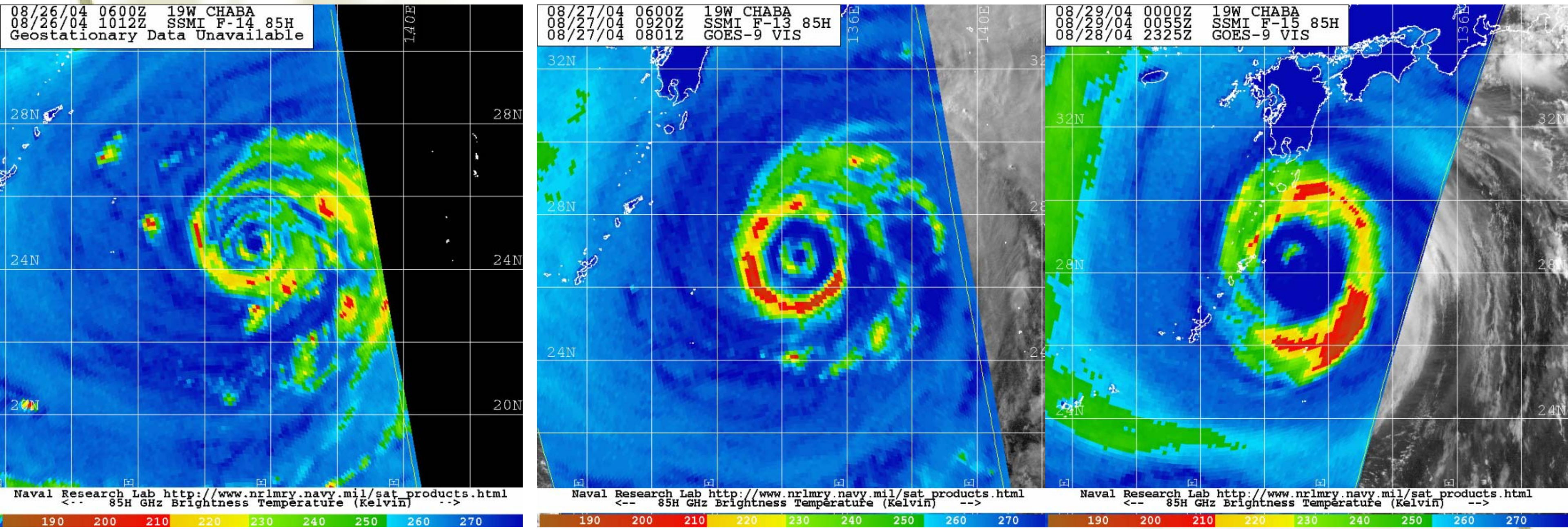
(a)



(b)

Figure 4. (a) WSR-88D San Juan radar reflectivity image of Hurricane Earl at 0557 UTC 31 August when the hurricane was passing north of the island. The white line shows a portion of the Air Force reconnaissance aircraft flight leg around the same time. (b) Flight-level winds along the flight leg shown in (a).

Secondary Eyewall Replacement Cycles



Chaba (2004)

A secondary eyewall replacement cycle includes:

- **Formation of a secondary eyewall**
- Dissipation of the inner eyewall
- Organization of the new eyewall

Significance and challenge

- Common feature of intense Hurricanes
- Large range of intensity change during secondary eyewall replacement

Typhoon Sarah (1956): Maximum wind speed decreases 46 m/s

Anita (1977): marks the end of a deepening phase (or RI). -- Willoughby et al (1982)

41% (29%) cases over ATL(WNP) intensify after secondary eyewall formation (Kuo et al. 2009)

Questions

- What factors determine the location of secondary eyewall formation? (storm dynamics versus environmental condition)

  Winne (1997): **150 km,** Keith (1997): **10 km**

- What control storm intensity change during eyewall replacement?

- What determine the timing of the secondary eyewall formation?

Methodology

- Empirical study:

  -using satellite observation to determine the location and strength of he secondary eyewall formation

  -Linking to environmental forcing and intensity change

- Numerical study of the mechanisms of secondary eyewall replacement

Model and Sensitivity Experiments

- WRF-ARW model
- 4 nesting domains (2, 6,18, and 54 km)
- Microphysics scheme: Lin et al (1983)
- No cumulus scheme for fine domains
- f –plane
- SST=29^{o}C
- Rest environment
- Initial disturbance:

A weak vortex with maximum tangential wind 15m/s

❖ **Two experiments: CTL** and **ICE**

➢ Same model parameters and initial conditions

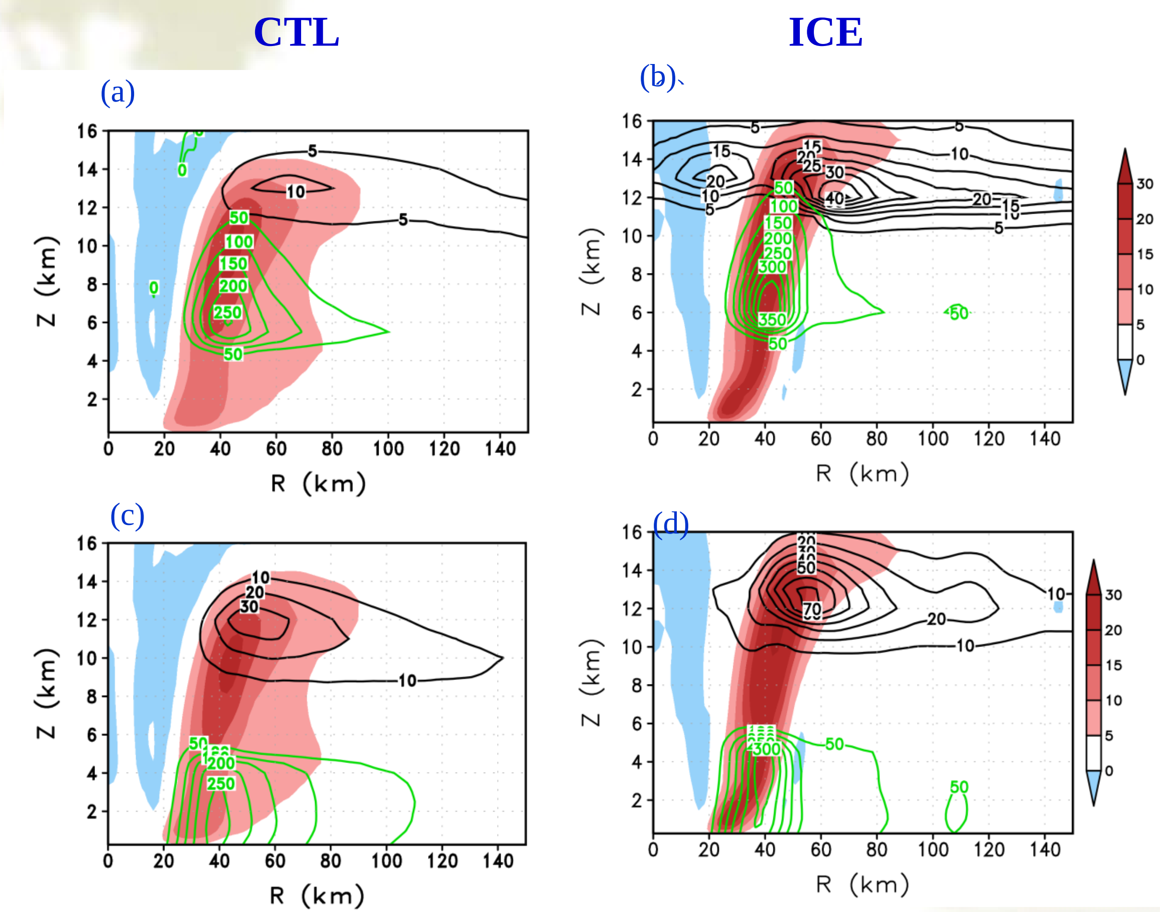
➢ Only difference: Ice particle concentration

CTL: Control run

ICE: Concentration of ice particles is enhanced

Effects of Concentration of Ice Particles

Concentrations of freezing hydrometers prior to the formation of secondary eyewall



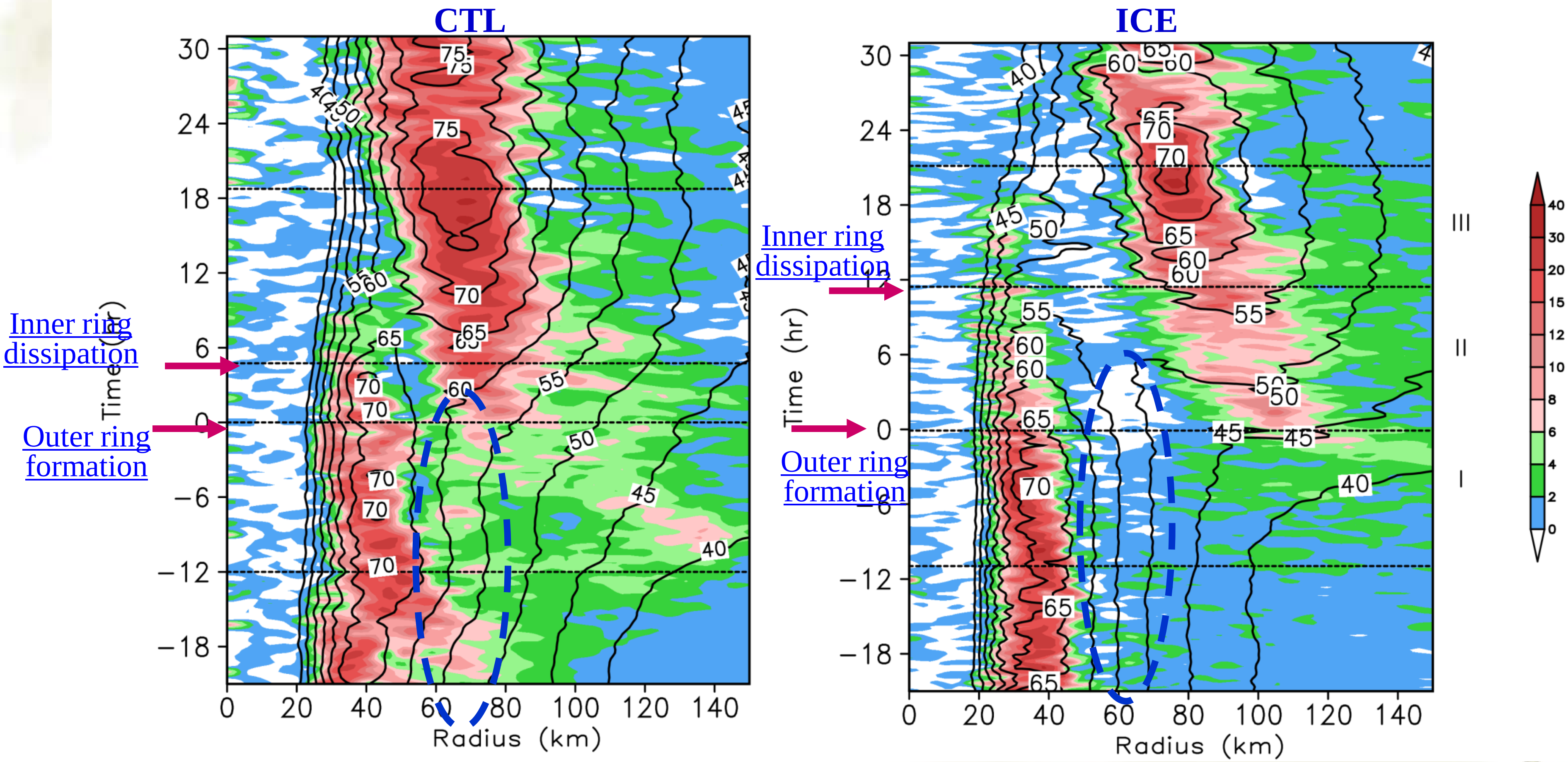
Cloud ice (black contours)
Graupel (Green contours)

Snow (black contours)
Rain water (Green contours)

Units: 10^{-2} g kg^{-1}

Contrasting Eyewall Replacement Cycles

Hovmoller diagram of symmetric 500 hPa vertical velocity (shading) and 700 hPa tangential wind (contour)

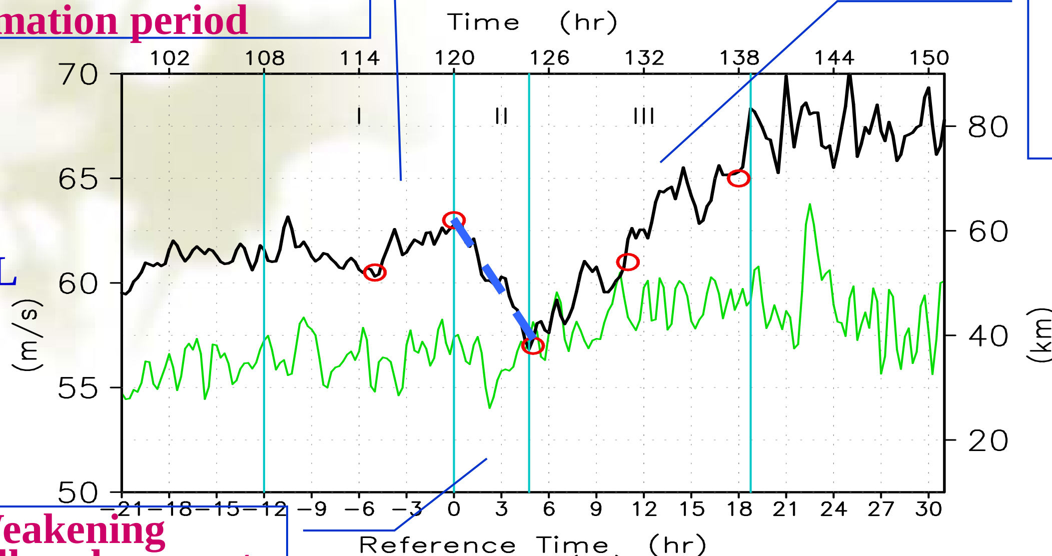


Intensity Changes

Secondary eyewall Formation period

Re-intensification Formation of an Annual Hurricane

CTL



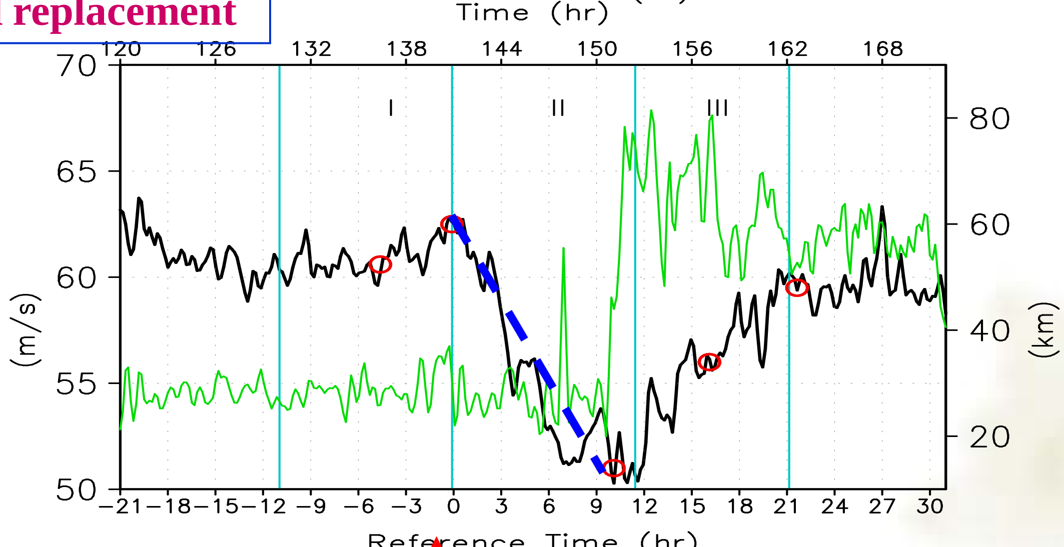
Weakening Eyewall replacement

Green-RMW

Black –Maximum Surface Wind

- Minor weakening (short duration)
- Considerable increase in intensity

ICE



- Significant weakening
- Abrupt change of RMW

•Secondary eyewall formation

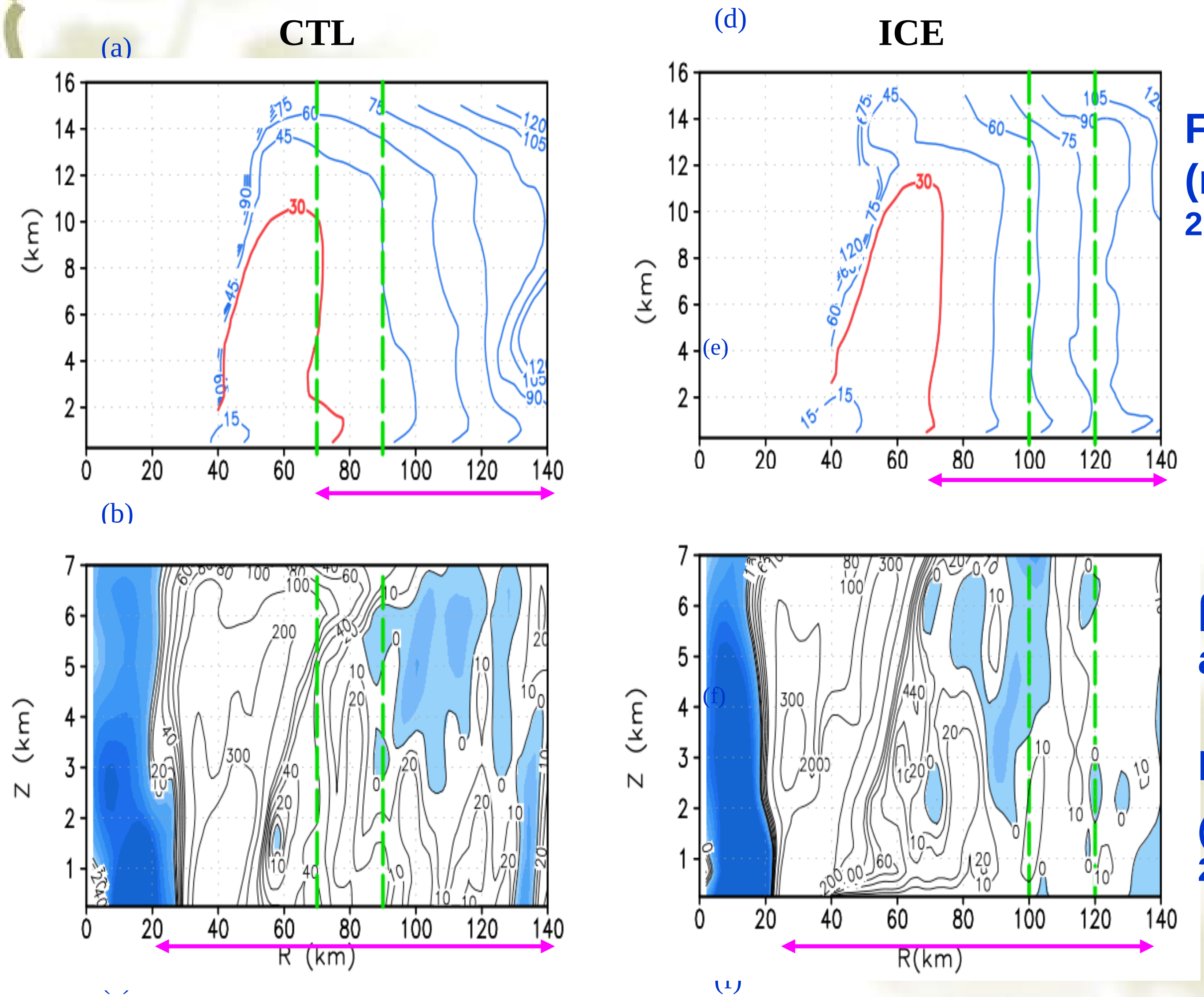
Effects of enhanced concentration of ice particles

	CTL	ICE
Location of Secondary Eyewall	Smaller radius	Larger radius
Duration of Eyewall replacement	Short	Long
Intensity Change	Small reduction followed by strong intensification	Large reduction, weaker recovery

I. What factors determine the location of secondary eyewall?

Storm dynamics and environmental conditions

Internal dynamics



Filamentation time (minutes) **(Rozoff et al 2006)**

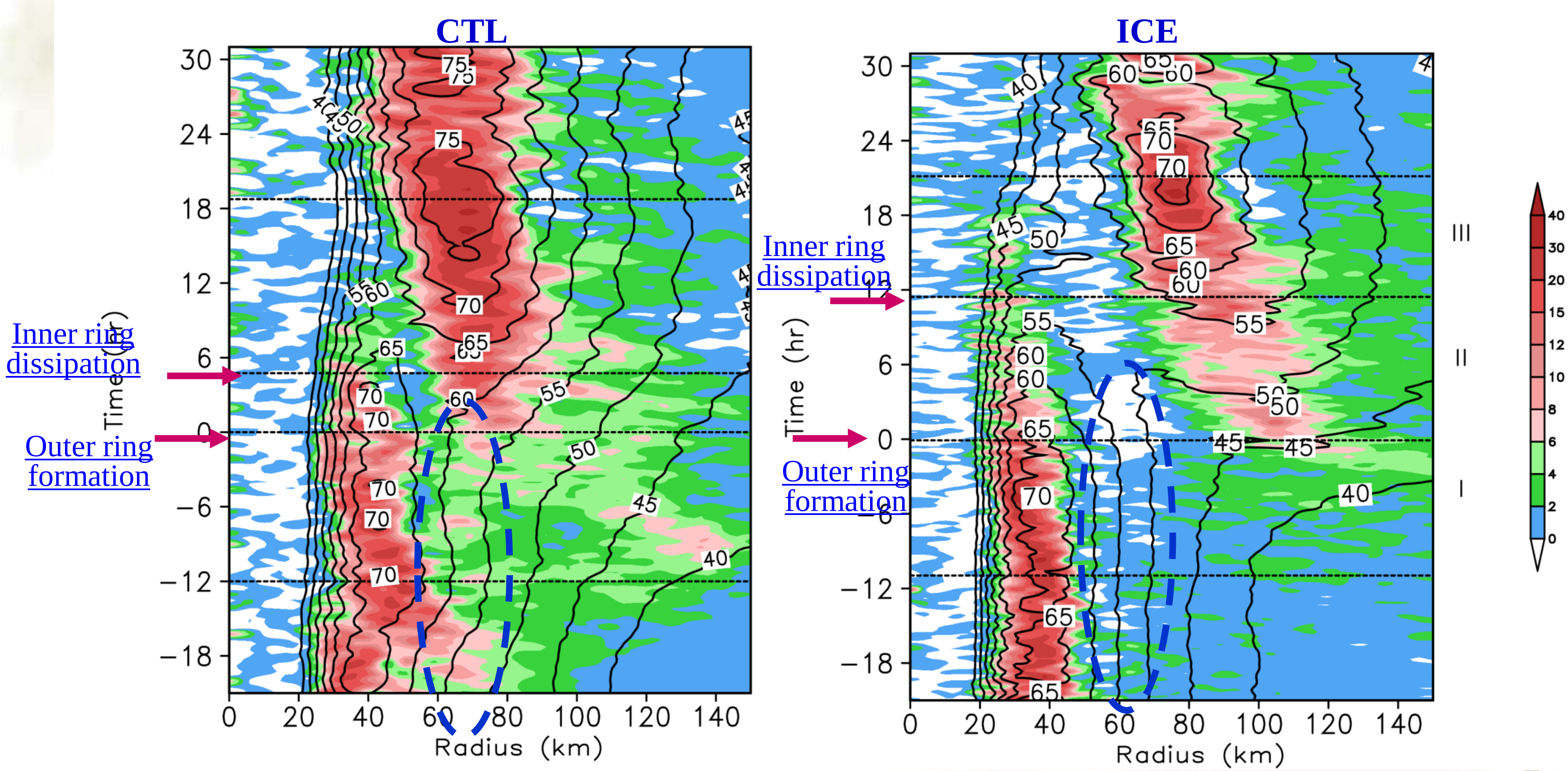
$$\tau_{fil} = \left[-\frac{\langle V_t \rangle}{r} \frac{\partial \langle V_t \rangle}{\partial r} \right]^{-1/2}$$

β-skirt: (un-shaded areas)

PV decreases with R

(Terwey and Montgomery 2008)

Moat and secondary eyewall formation



Hovmoller diagram of symmetric 500 hPa vertical velocity (shading) and 700 hPa tangential wind (contour)

What about large-scale environment effect on the size of secondary eyewall?

Data and Method

Data:

- 69 SE evens (1997-2009) over WNP (H.-C. Kuo)
- NCEP reanalysis 2
- JTWC best track

Method:

- Stepwise orthogonal selection
- Multiple regression

Potential synoptic predictors

Factor	Description
Static factors:	
VMX	Current intensity (knots)
LAT	Current central latitude
DVMX	12-hour intensity change
SPD	Storm translational speed
Dynamic factors	
200 hPa	
U200	200 hPa zonal wind (300-600 km)
DIV200	200 hPa divergence(<1000 km)
REFC	200 hPa relative eddy flux convergence (<600 km)
850 hPa:	
VOR850	850 hPa vorticity (<1000 km)
TWAC	850 hPa symmetric tangential wind (300-600 km)
Wind Shear:	
SHRD	200-850hpa horizontal wind vertical shear (300-600 km)
SHRS	500-850hpa horizontal wind vertical shear (300-600 km)
USHRD	200-850hpa zonal wind vertical shear (300-600 km)
USHRS	500-850hpa zonal wind vertical shear (300-600 km)
PENC	Azimuthally averaged surface pressure at (400-500 km)
Thermodynamic factors:	
RHHI	500-300 hPa relative humidity (300-600 km)
RHLO	850-700 hPa relative humidity (300-600 km)
MPI	Maximum potential intensity (300-600 km)
T200	200 hPa temperature (300-600 km)
CAPE	Convective available potential energy (300-600 km)
SST	Sea surface temperature (300-600 km)

Selected Predictors and Multiple Regression Normalized regression coefficients

	1	2	3	4	5	6	7		
	VMX	LAT	SHRD	PENC	RHHI	T200	MPI	MAE	R^2
0h	**-0.3132**	-0.0135	-0.1276	0.0138	**0.3684**	**0.3895**	-0.0289	0.58	0.45
-6h	**-0.3458**	0.0596	**-0.2235**	0.0051	**0.4453**	**0.4558**	-0.0154	0.53	0.51
12h	**-0.3535**	**0.1781**	**-0.2693**	**-0.2313**	**0.4084**	0.171	-0.0498	0.56	0.46
18h	**-0.2921**	0.1341	-0.2559	-0.0335	0.3517	**0.2717**	-0.1286	0.57	0.39
24h	**-0.2511**	**0.1849**	-0.155	**-0.4206**	0.1894	0.0933	-0.0911	0.56	0.40
30h	-0.1668	**0.1915**	-0.1766	**-0.3946**	0.1761	0.1126	-0.129	0.56	0.38
36h	-0.0693	**0.181**	0.0309	**-0.4767**	0.0679	0.0678	**-0.1904**	0.53	0.40
42h	-0.0464	0.171	-0.0764	**-0.3755**	0.0444	0.1194	**-0.1915**	0.58	0.35
48h	0.0509	**0.2019**	-0.0283	**-0.6482**	0.0445	-0.1191	-0.1588	0.55	0.43

The forecast times are listed at the left side of the table. The 99% statistical significance level from an *F* test is indicated by large bold fonts. Small bold represents 95% significance level.

Mean absolute error (MAE)
variance explained (R^2)

Predictors and empirical model

The size of SEs depends on environmental conditions:

✧Azimuthally averaged Surface pressure (400-500 km)

✧Maximum Potential Intensity

✧500-300 hPa relative humidity (300-600 km)

✧Vertical shear of horizontal wind (850 and 200 hPa)

✧200 hPa temperature (300-600 km)

And storm's

✧Central Latitude

✧Initial Intensity

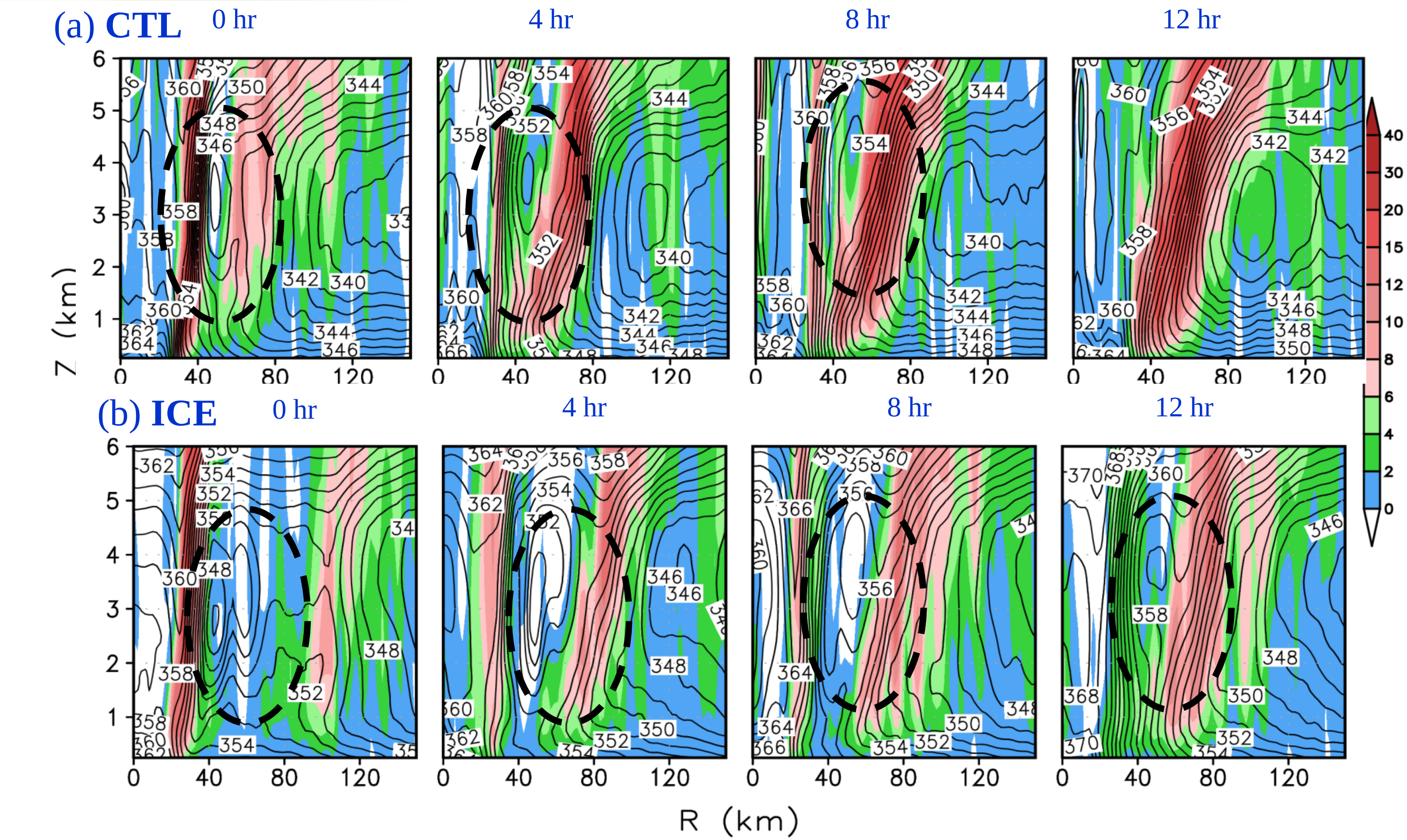
A prediction model with lead time up to 48 hours guidance is developed.

The prediction scheme is able to explain about 40-50% of the total variance of the SE size.

II. What control storm intensity change during eyewall replacement?

- Model
- Observation

Model results: Filling of Moat



Equivalent potential temperature (contours) and vertical velocity (shading)

Observational results: Strength of the Secondary eyewall

❖ Data:

TRMM 2A12: generated from TRMM microwave imager (TMI) brightness temperatures by blending the radiometric data with dynamical cloud models

TRMM 2A25: TRMM Precipitation Radar (PR)

JTWC TC best data over WNP

NRL tropical cyclone website

❖ Methods

1)Find TCs with concentric eyewalls on NRL website

2)check if TC is captured by TRMM swath

3)Check if TC moves 25^0N north or moves close to land

4)Check intensity change of TC

Two groups of TC with concentric eyewalls were identified:

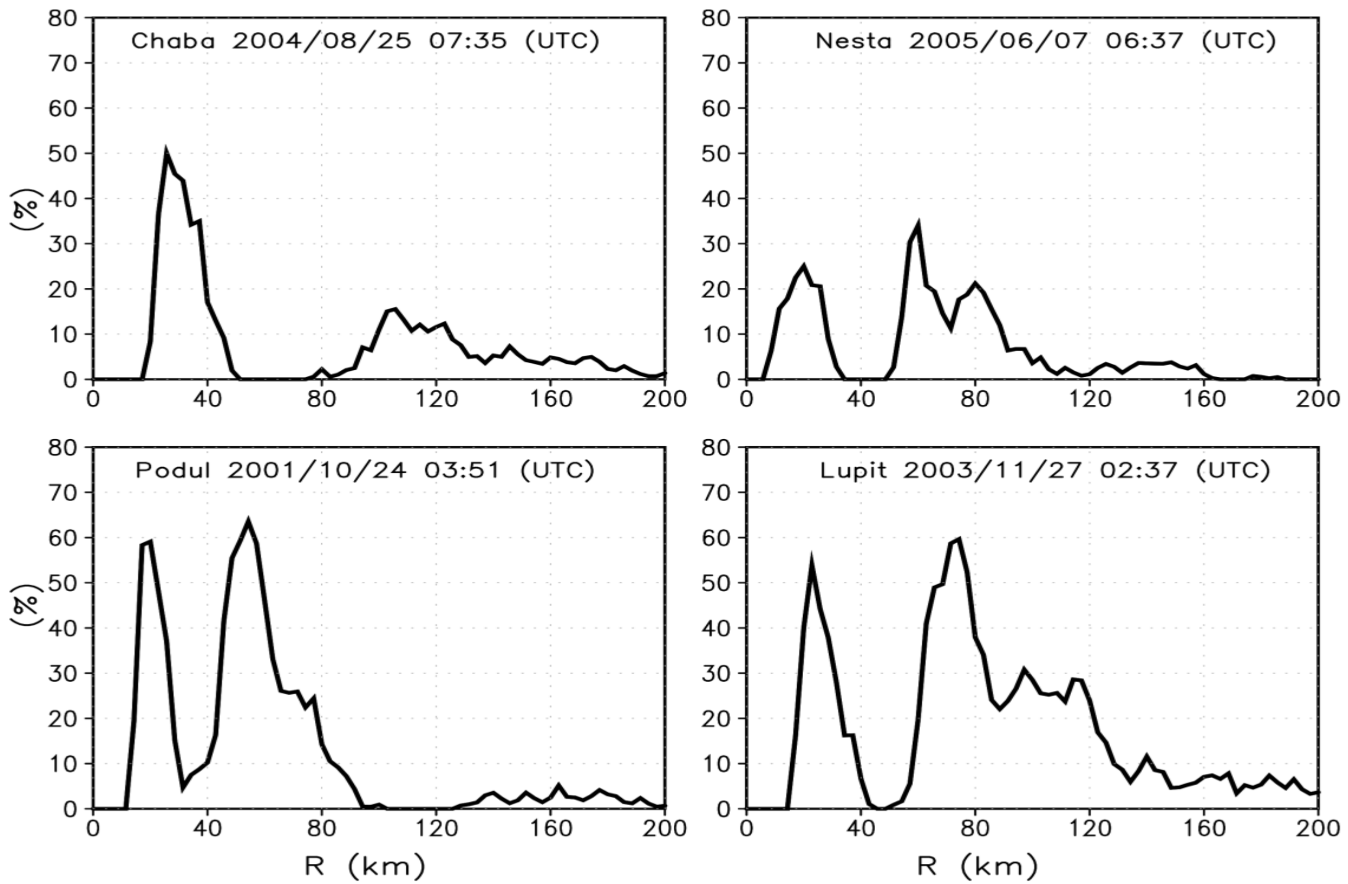
a) with more than 10 m/s weakening (LC)

b) small intensity fluctuation (SC)

Strength of the secondary eyewall

Strong Weakening

No weakening or intensification



- The radial distributions of the deep convection Area coverage (the maximum radar reflectivity > 40 dBZ) in the LC (upper panels) and SC (lower panels) group based on TRMM 2A25 data

Reuslts

- When moat area is large and strong, the replacement takes longer time, so is the weakening. In addition, the presence of lower equivalent potential temperature air in the moat leads to more significant weakening of the storm intensity.

- When the secondary eyewall has a large potion of deep convection, the TC would experience a little weakening or even intensification after the replacement.

On-going works

-Predictability study with ENKF forecast analysis:

Genesis of Karl (see poster)

Rapid intensification and secondary eyewall of Earl

-Convective structure in pouch: developer vs non-developer using CMORPH

-Environmental control of RI

Relevant Publication

Zhou X. and B. Wang, 2011: Mechanism of concentric eyewall replacement cycle and associated intensity change, *J. Atmos. Sci* . 68, 972-988.

Zhou X., B. Wang, X. Ge, T. Li, 2011: Impact of Secondary Eyewall Heating on Tropical Cyclone Intensity Change. *J. Atmos. Sci.*, 68, 450–456.doi: 10.1175/2010JAS3624.1

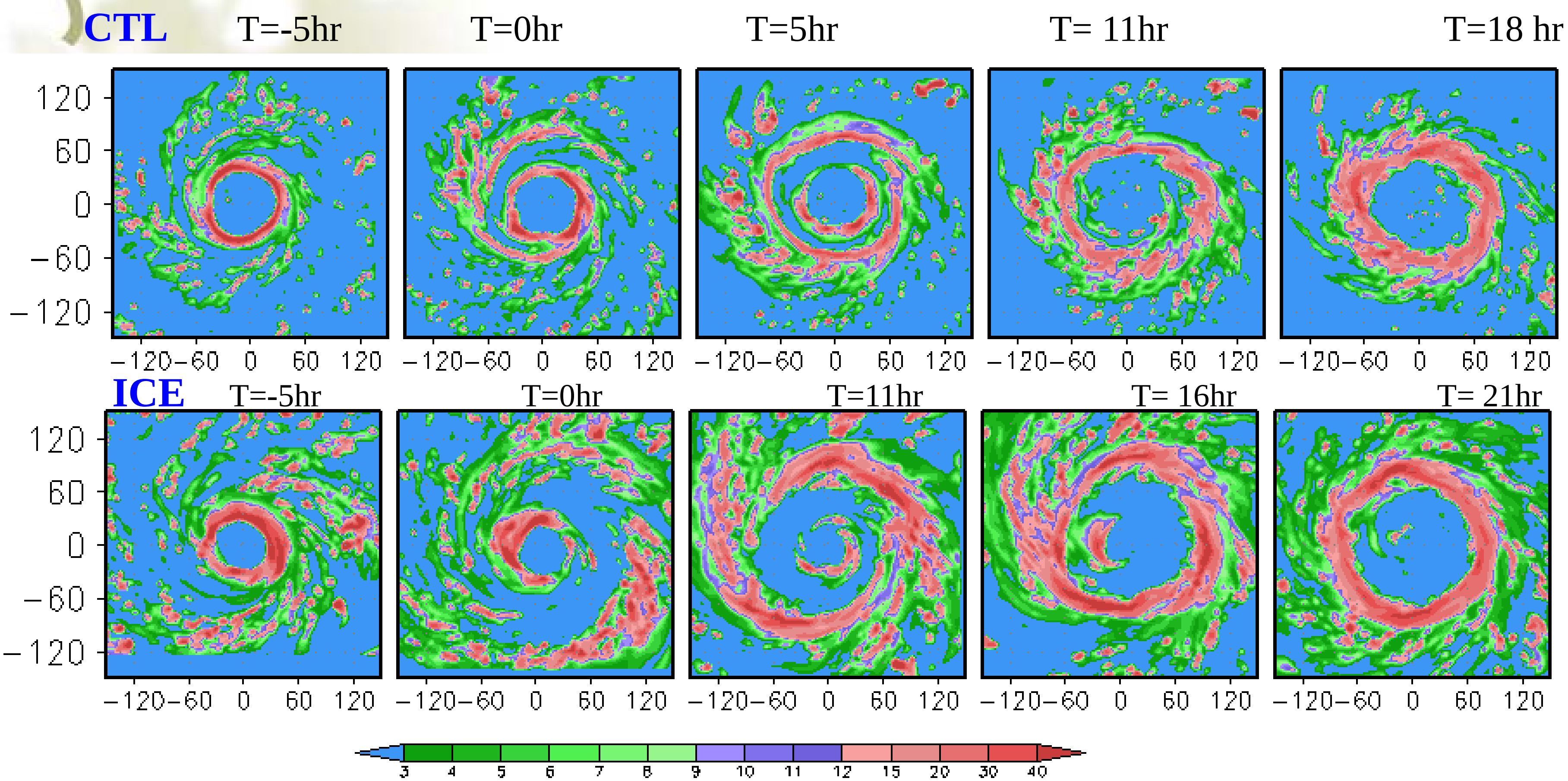
Zhou X. and B. Wang, 2011, Influence of large-scale environment on the size of secondary eyewalls, *Mon. Wea. Rev.* (Submitted)

Thank you

Part I:

Mechanism of concentric eyewall replacement cycle and associated intensity change

Secondary Eyewall Replacement Cycles



Rainwater at 550hPa

Interpretation

Ice-phase microphysics affect concentric eyewall replacement cycles

1) Location of the secondary eyewall

More ice particle create strong moat

the secondary eyewall forms at a large radius

2) The duration of the inner eyewall dissipation

The direct/interception effect of the outer eyewall plays an essential role on the dissipation of the inner eyewall.

The interception mechanism is more efficient when the outer eyewall is close to the inner one (moat is narriower)

3) Intensity fluctuation

The presence of lower equivalent potential temperature air in the moat leads to more significant weakening of the storm intensity during the eyewall replacement process.

Why Does Inner Eyewall Collapse?

Difficult to maintain an inflow of high-entropy to the inner eyewall

- **Indirect effect:**

  Downdrafts induced by the outer eyewall would advect low entropy air from the middle level to boundary inflow layer, which chokes off convections and higher vorticity in the inner eyewall. (Shaprio and Willoughby 1982; Barnes et al. 1983)

- **Direct effect/Interception mechanism:**

  The outer eyewall would rob the inward radial flux of moist entropy and momentum from the inner eyewall directly (Willoughby et al 1982; Samsury and Zipser, 1995; Rozoff et al. 2008).

Indirect Effect

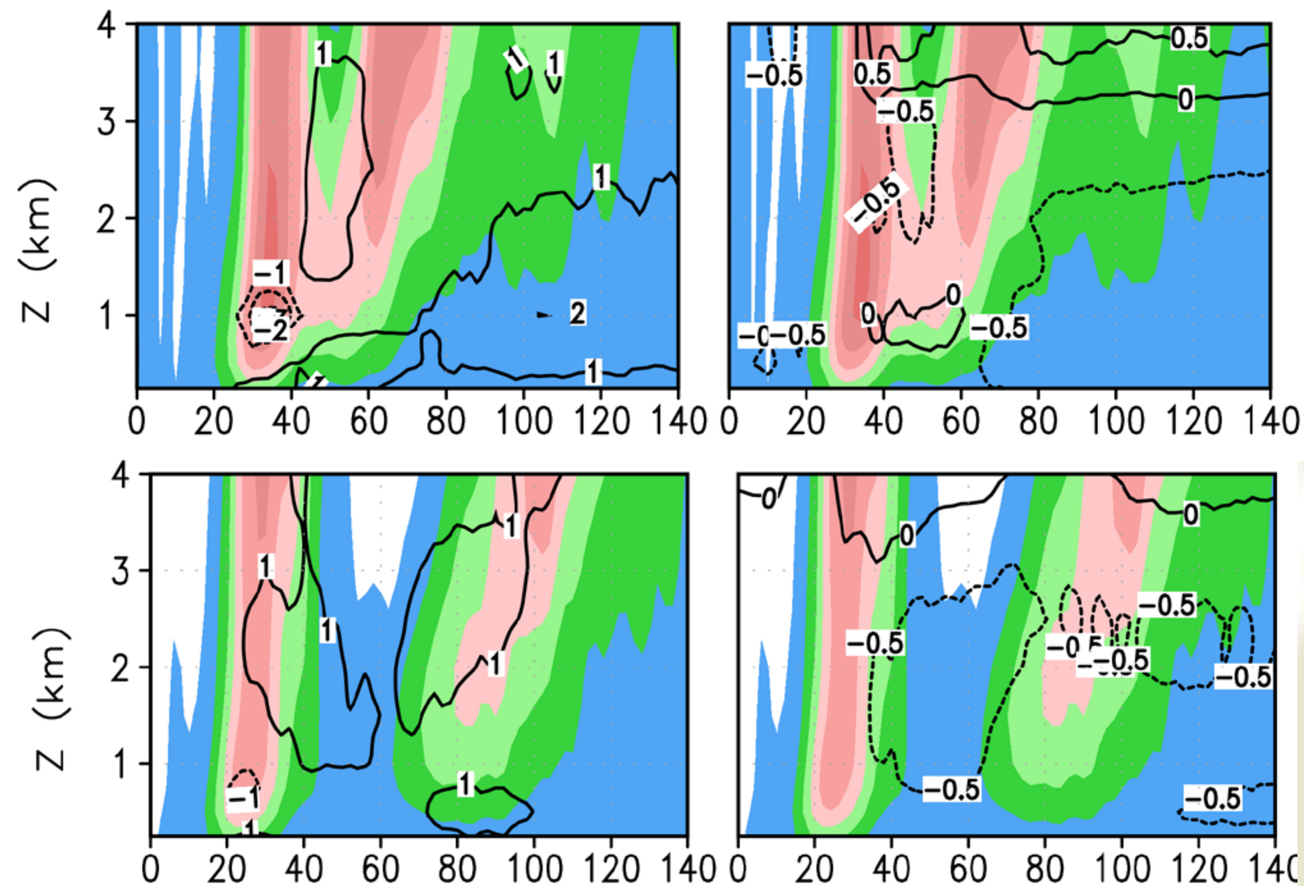
Contributions of updraft and downdraft to axisymmetric theta_e

Averaged from 0 hr to 3 hr

Updraft Downdraft

CTL

ICE



Shading is vertical velocity

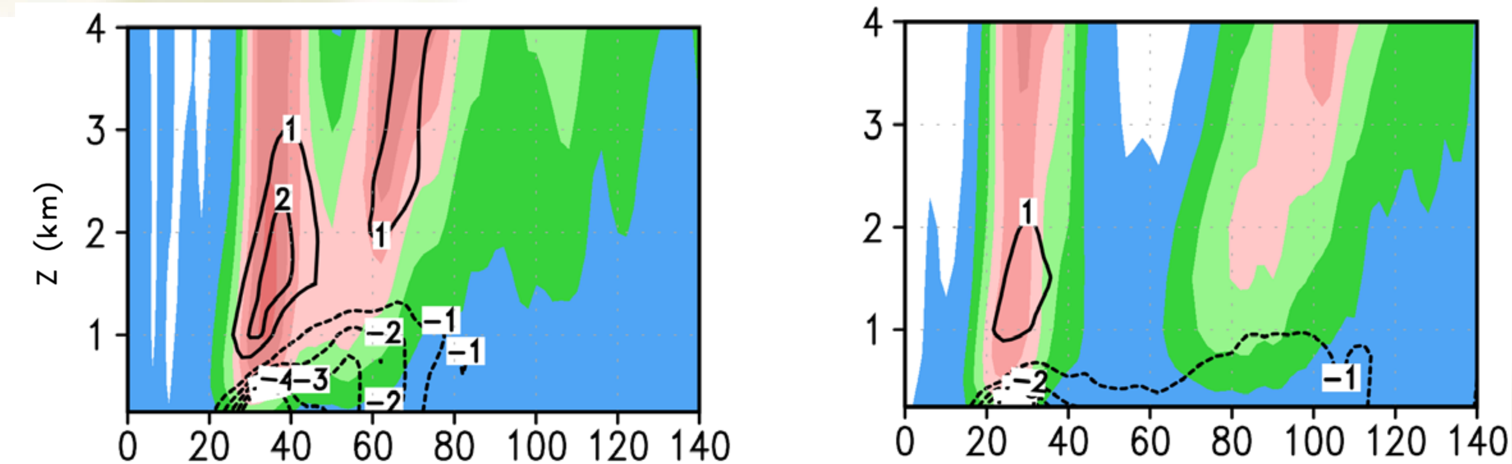
Contour unit: 10^{-3} K s^{-1}

Interception/Direct mechanism

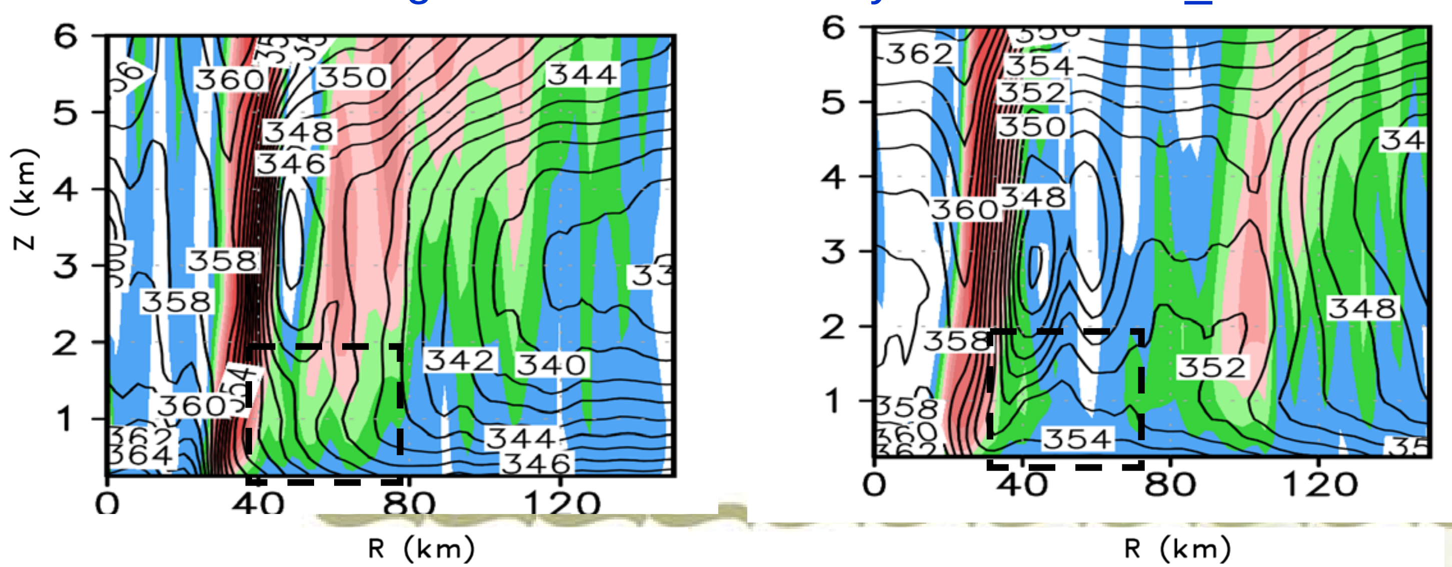
Contributions of mean horizontal advection to axisymmetric theta_e averaged from 0-3 hr

CTL **ICE**

Mean horizontal advection



Radius-height distribution of axisymmetric theta_e at t= 0hr



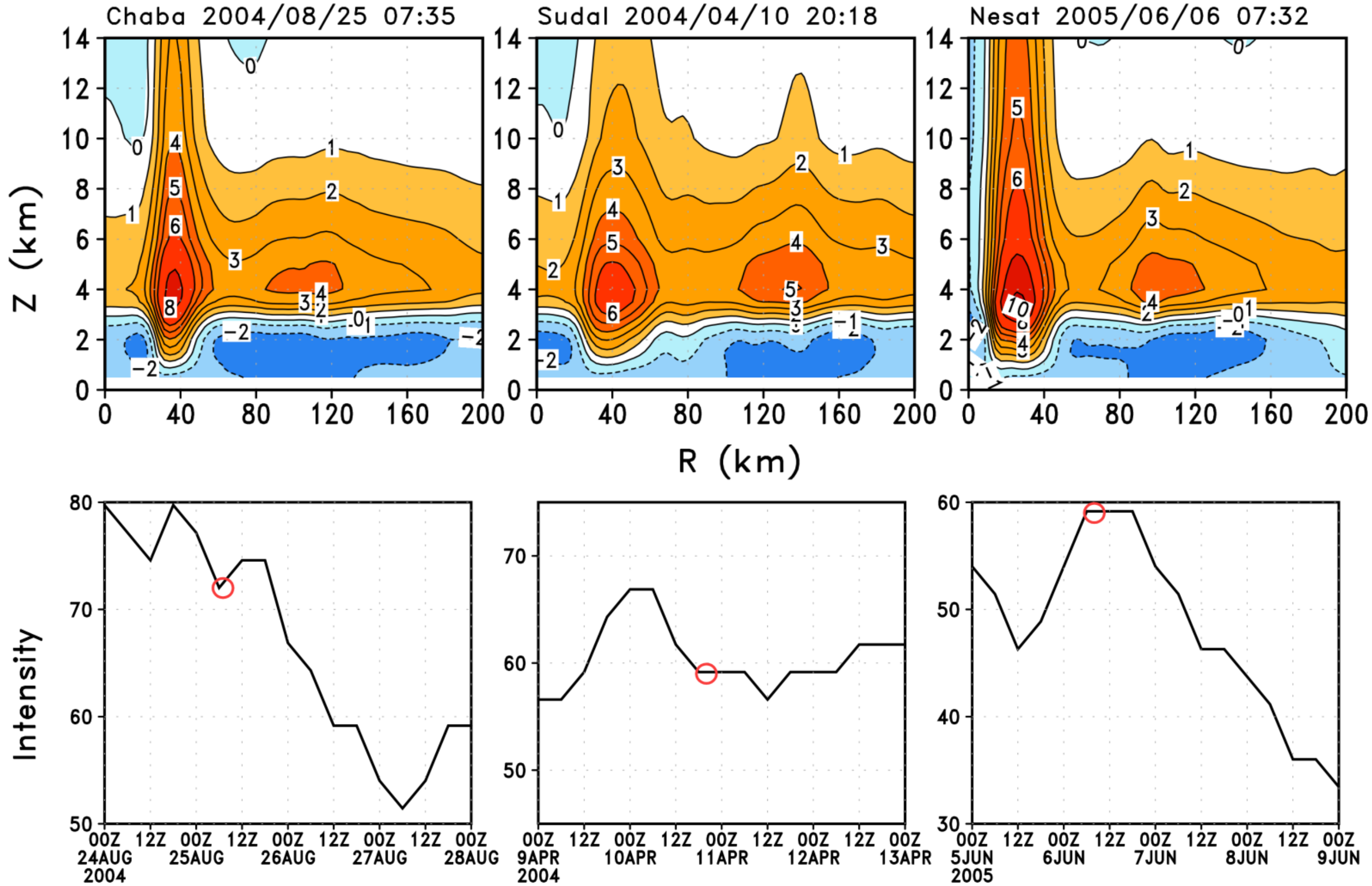
Motivations

- To investigate whether the secondary eyewalls and associated intensity fluctuation simulated by numerical models are consistent with the observations

- To investigate whether observed thermodynamic structure differ between the concentric eyewall TCs with and without large intensity fluctuations

The Impact of Secondary Eyewall Heating on Tropical Cyclone Intensity Change

TCs with Strong Weakening



- The symmetric component of diabatic heating rates (unit: K hr-1) from the TRMM 2A12 dataset (upper panels) and the time evolution of TC intensity (m s-1, lower panels)

TCs with small intensity reduction or intensification