Double Warm-Core Structure and Potential Vorticity Diagnosis during the Rapid Intensification of Supertyphoon Lekima (2019)

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Introduction

- Rapid intensification (RI; 15 m/s per 24 hr) is more likely to occur under favorable environment, such as high SST, low VWS, high low-level humidity. The TC inner-core process is assumed to be critical for RI occurrence. (Hendricks et al. 2010)

- Positive feedback between primary and secondary circulation:

  Eyewall diabatic heating → secondary circulation → advect AAM inward → primary circulation spinup → enhance inertial stability → increase efficiency in converting heating to kinetic energy.

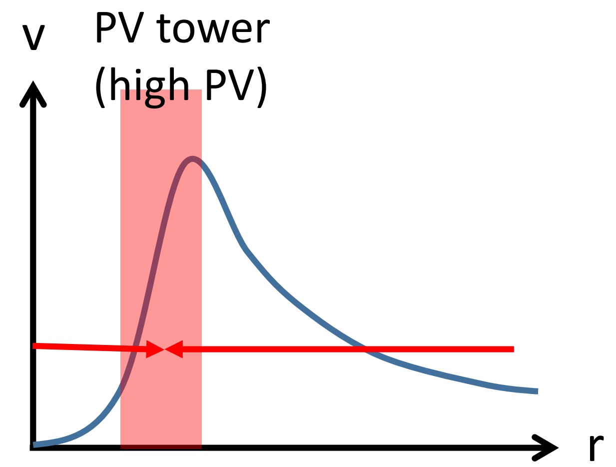
  (Schubert and Hack 1982; Shapiro and Willoughby 1982)

- Deep convections inside the RMW is more favorable for RI than those outside the RMW due to higher heating efficiency. (Schubert and Hack 1982; Vigh and Schubert 2009)

Introduction

- TC features evident asymmetries during intensification phase.
- Asymmetries caused by PV:
  - The sign reversal of PV radial gradient at the PV tower
  - Generating meso-vortices in the eyewall inner edge
  - Making eyewall polygonal
  - Transporting PV from eyewall to eye by PV mixing
  - Inducing eye warming at low to mid levels

  (Montgomery and Shapiro 1995; Schubert et al. 1999; Hendricks and Schubert 2010; etc.)



- That PV mixing induced midlevel warming of Typhoon Haiyan (2013) may account for 50% of central pressure decrease at the early stage of RI. (Tsujino and Kuo 2020)

Introduction

- TC features evident asymmetries during intensification phase.
- Asymmetries caused by CBs:
  - The detrainment of CBs induces subsidence of warm air in stratosphere to eye.
  - Upper-level eye warming
  - The more significant dropping of the surface pressure (warming at upper-level)
  - Promoting RI
  - Facilitating RI by merging or axisymmetrization of strong convection and vorticity

  (Pendergrass and Willoughby 2009; Rogers et al. 2013; Zhang and Chen 2012; Nguyen et al. 2008; etc.)

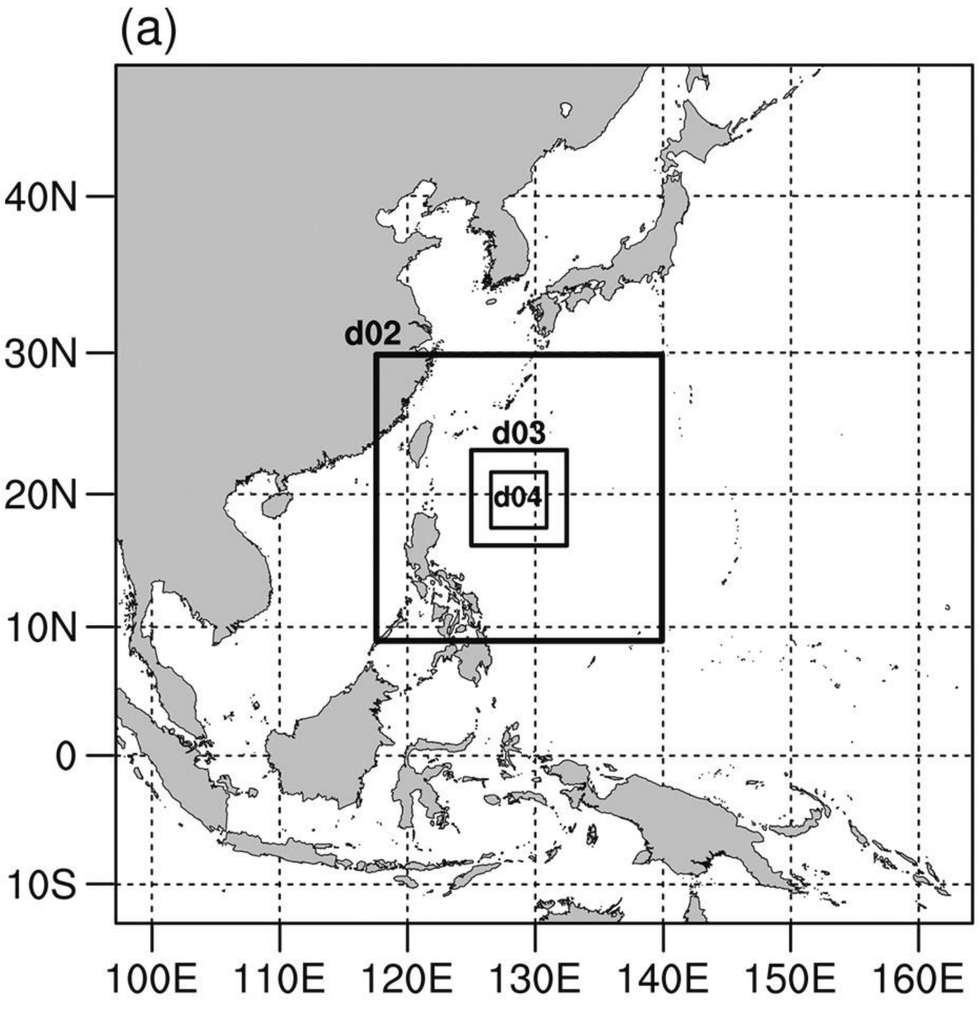
- CBs and PV mixing may occur together. CBs are frequently observed at the vertices of the polygon eyewalls, which illustrated the scale interactions in the inner cores of TC. (Hendricks et al. 2012; Menelaou et al. 2013; Lee and Wu 2018)

Introduction

- Relative roles of above processes in RI are still, especially the balanced PV dynamic.
- The questions were be addressed:
  1. How does the inner-core PV evolve in a RI TC?
  2. To what extent can the TC RI be interpreted by the balanced response to the inner-core PV changes?
  3. How are the relative contributions of the eyewall PV generation, the PV mixing, and other possible processes to the enhancement of inner core wind, the warm-core formation and the central pressure fall during the RI?
  4. The effect of CBs in PV dynamic

- CASE: Typhoon Lekima (2019)

WRF Configuration



(Shi et al. 2020)

Version	3.6.1
Domains	4, d02 to d04 are moving
Grid size	27, 9, 3, 1 (km)
Start time	2019-08-06 12:00:00 Z
Start time (d04)	2019-08-07 00:00:00 Z
End time	2019-08-09 12:00:00 Z
Eta levels	55
Model top	30 hPa
Cumulus Scheme	Kain-Fritsch (d01 only)
Microphysics Scheme	Thompson
Longwave Scheme	RRTM
Shortwave Scheme	Dudhia
PBL Scheme	YSU
Boundary update cycle	6 hr
DATASET	GFS-FNL ($1.0^o \times 1.0^o$)
SST DATASET	OISST (update daily)

Azimuthal mean PV budget analysis

- Storm-relative cylindrical coordinate (r, λ, z):

$$P = \nabla\theta \cdot \frac{\zeta_a}{\rho_0}$$

P: potential vorticity
ρ_0: horizontally averaged air density
$\zeta_a = \mathrm{f}\hat{\mathbf{k}} + \nabla \times \vec{\boldsymbol{v}}$
$\vec{\boldsymbol{v}} = u\hat{\boldsymbol{r}} + v\hat{\boldsymbol{\lambda}} + w\hat{\boldsymbol{z}}$ (storm relative)

$$\frac{\partial \bar{P}}{\partial t} = AXADV + ASADV + DIAQ + FRIC$$

$$AXADV = -\bar{u}\frac{\partial \bar{P}}{\partial r} - \bar{w}\frac{\partial \bar{P}}{\partial z}$$

$$ASADV = -\overline{u'\frac{\partial P'}{\partial r}} - \overline{v'\frac{\partial P'}{r\partial \lambda}} - \overline{w'\frac{\partial P'}{\partial z}}$$

$$DIAQ = \overline{\nabla Q \cdot \frac{\zeta_a}{\rho_0}}$$

$$FRIC = \overline{\nabla\theta \cdot \frac{\nabla\times\boldsymbol{F}}{\rho_0}}$$

$Q = \frac{\partial \theta}{\partial t} + V \cdot \nabla\theta$: diabatic heating

$\boldsymbol{F}$: momentum source
- boundary layer
- turbulence mixing
- numerical diffusion

Piecewise PV inversion (PPVI) algorithm

- To quantify the nonlinear response of mass (ϕ') and wind field (ψ') to PVAs and separate the balance and unbalance flow.

- PPVI: separate PVAs into pieces and obtain the corresponding ϕ' and ψ' responses.
    1. Compute the reference state of $\bar{\psi}$: by azimuthal-mean v at the RI onset.
       $\bar{\phi}$: solve →
       $$\nabla_h^2 \phi = \nabla_h (f \nabla_h \psi) + 2\left[\frac{\partial^2 \psi}{\partial x^2}\frac{\partial^2 \psi}{\partial y^2} - \left(\frac{\partial^2 \psi}{\partial x \partial y}\right)^2\right]$$
       B.C.: simulated ϕ
       420 x 420 km (1 km grid size)
    2. Invert the PVAs (Wang and Zhang 2003)
    3. Solve the PPVI equation system

PVAs (PV anomalies=the PV at the onset of RI – the PV at the end of RI)

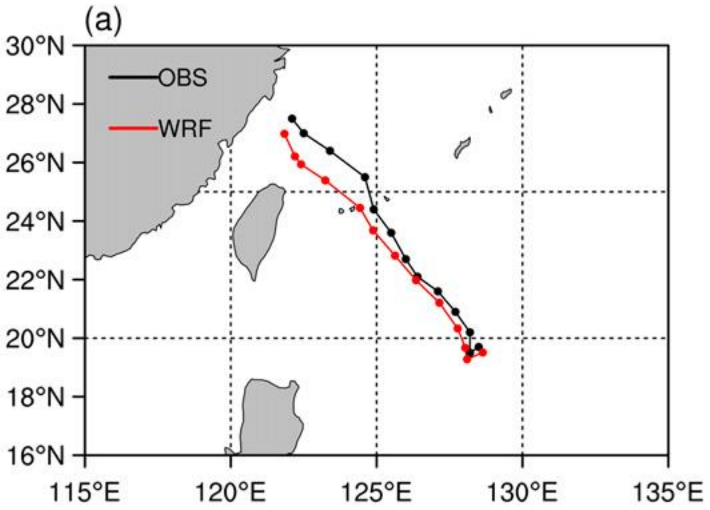
Synopsis of Lekima and verification

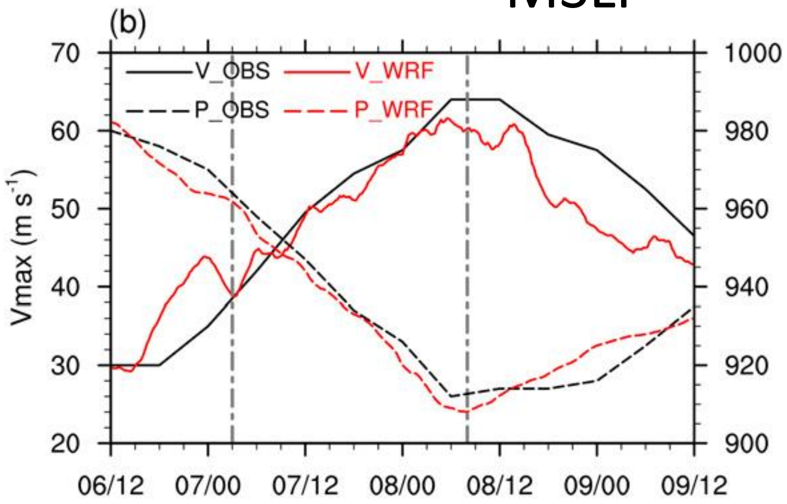
Track

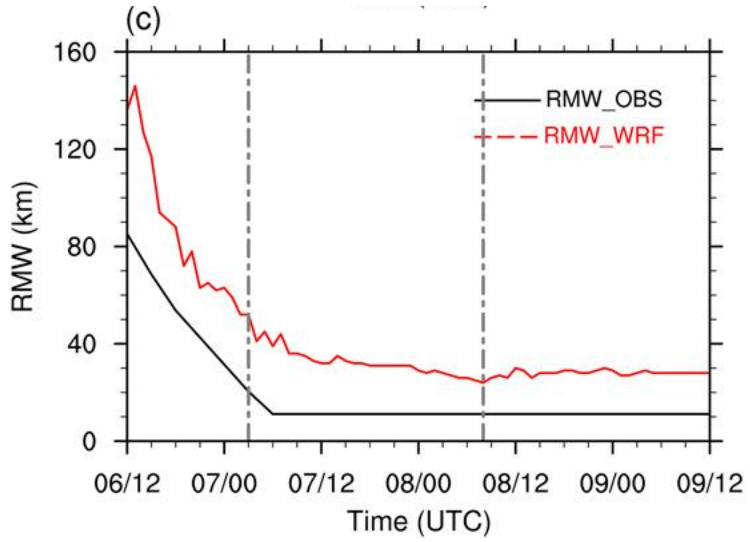
10-m wind

MSLP

RMW







Best track from IBTrACS

OBS

WRF

RI rate: 23 m/s per 24 hr

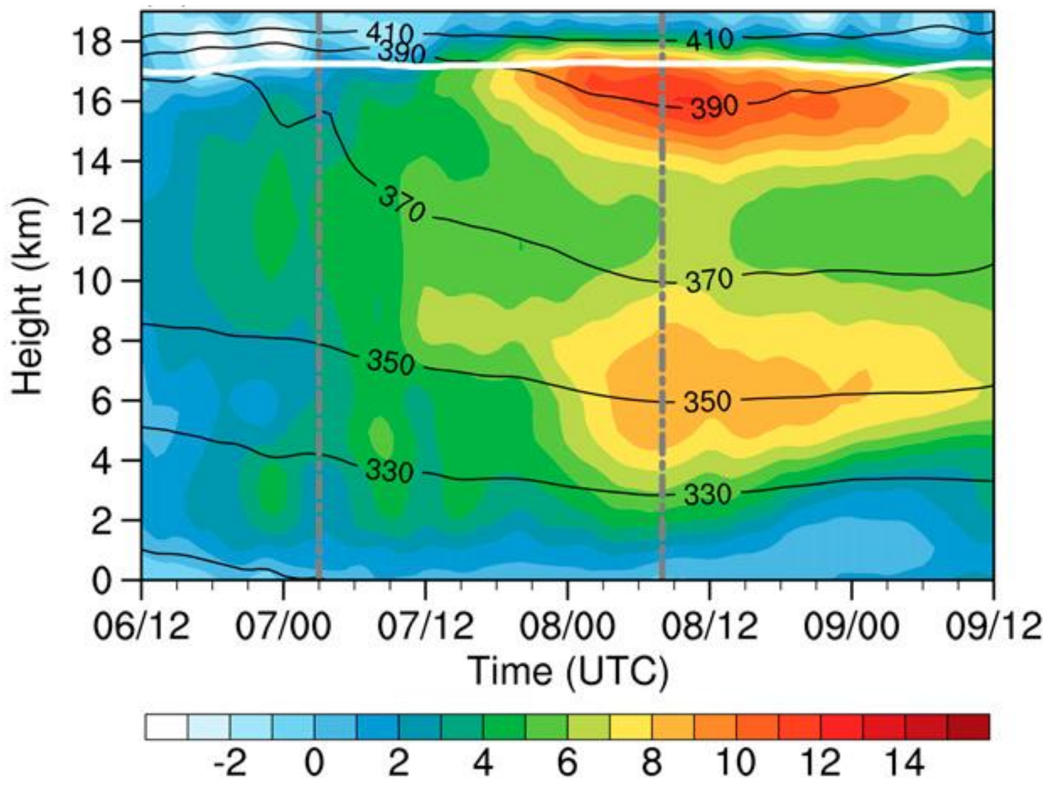
Criterion of RI: 15 m/s per 24 hr

3.7 m/s at the first 6 hr of 24 hr

(Rios-Berrios et al. 2018)

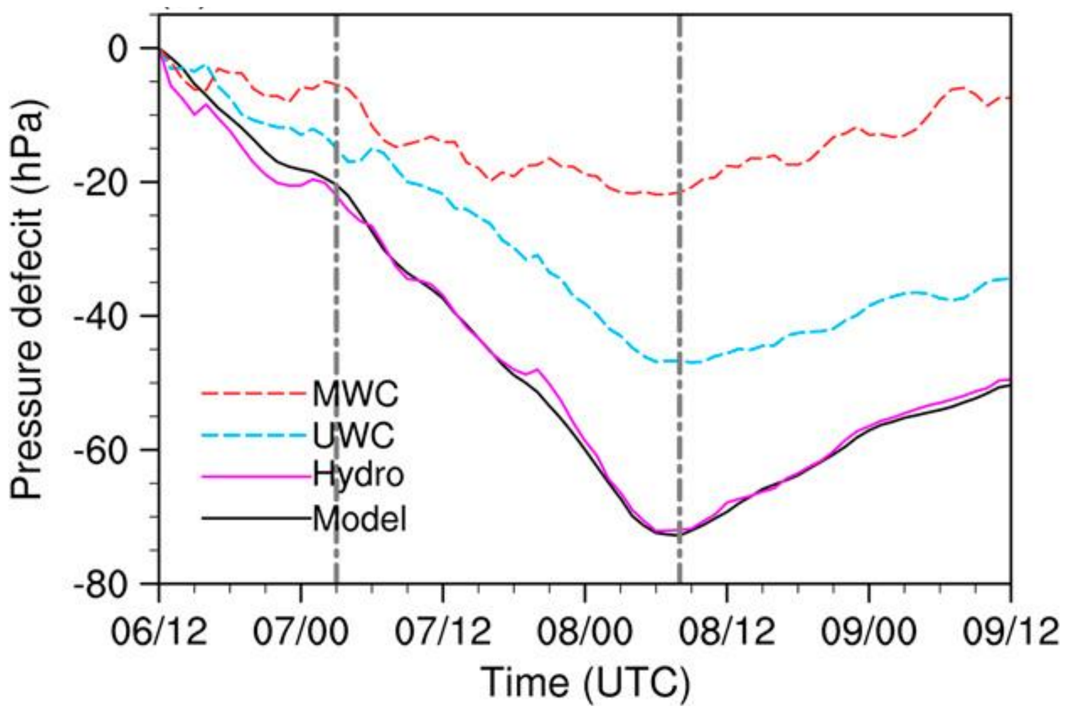
The evolutions of warm core

0~20 km average:
Colored: T_v' (respect to 270-300 km average T_v)
Contour: θ
White plot: tropopause



Pressure deficit:

(*) by warm core < z = 10 km
(*) by warm core > z = 10 km
hydrostatic equation (*)
model output



hydrostatic equation: $p_{\mathrm{sur}} = p_{\mathrm{top}} \exp\left[\frac{g}{R_d}\int_0^{z_{\mathrm{top}}} \frac{1}{T_v(z)}\,dz\right]$

The PV structures during RI

Axisymmetric view:
Colored: PV (PVU)
Contour: Diabatic heating

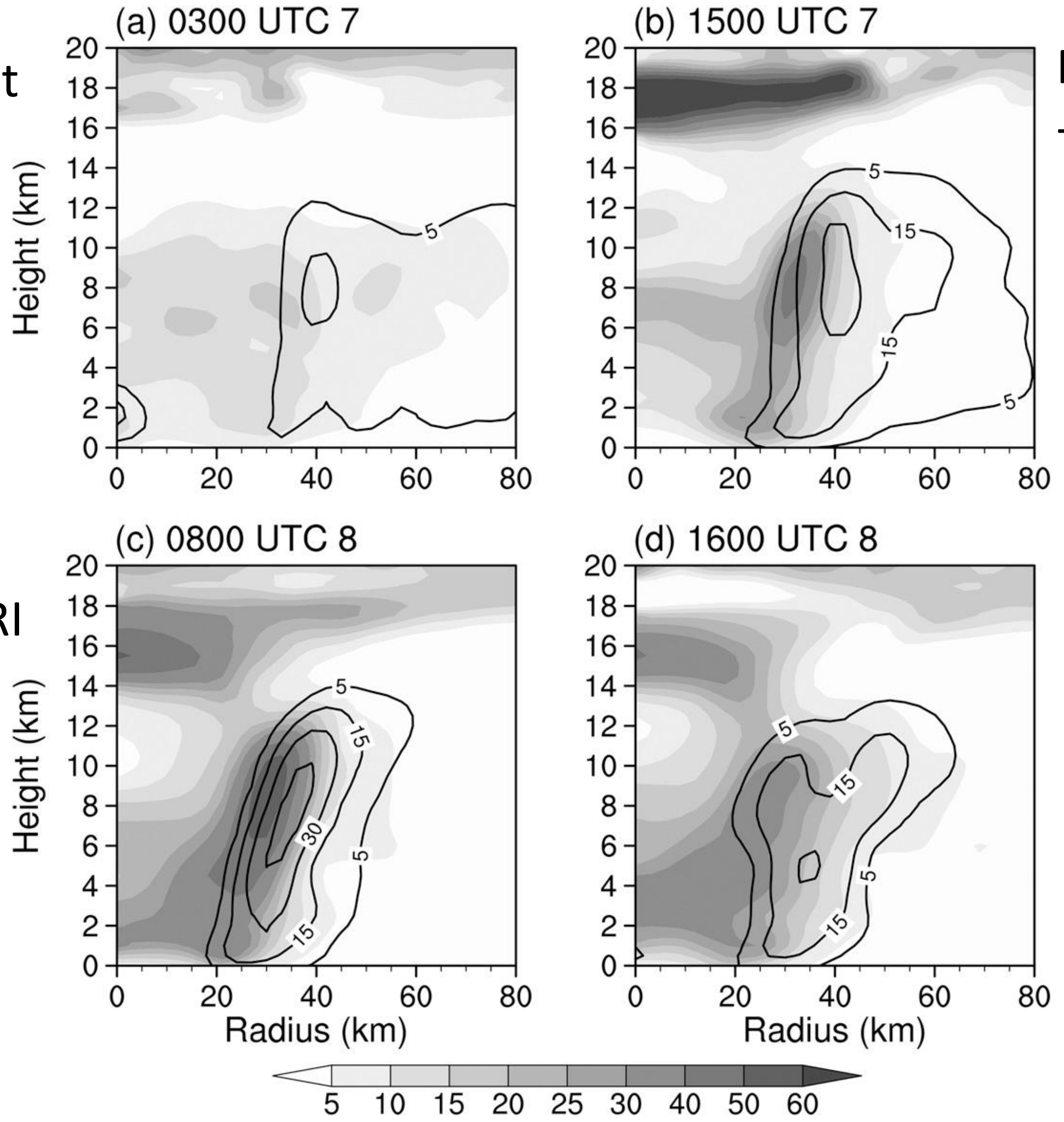
a) Strong PV existed inside r = 40 km at low- to mid- levels.
b) PV generated inside the eyewall heating at z < 13 km.
c) Stronger PV and diabatic heating existed in the eyewall.
d) Both PV and diabatic heating weakened.

RI onset

RI onset + 12 hr

End of RI

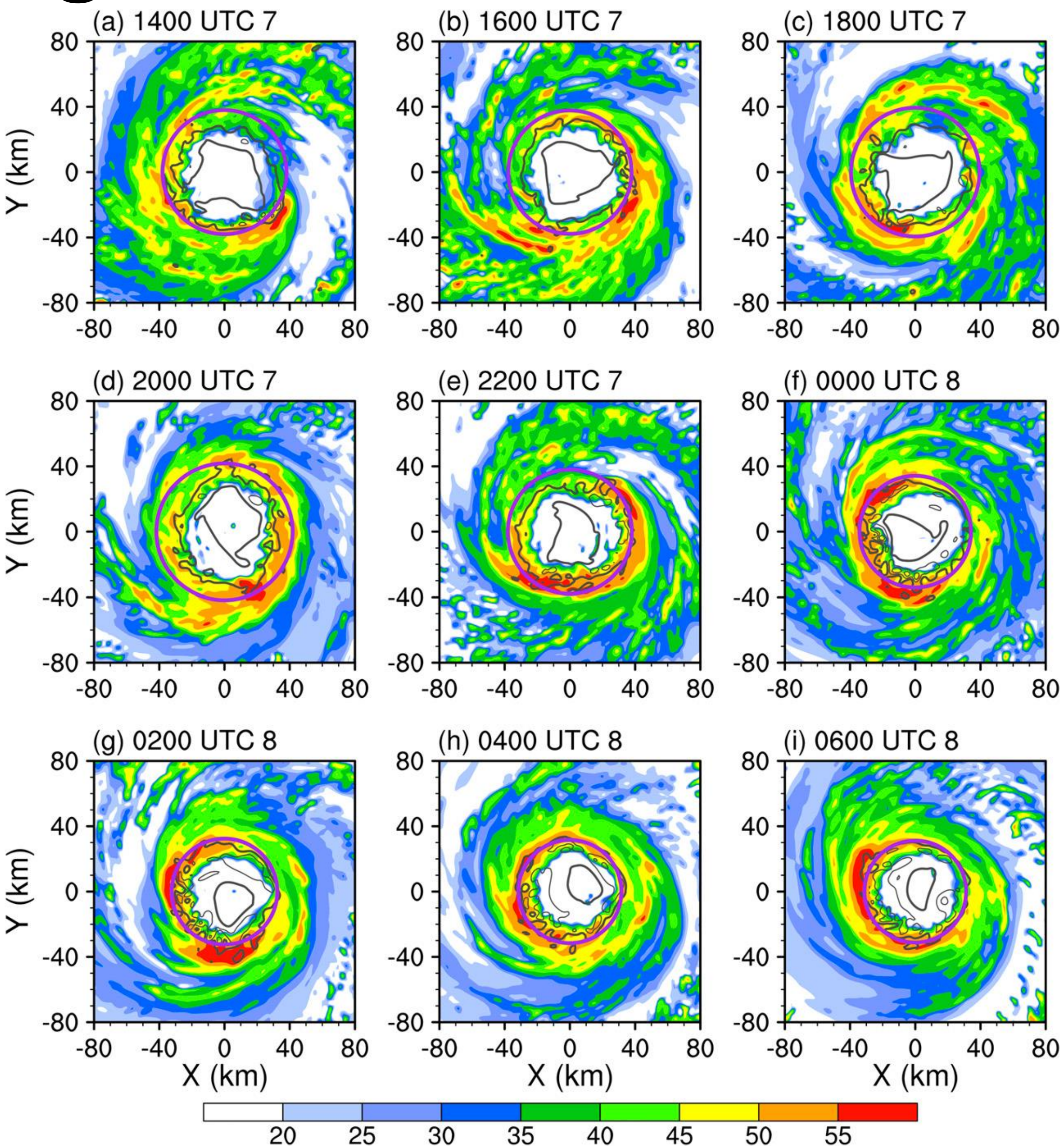
Start to weaken



The PV structures during RI

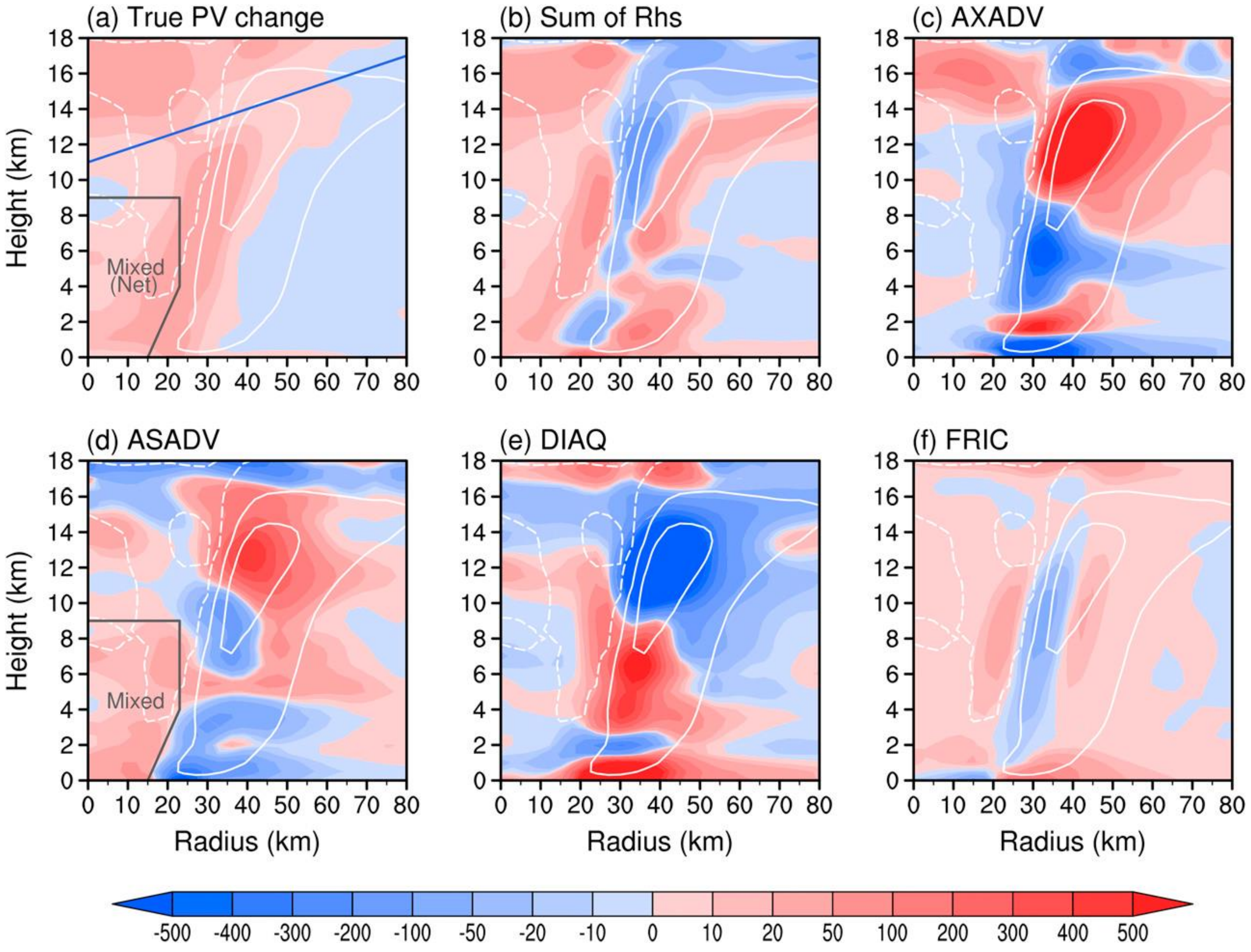
Axisymmetric view:
Colored: z = 1 km dBZ
Contour: z = 0-5 km average PV
Purple plot: z = 2 km RMW

Polygon eyewall existed.
PV increased in the eye and RMW compressed because of the PV mixing process.



Azimuthal mean PV budget analysis

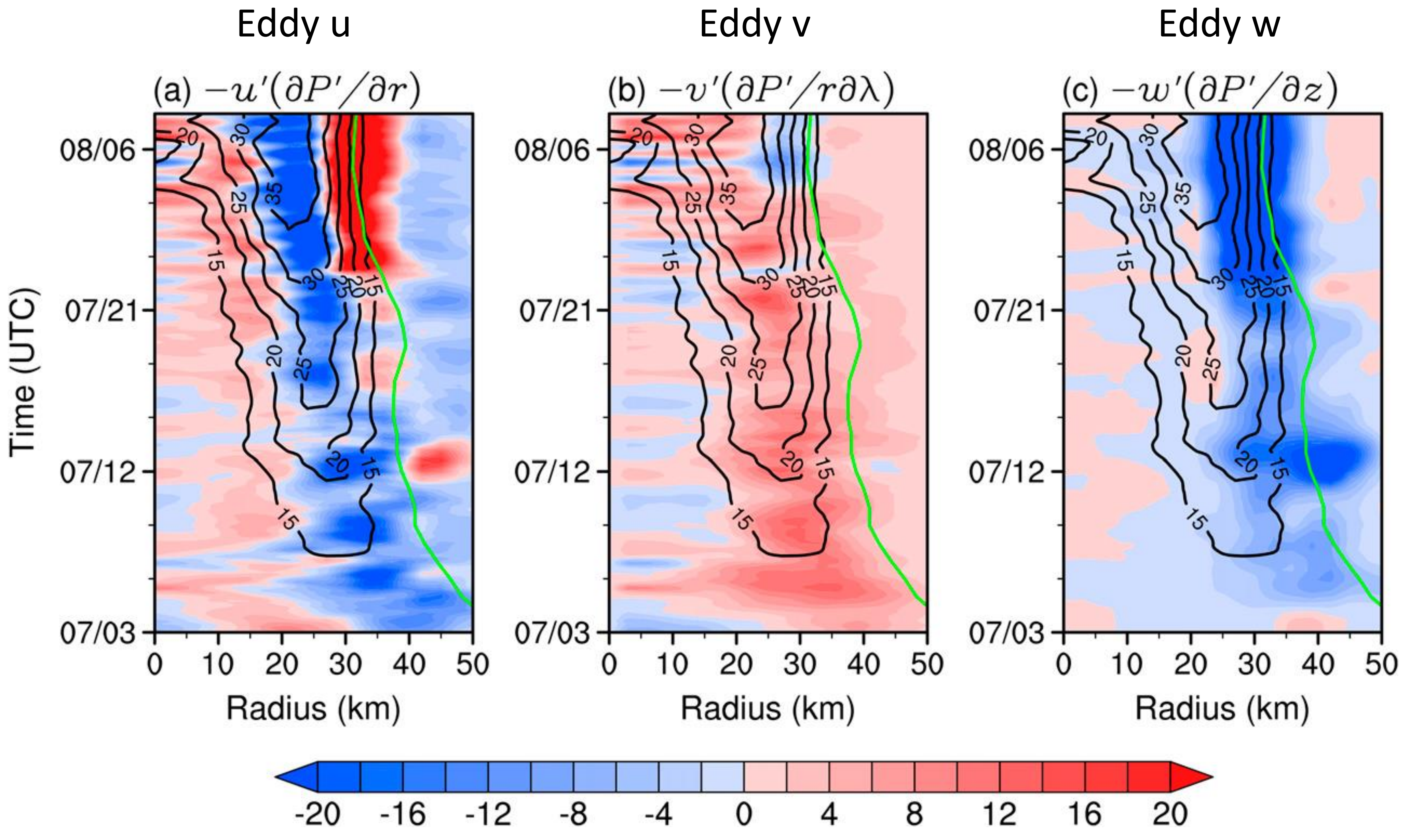
Axisymmetric view:
Colored: each term of PV equation
Contour: w
(Time average from 07/03Z to 08/08Z)



Azimuthal mean PV budget analysis

Axisymmetric view:
Colored: each terms in ASADV
Contour: axisymmetric PV
Green plot: RMW

(z=0 ~ 4 km average)
(1-hr running mean)

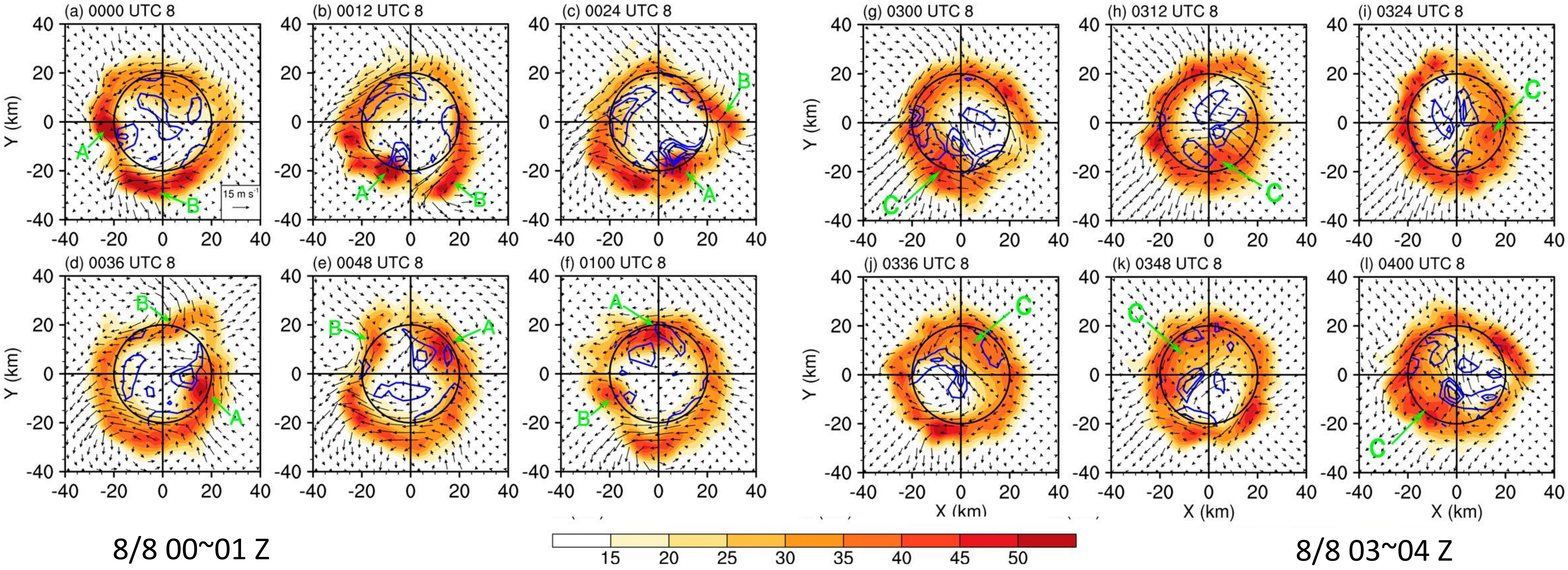


Azimuthal mean PV budget analysis

Plan view:
Colored: PV
Contour: eddy u advection
Vector: asymmetric wind
Green A, B, C: MCVs

(z = 0 ~ 2 km average)
(snapshot with 12-min interval)

$$\overline{-u'(\partial P'/\partial r)}$$

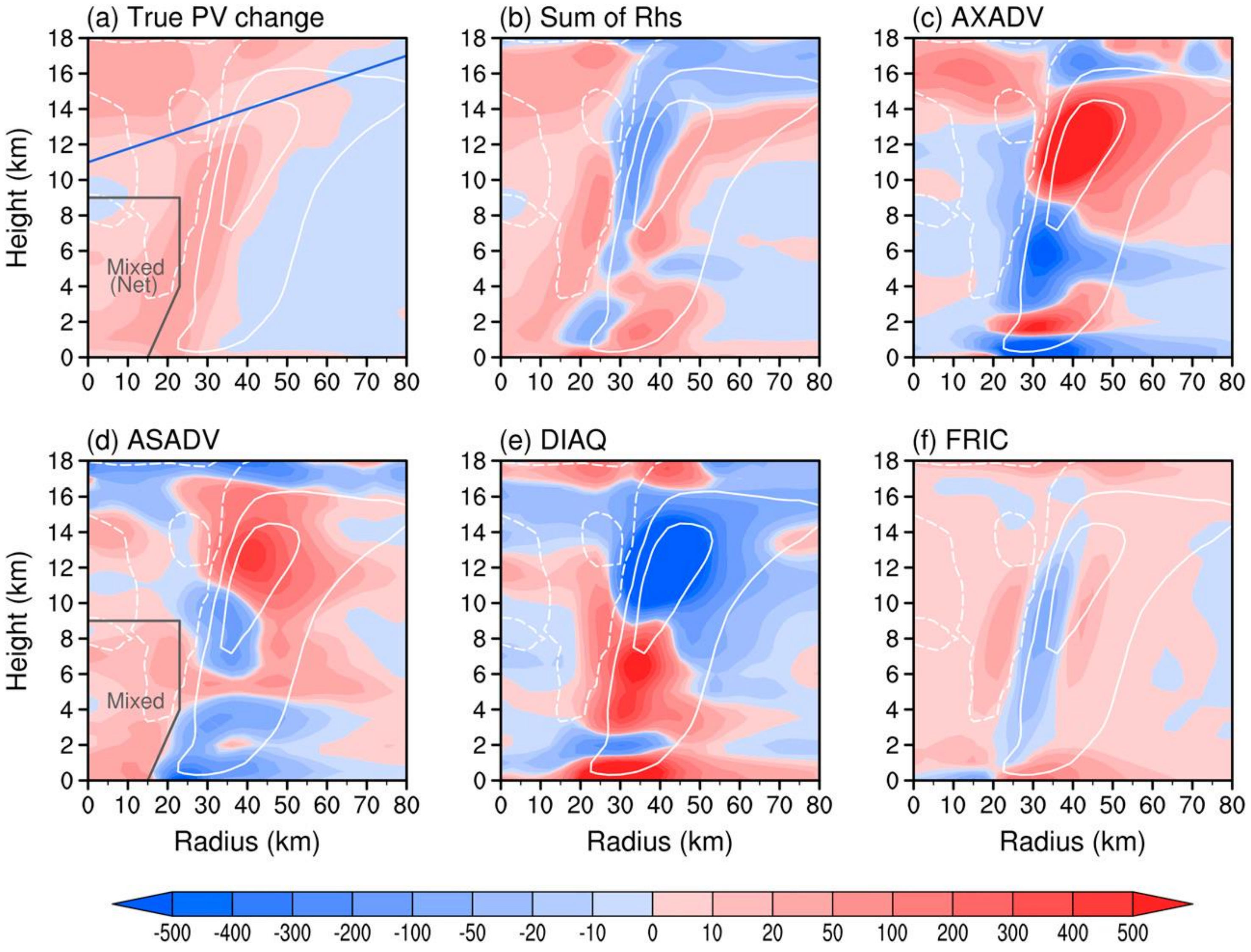


8/8 00~01 Z

8/8 03~04 Z

Azimuthal mean PV budget analysis

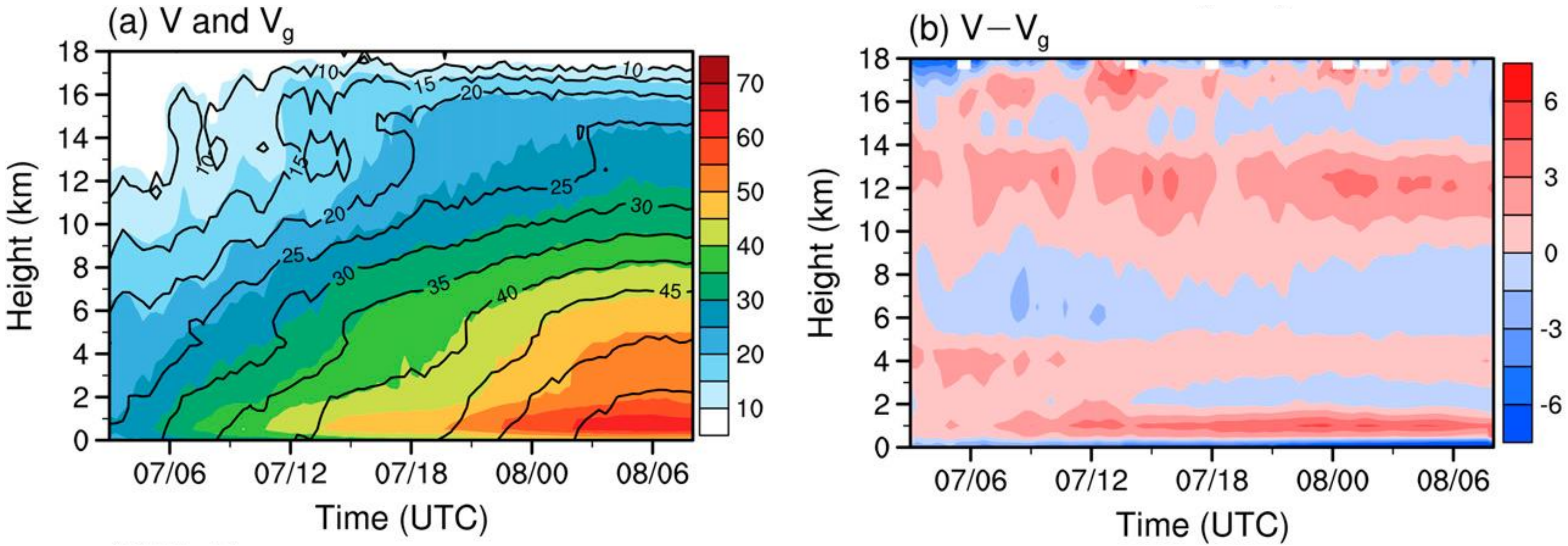
Axisymmetric view:
Colored: each term of PV equation
Contour: w
(Time average from 07/03Z to 08/08Z)



Verification of PPVI

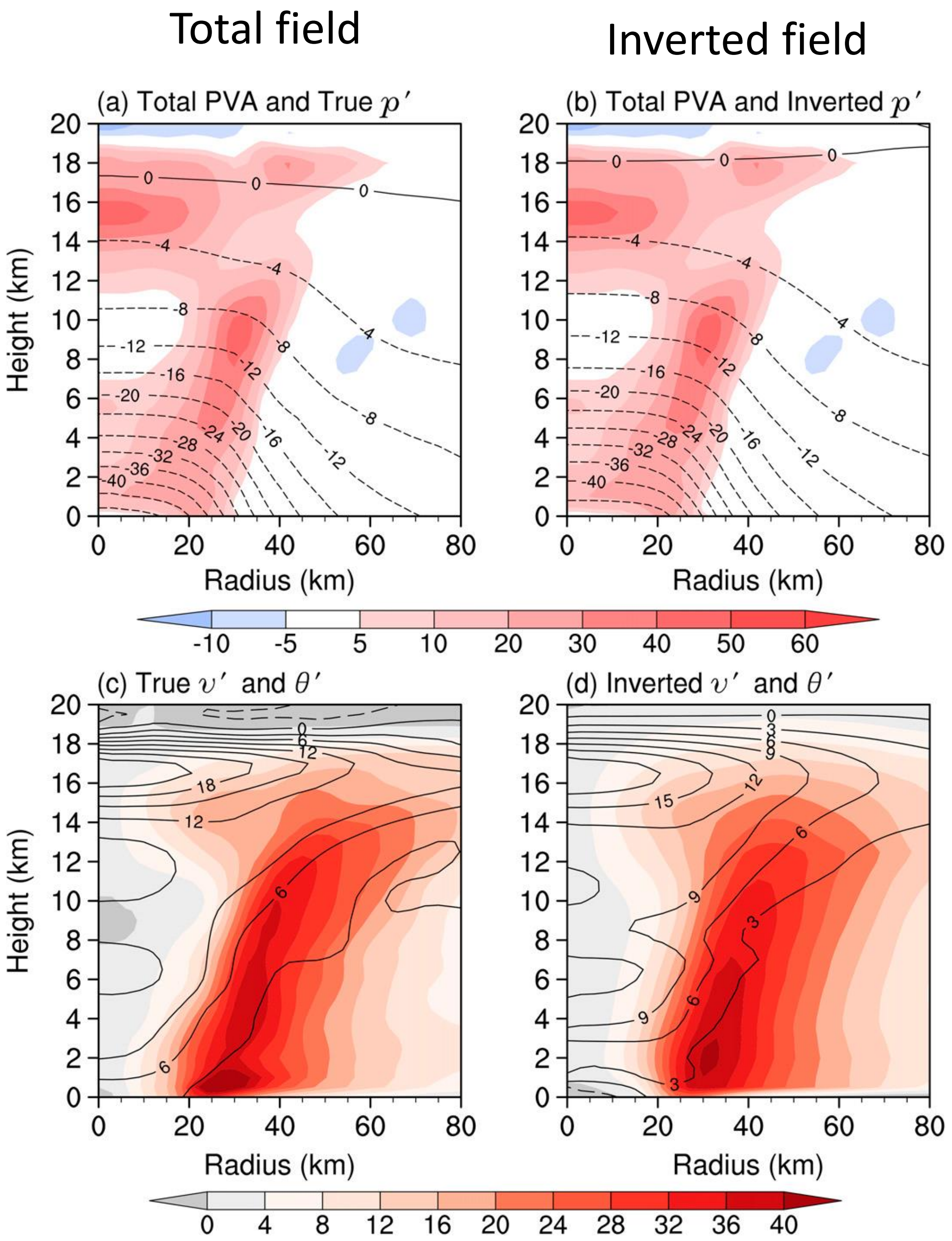
Axisymmetric view:
Colored: V
Contour: Vg
(r = 20 ~ 40 average)

Axisymmetric view:
Colored: V - Vg
(r = 20 ~ 40 average)



Verification of PPVI

Axisymmetric view:
Colored: total PVA
Contour: p’



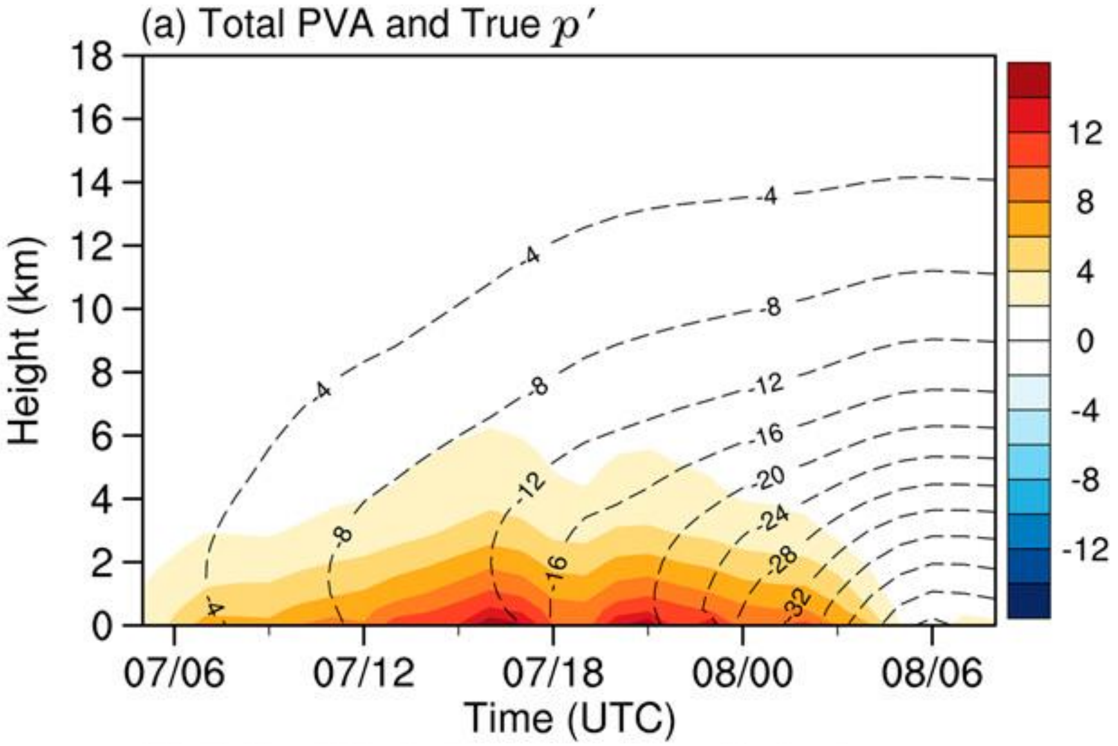
Axisymmetric view:
Colored: v’
Contour: θ'

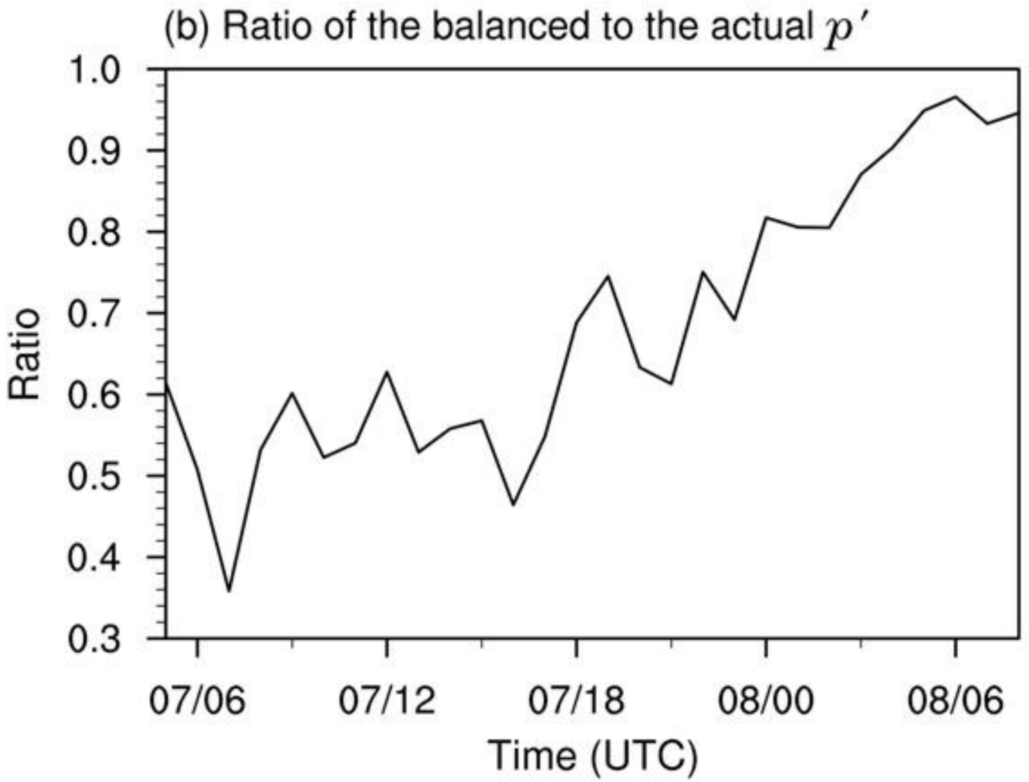
(Relative to RI onset)
(08/08Z)

Verification of PPVI

Axisymmetric view:
Colored: balanced p' – True p'
Contour: balanced p'
(r < 10 km average)

Axisymmetric view:
Balanced p' / True p'

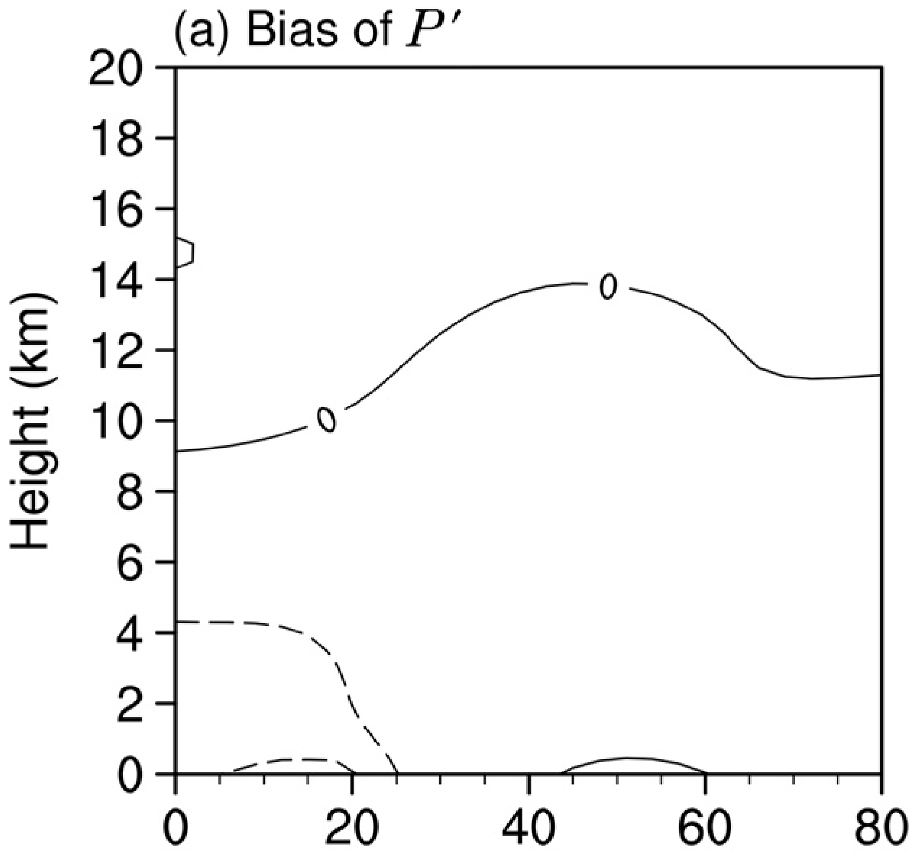




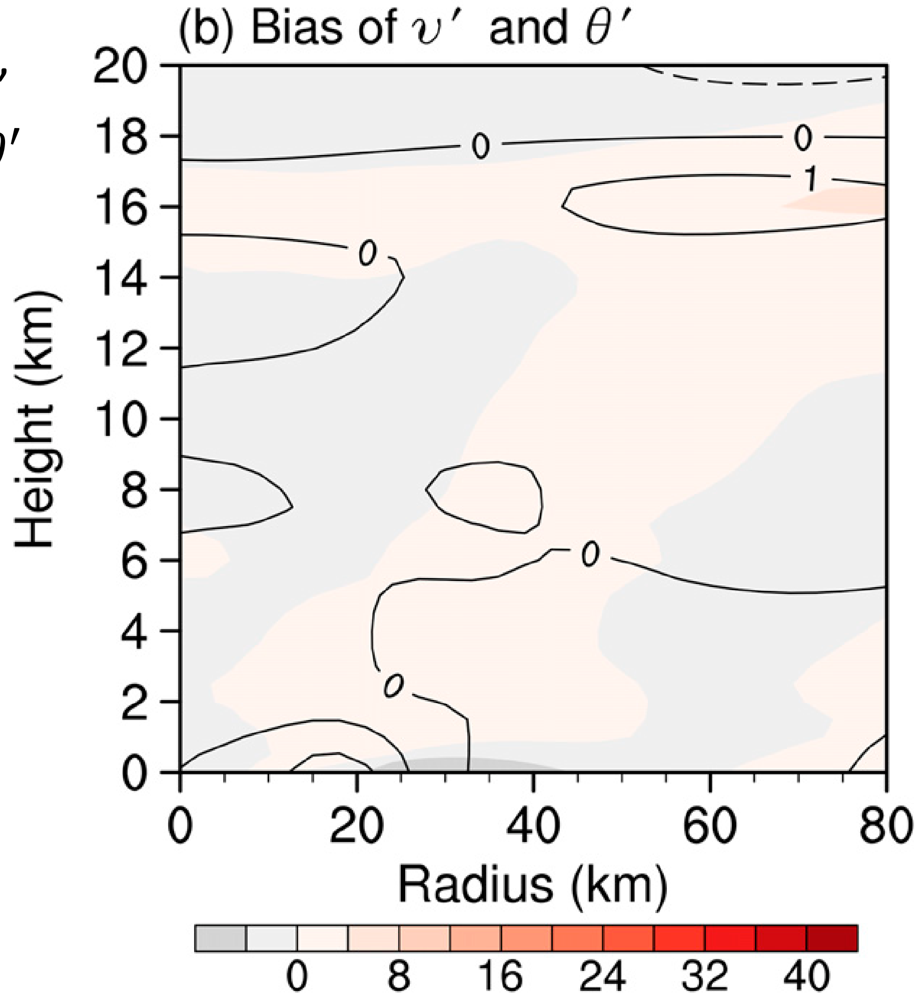
Verification of PPVI

Summation of the inversions of 4 PVAs – the inversions of total PVAs

Polt: P’



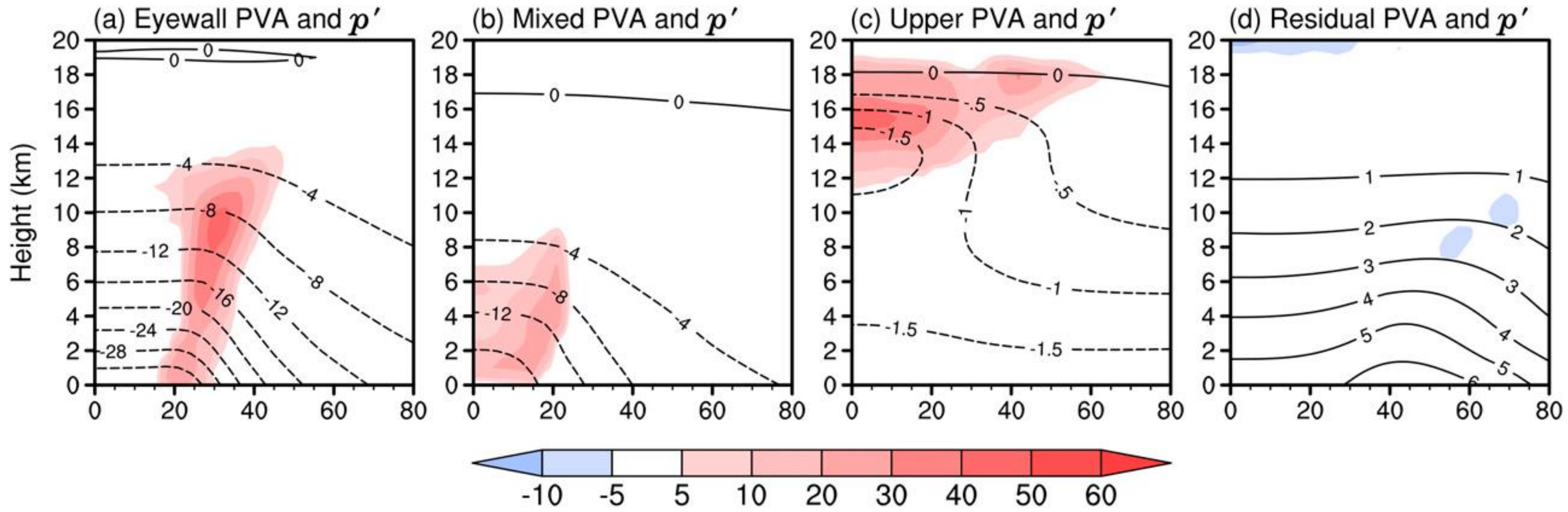
Colored: v’
Contour: θ'



PPVI analysis

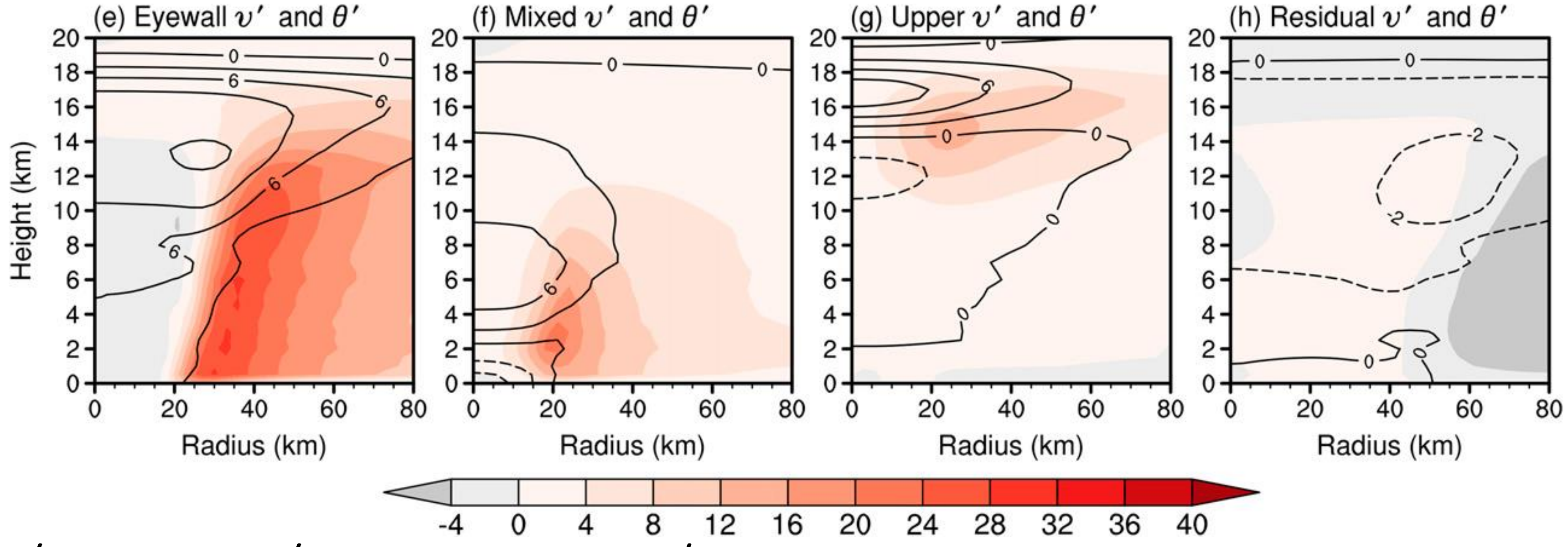
Eyewall PVA | Mixed PVA | Upper core PVA | RSL PVA

Axisymmetric view:
Colored: total PVA
Contour: p’



Total p’: -48 hPa -32 hPa -16 hPa -1.5 hPa + 6 hPa

Axisymmetric view:
Colored: v’
Contour: θ'



Total v’: +34 m/s +24 m/s +20 m/s

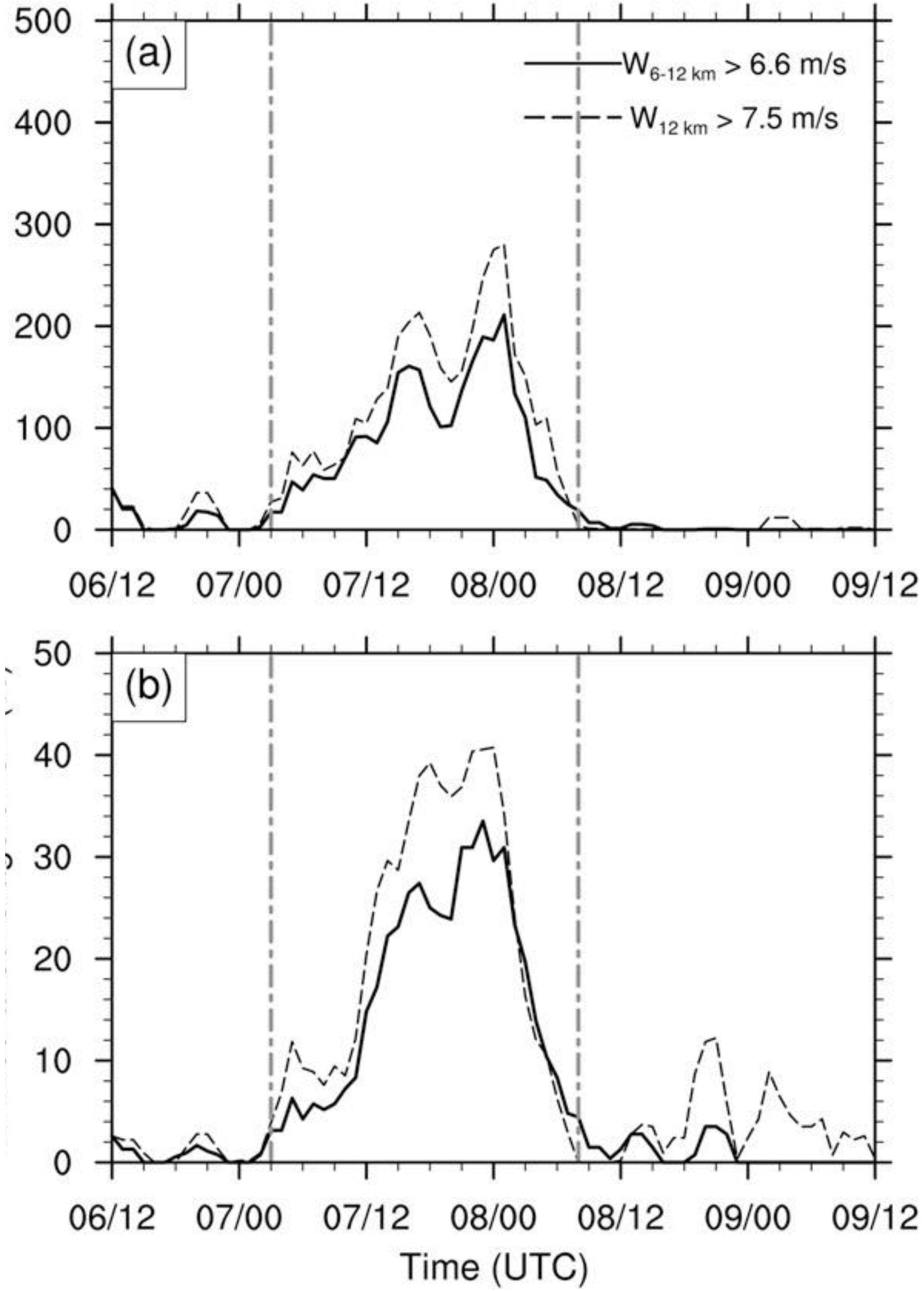
CB in eyewall PVA

$w_{12km} > 7.5\ m/s$ (solid line)

$w_{6-12km} > 6.6\ m/s$ (dashed line)

CB number

Azimuthal coverage of CB (%) (r = 20 ~ 40 km)



The pattern of CB selected by 2 criterion were similar.
The number of CBs were large during RI period only.

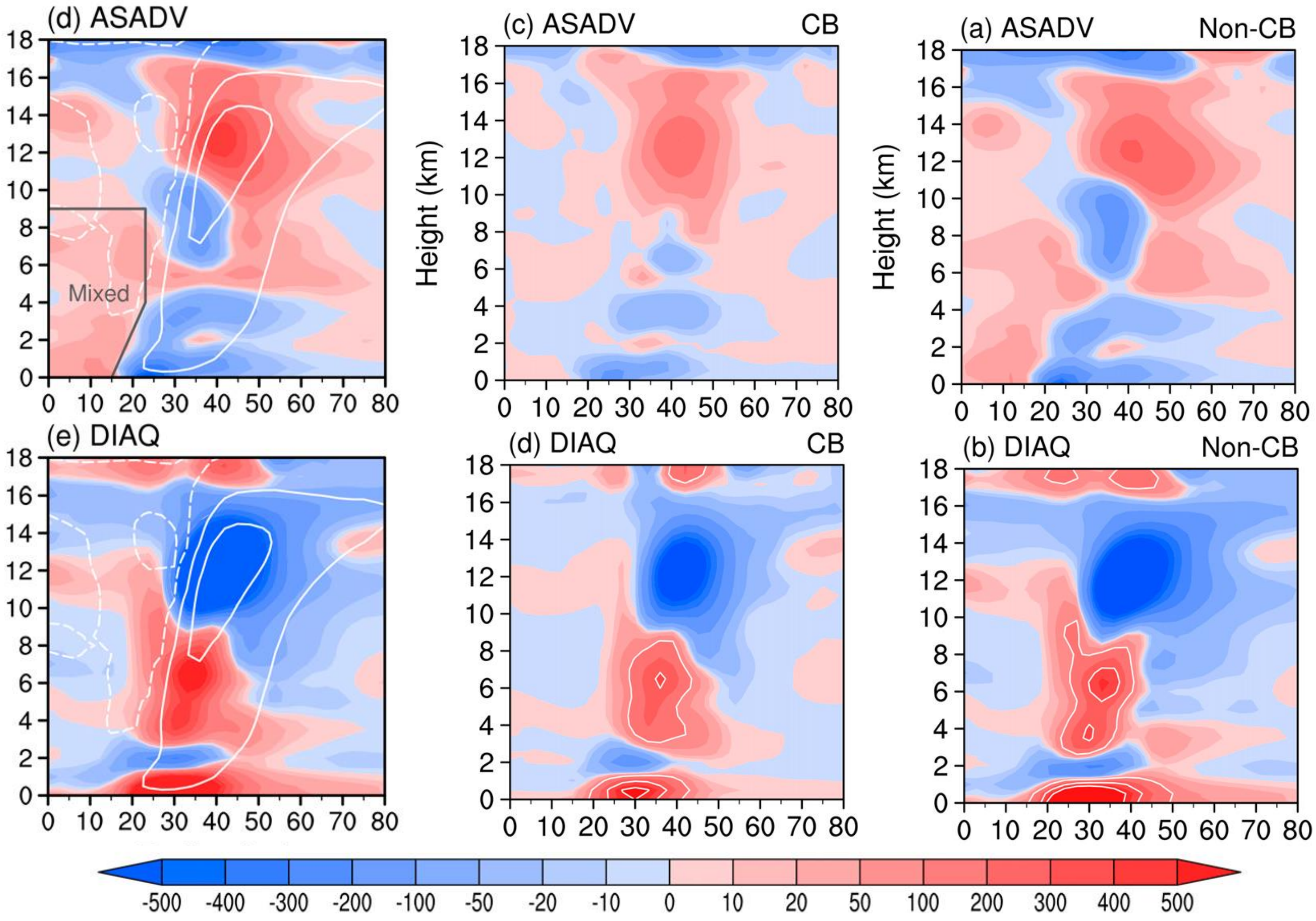
CB criteria: $w_{6-12km} > 6.6\ m/s$

Colored: each term of PV equation

Contour: 100, 300, 500 PVU

(Time average from 07/03Z to 08/08Z)

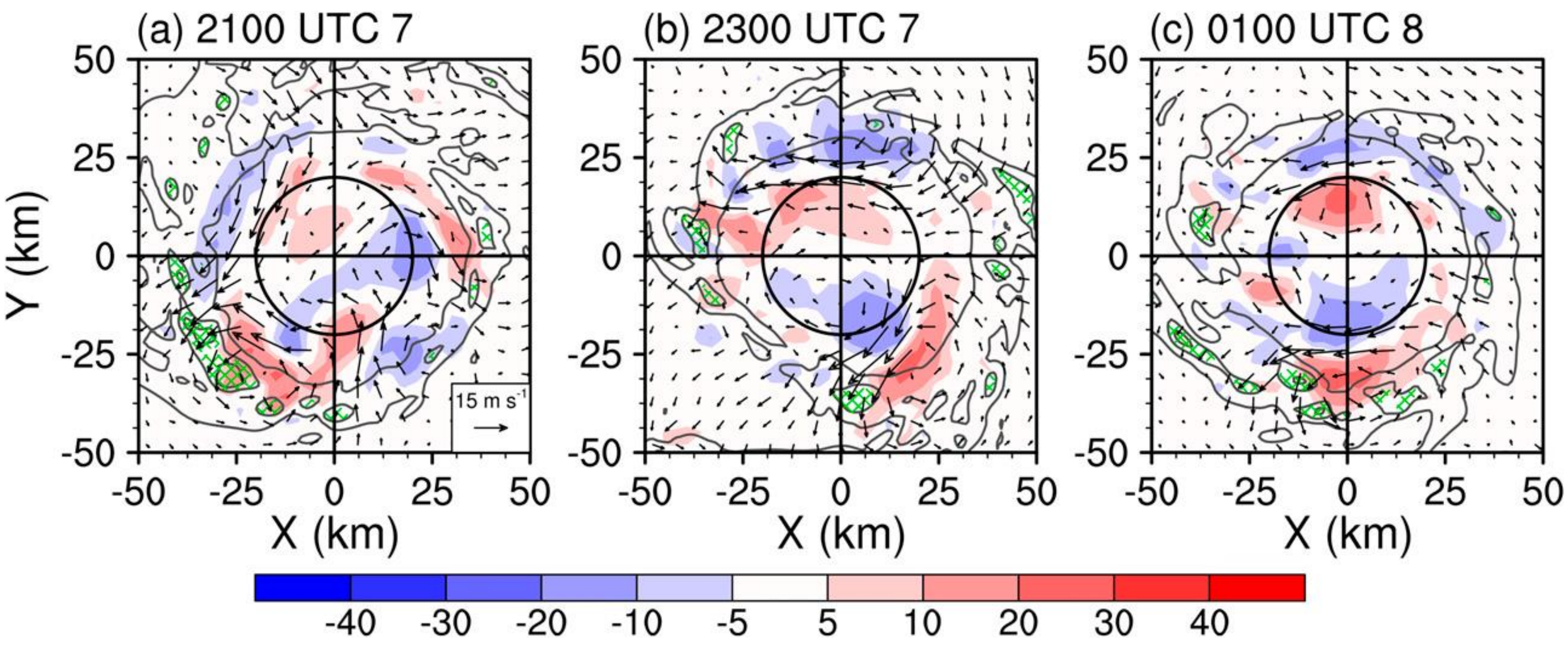
Although the mean CB coverage is only 16% during RI, CB DIAQ is comparable in magnitude to the non-CB DIAQ.



CB in eyewall PVA

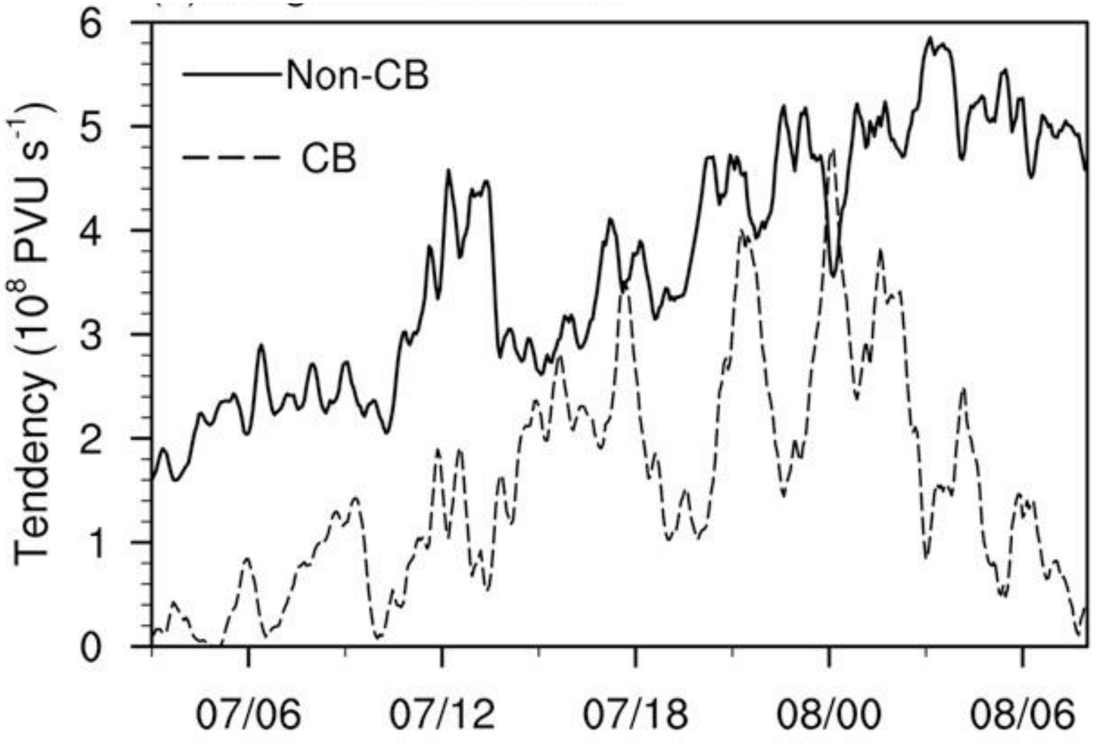
Asymmetric component:
Colored: PV
Vector: wind
Hatches: CB location
(z = 0 ~ 2 km)

Contour: diabatic heating
(z = 6 ~ 12 km)

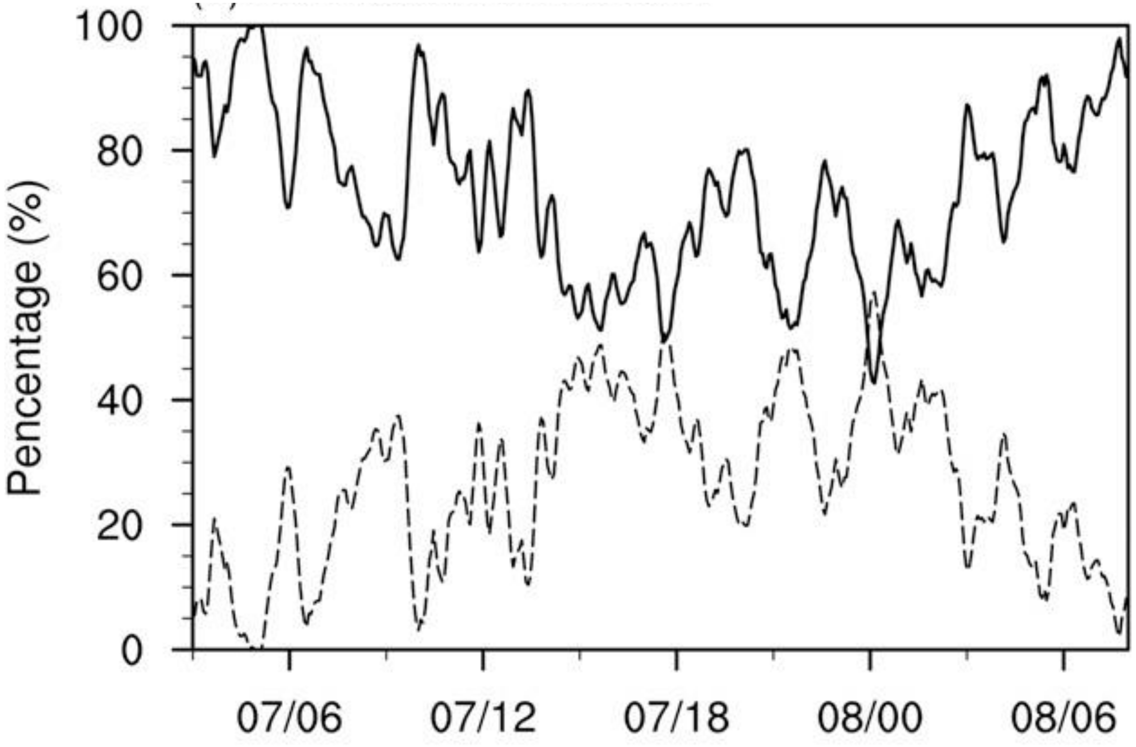


DIAQ contribution of CB in eyewall PVA

Integrated DIAQ
(z = 0 ~ 12 km)
(r = 20 ~ 40 km)



Normalized contribution
Non-CB
CB



CB coverage: 16%   DIAQ contribution of CB: 27%

Conclusions and discussions

- Typhoon Lekima (2019) experienced RI and became a strong typhoon. Double warm-core structure existed after RI. The hydrostatic equation indicated that the surface pressure fall by warm core at $z > 10$ km was twice as much as that warm core at $z < 10$ km.

- PVA formation by PV analysis:
    1. Eyewall PV: eyewall diabatic heating and advection of eyewall updraft.
    2. Mixed PV: the asymmetric mixing by the eyewall mesovortices.
    3. Upper warm core PV: intrusion of the PV from the lower stratosphere.

- PV inversion indicates that the unbalanced dynamics is important to the surface pressure fall during early RI period (50%), while the TC evolves into a quasi-balanced state during the late RI Period (90%).

Conclusions and discussions

- PPVI analysis:
  1. TC intensification is mainly driven by eyewall PVA and mixed PVA.
  2. θ' is maximized (warm core) at z = 10 ~ 17 km and z = 4 ~ 10 km.
  3. Surface pressure fall induced by eyewall PVA is twice to that by mixed PVA.
  4. Upper warm core PVA enhanced upper-level tangential wind and warm core, but induced cooling below the PVA. The pressure fall were canceled.

- The contribution of CBs to RI:
  1. Asymmetric winds by CBs contribute little to the inward PV mixing
  2. CBs has higher efficiency in generating eyewall PV.
  3. CBs were not the main contribution of eyewall PV (27% only).

Conclusions and discussions

- The RI of Lekima is driven by the eyewall diabatic heating and the asymmetric PV mixing.

- The role of upper warm core PVA:

  The eyewall heating
  → generate PV
  → transported upward by the secondary circulation
  → spinups and vertical extends the primary circulation
  → extends into low stratosphere
  → forces downdrafts
  → brings high θ and PV to upper eye
  → induces thermal wind balance
  → enhances upper warm core and cools the layers under UWC
  → cancels the surface pressure fall.