# Outer Rainbands–Driven Secondary Eyewall Formation of Tropical Cyclones

YI-FAN WANG AND ZHE-MIN TAN

*School of Atmospheric Sciences, Nanjing University, Nanjing, China*

(Manuscript received 28 October 2019, in final form 6 April 2020)

# Introduction

- Secondary eyewall formation (SEF) is defined as the codevelopment of a **convective ring** beyond the primary eyewall and an **secondary tangential wind maximum**. 70% of rainband outside the primary eyewall without collocated the wind maxima, indicating that formation of wind maximum and convective ring have different dynamical pathway. (Samsury and Zipser, 1995)

- SEF is closely related to outer rainbands (ORBs). Stratiform heating at downwind end of ORBs can trigger asymmetric descending inflow in boundary layer (BL), which reinforces BL convergence, enhances convection, and spins up tangential wind. (Qiu and Tan, 2013) It is supported by observations (Didlake et al., 2018) and numerical simulation (Yu and Didlake, 2019).

Outer rainbands (ORBs): Position outside 3 × RMW
Inner rainbands (IRBs): Position inside 3 × RMW

Radius of maximum wind (RMW)

# Introduction

- The spinup of secondary tangential wind in associated with unbalanced BL process. Broaden wind field -> increase BL inflow -> cause supergradient flow at upper portion of BL -> decelerate inflow -> reinforce BL convergence. The initiative unbalanced BL process and when and where to SEF are uncleared. (Huang et al., 2012)

- Questions investigated in this paper:
  - Are the ORBs essential for SEF?
  - What is the dynamical process of the interaction between ORBs and BL that cause SEF (convective ring and tangential wind maximum)?

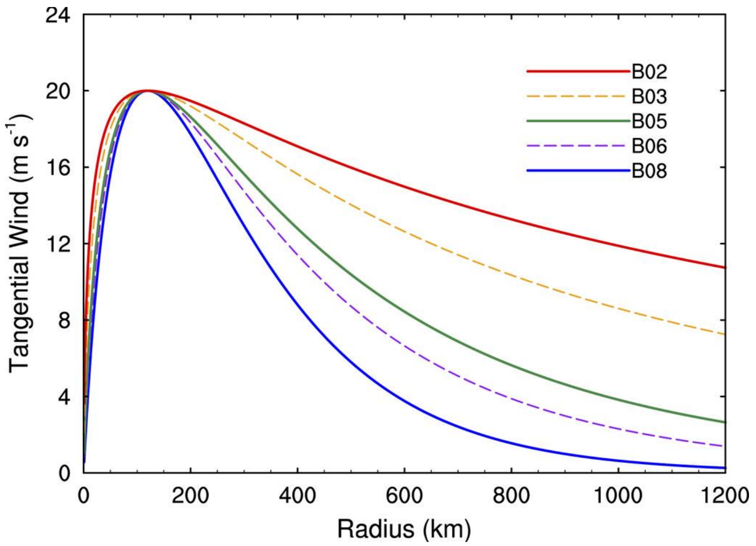
# Methodology

## WRF Configuration

- Idealized WRF v3.8.1
- Domain: 18, 6, 2 km (301, 181, 301 grids per dim)
- B.C.: Symmetric
- Vertical levels: 45 half-sigma levels (10 levels are below 1.5 km height)
- Parameterization:
    - Thompson (microphysics)
    - MYJ (boundary layer)
    - RRTM (longwave)
    - Goddard (shortwave)
    - Kain-Fritch (cumulus, 18- and 6-km only)

- 2-km domain is vortex-following.

# Methodology
## Experiment



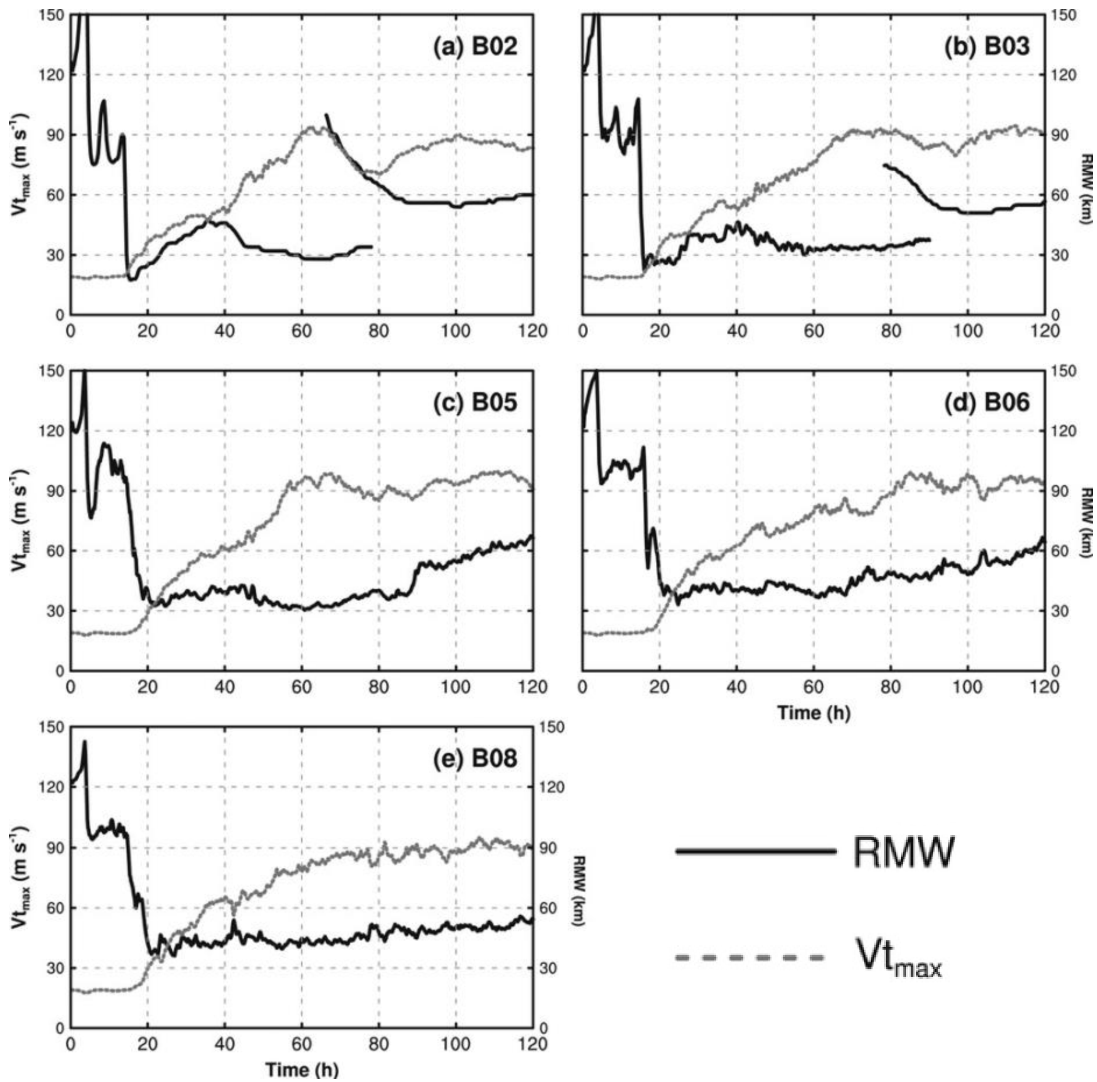

- Environment:
  - f-plane at 20°N
  - constant SST 28°C
  - The mean Caribbean sounding during hurricane seasons

- Vortex profile:
  - $V(r) = v_{max}\left(\frac{r}{r_{max}}\right)\exp\left(\frac{1}{b}\left[1-\left(\frac{r}{r_{max}}\right)^{b}\right]\right)$ (axisymmetric)
  - $v_{max}$: maximum tangential wind, 20 m/s
  - $r_{max}$: RMW, 120 km
  - $b$: lapse rate of tangential wind, **0.2**, 0.3, **0.5**, 0.6, **0.8**
  - Experiment name: **B02**, B03, **B05**, B06, **B08**

# Overview of SEF in the Experiment

Evolutions of Size, Intensity, and Rainbands

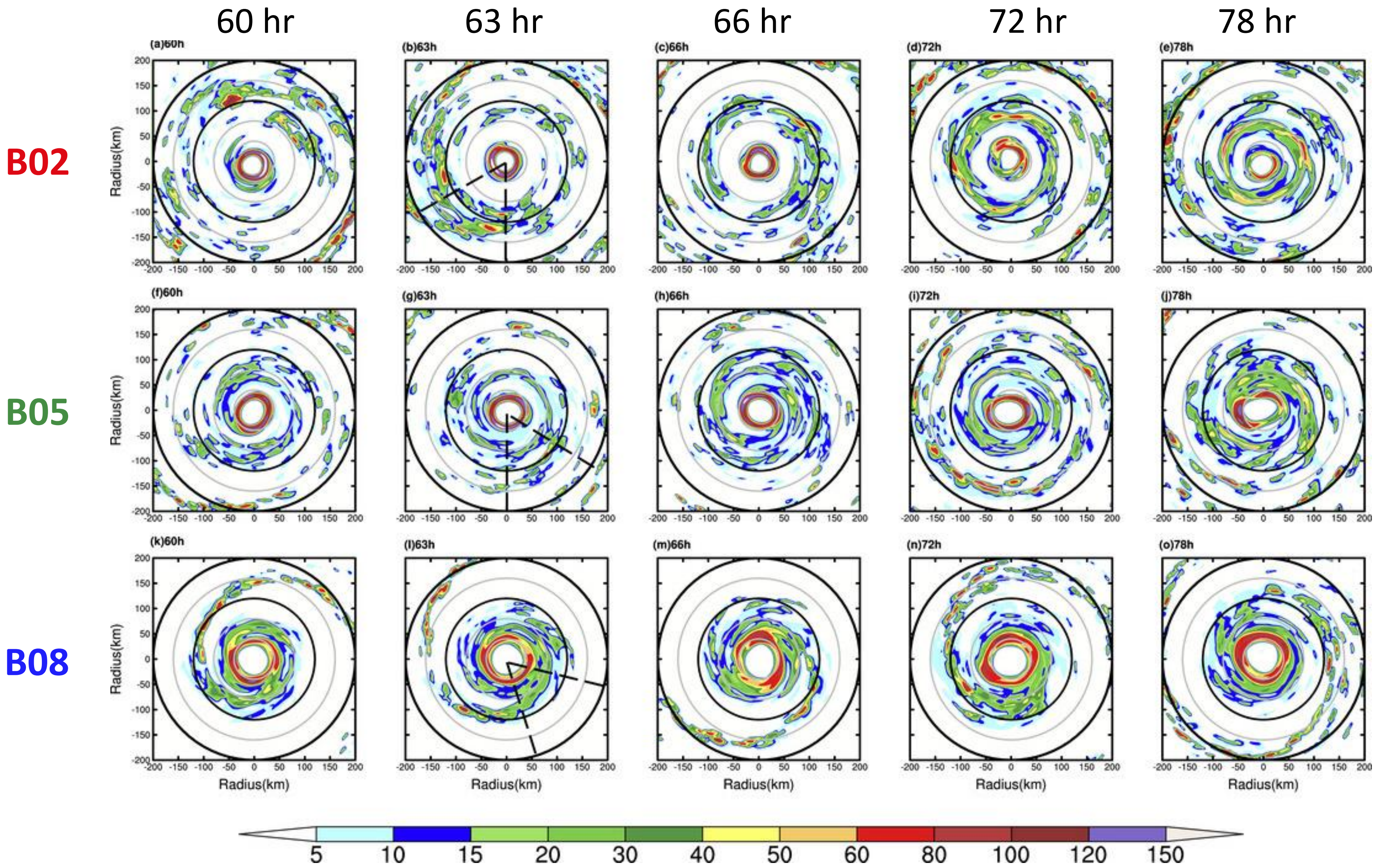
1 ~ 2 km height



Plot domain: 400 x 400 km

Color: Surface Rain Rate (mm/hr)

Concentric circles: 40, 80, **120**, 160, **200** km

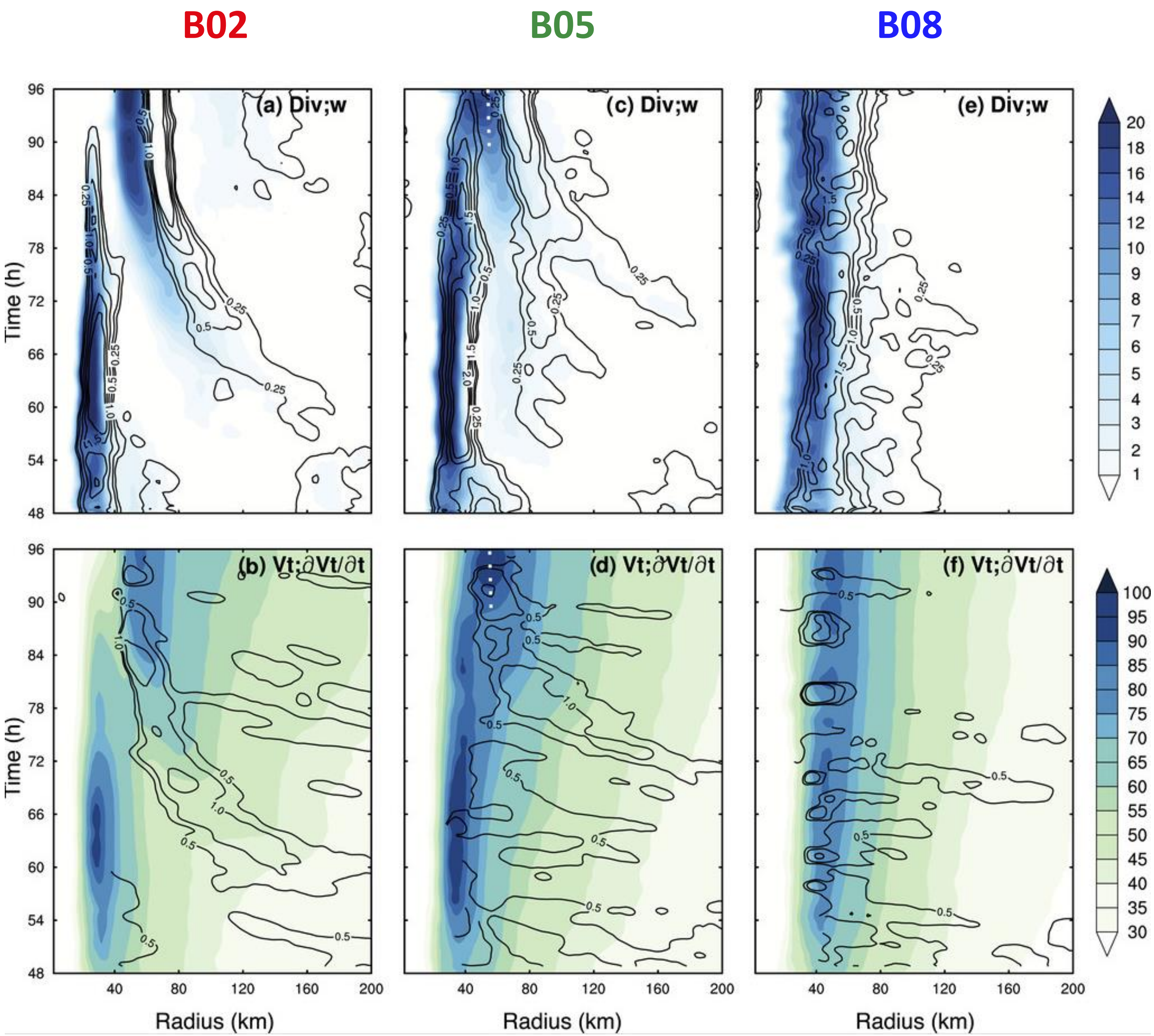


# Evolutions of Axisymmetrice Storm Structures

Hovmoller diagram
Azimythal-mean

Color: BL div
Contour: 5-km w

Color: 1-km v
Contour: 1-km $\frac{\partial v}{\partial t}$



Azimuthal-mean

63 hr

66 hr

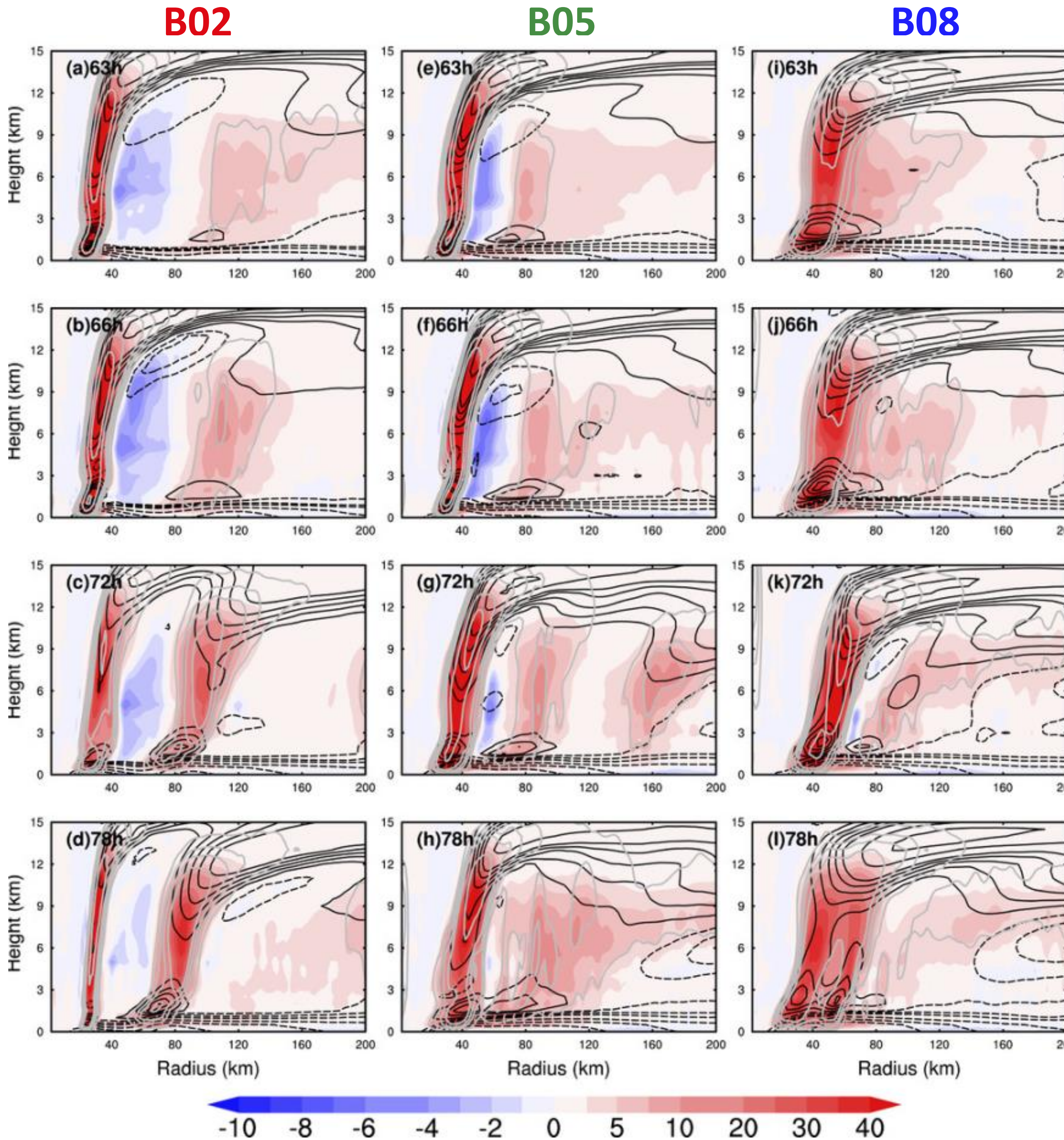
Color: diabatic Heating

Contour: black u

grey  w

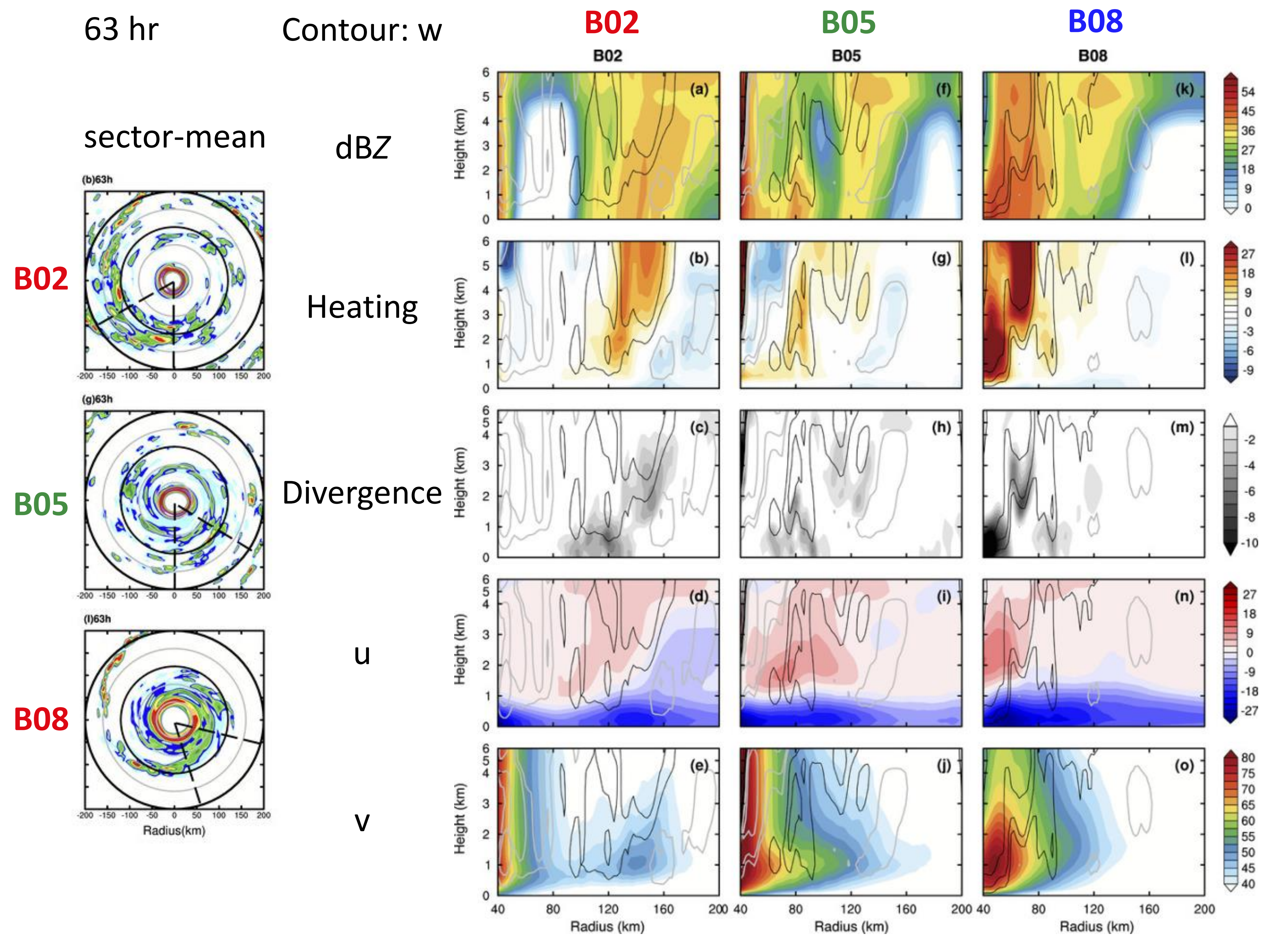
72 hr

78 hr




B02 3 stages of SEF:

1. 60~66 hr: asymmetric
2. 66~72 hr: local inflow
3. 72~ hr: mature stage


63 hr
Contour: w
sector-mean
dBZ
Heating
Divergence
u
v
B02
B05
B08
(b)63h
(g)63h
(l)63h
Radius(km)
Height (km)
Radius (km)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)

# AGF Analysis

$$AGF = \underbrace{-\frac{1}{\rho}\frac{\partial P}{\partial r}}_{PGF} + \underbrace{fv + \frac{v^2}{r}}_{CFS}$$

sector-mean

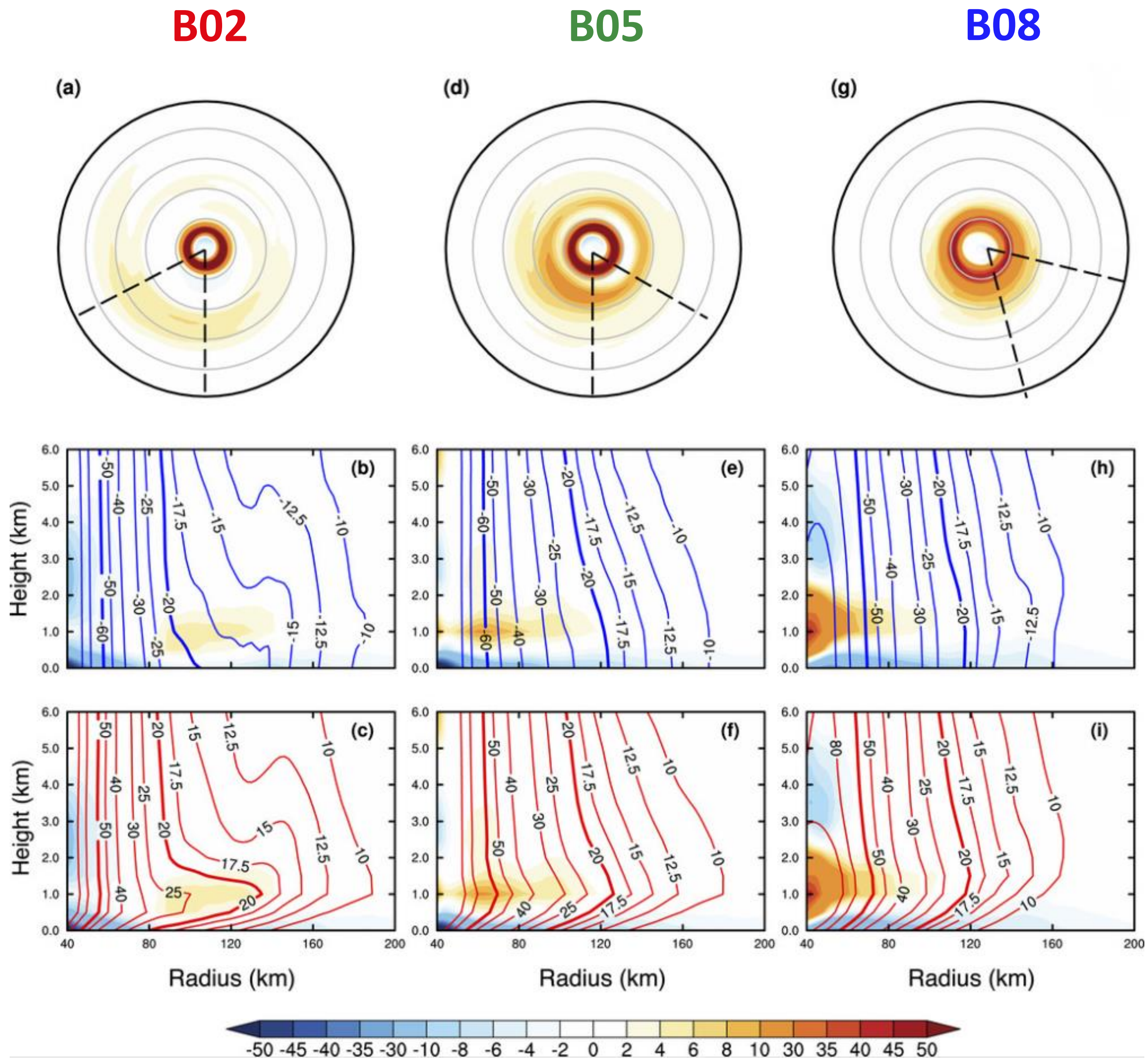
*PGF*

AGF > 0 supergradient outflow

AGF < 0 subgradient inflow

*CFS*

*Color AGF*



# A Brief Summary

- Early Stage of SEF:
  - Asymmetric **ORBs** arouse **inflow maximum** and **tangential wind maximum**, collocated with ORBs.
  - Asymmetric ORBs arouse **BL convergence** and **supergradient force** at the radially inward side of ORBs.
  - AGF weakens the inflow and causes relative stagnated rainbands radially.
  - The convection is extended downwind by the tangential flow, facilitating axisymmetrization.

# Developing Stage of SEF

## Spinup of Tangential Wind Within and Abobe BL

$$\frac{\partial \bar{v}}{\partial t} = -\overline{u(\zeta + f)} - \overline{w\frac{\partial v}{\partial z}} + \bar{F}_{\lambda}$$

Tangential wind tendency

Radial advection of vorticity

vertical advection of tangential wind

diffusion

Diffusion: friction and vertical mixing

# Developing Stage of SEF

## Spinup of Tangential Wind Within and Abobe BL

66~72 hr average

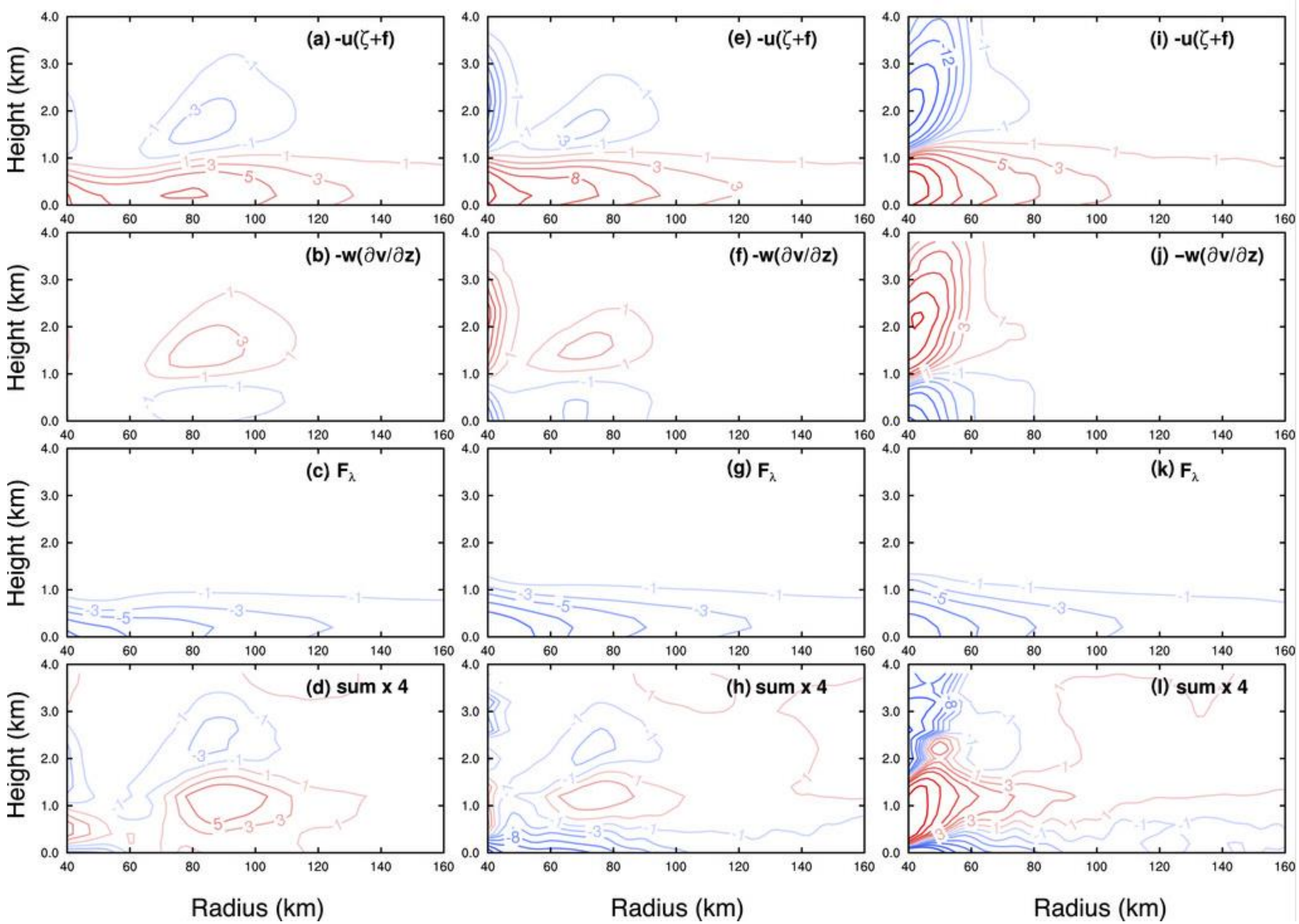
**B02** **B05** **B08**

$-\overline{u(\zeta + f)}$

$-\overline{w\frac{\partial v}{\partial z}}$

$\overline{F_\lambda}$

$4 \times \frac{\partial \bar{v}}{\partial t}$



# Developing Stage of SEF

## Spinup of Tangential Wind Within and Abobe BL

60h
63h
66h
69h
72h

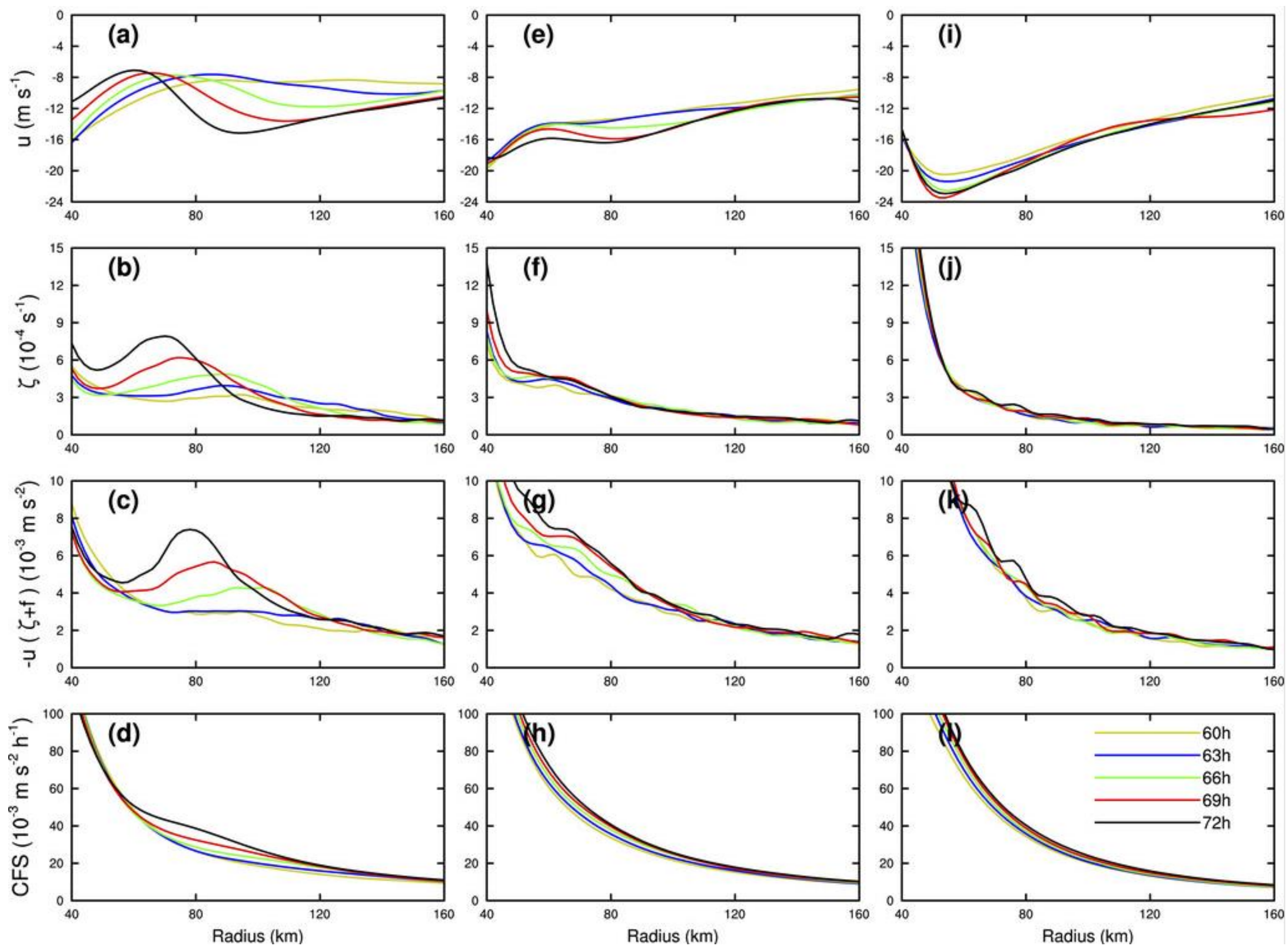
**B02** **B05** **B08**

$u$

$\zeta$

$-\overline{u(\zeta + f)}$

$CFS$

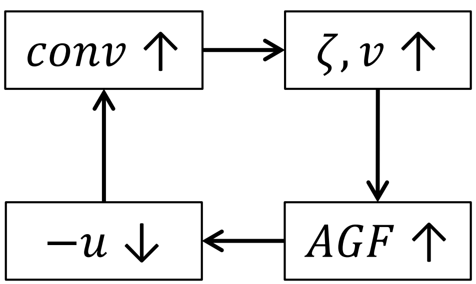


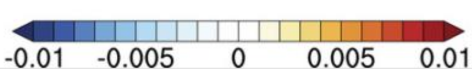
# Developing Stage of SEF

## Increasing AGF Within and Above BL

60~100 km average

--- top of BL

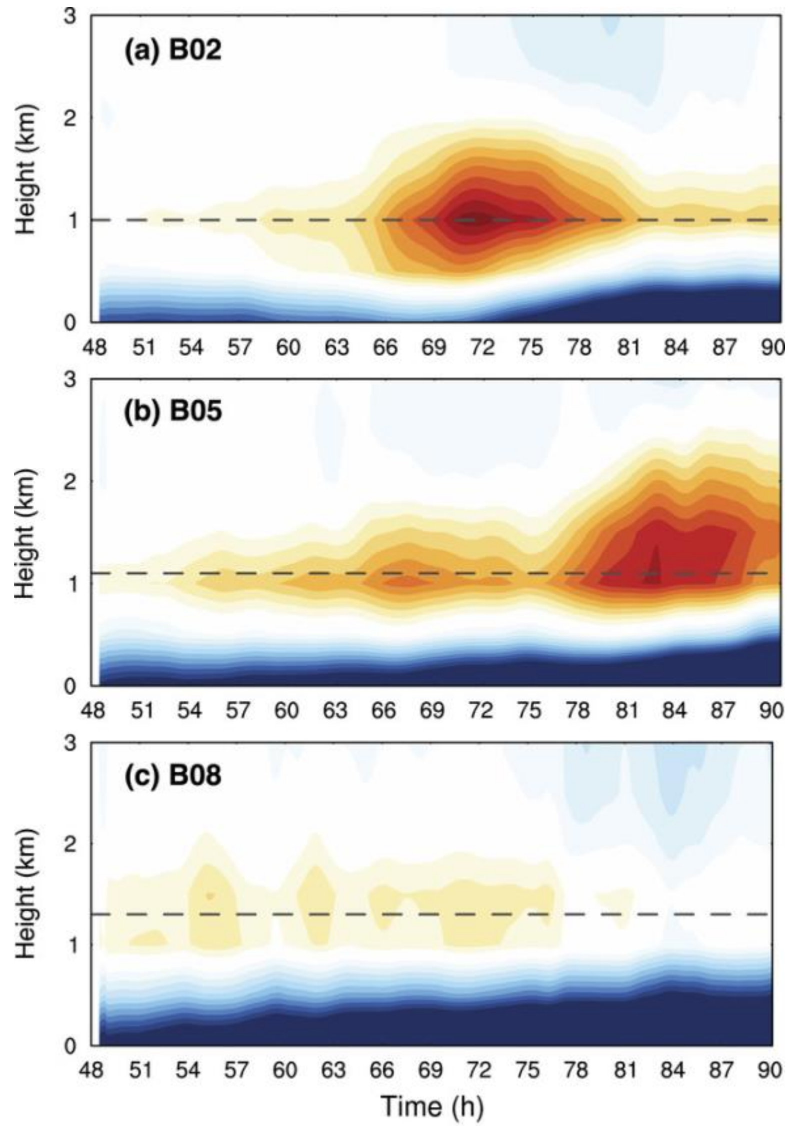



B02

B05

B08



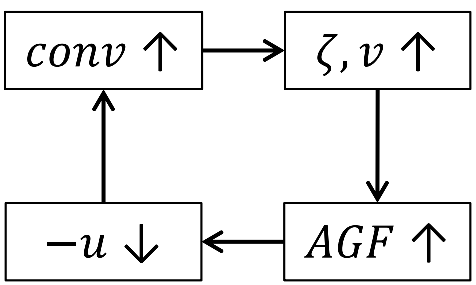
# Establishment of Deep Convection

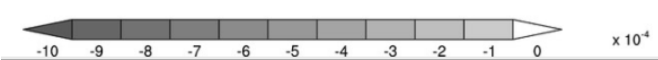
Azimuthal-mean

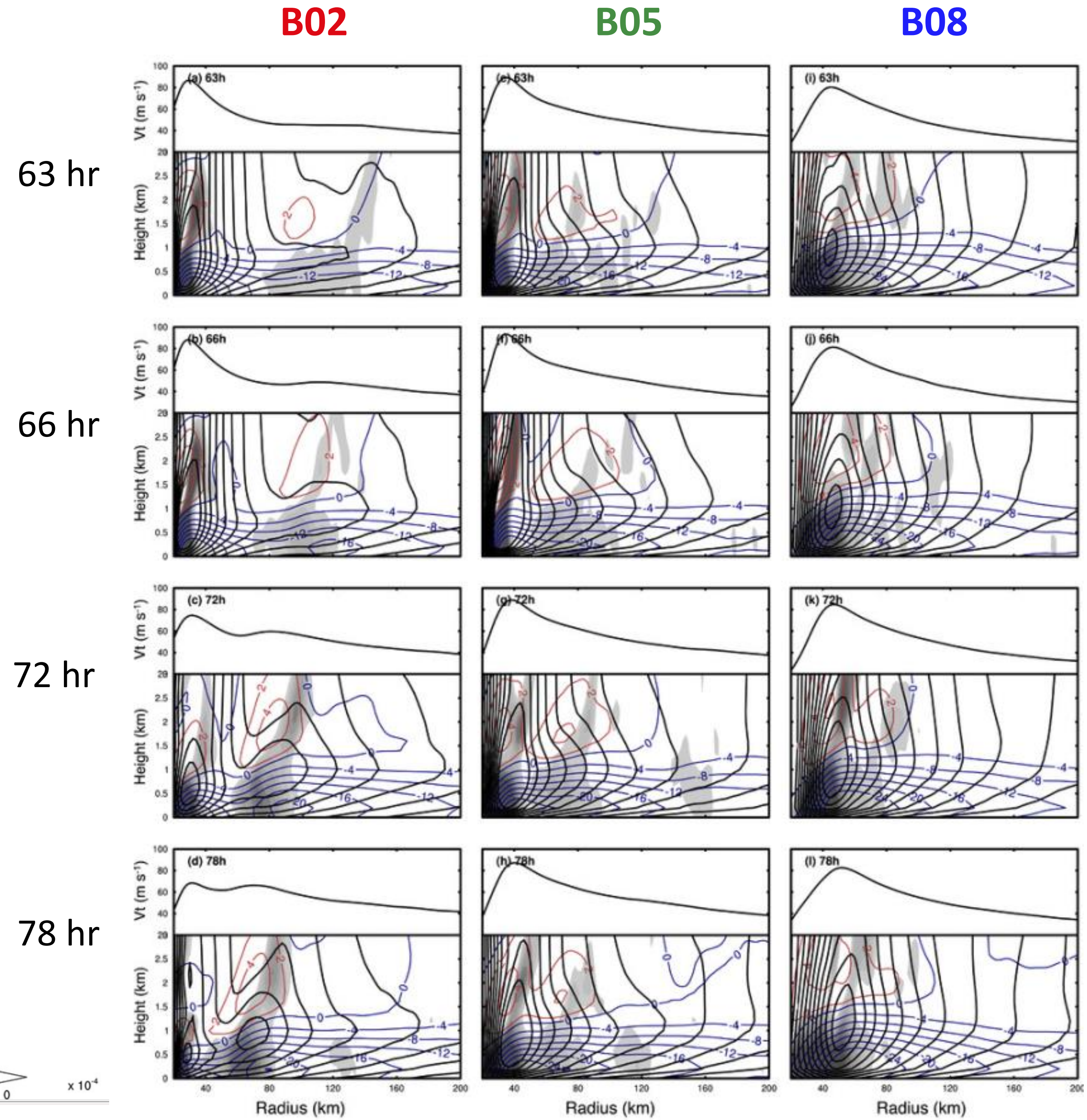
Shading: divergence

Contour: inflow
outflow
v

Line: 1-km v



# Developing Stage of SEF

## Establishment of Deep Convection

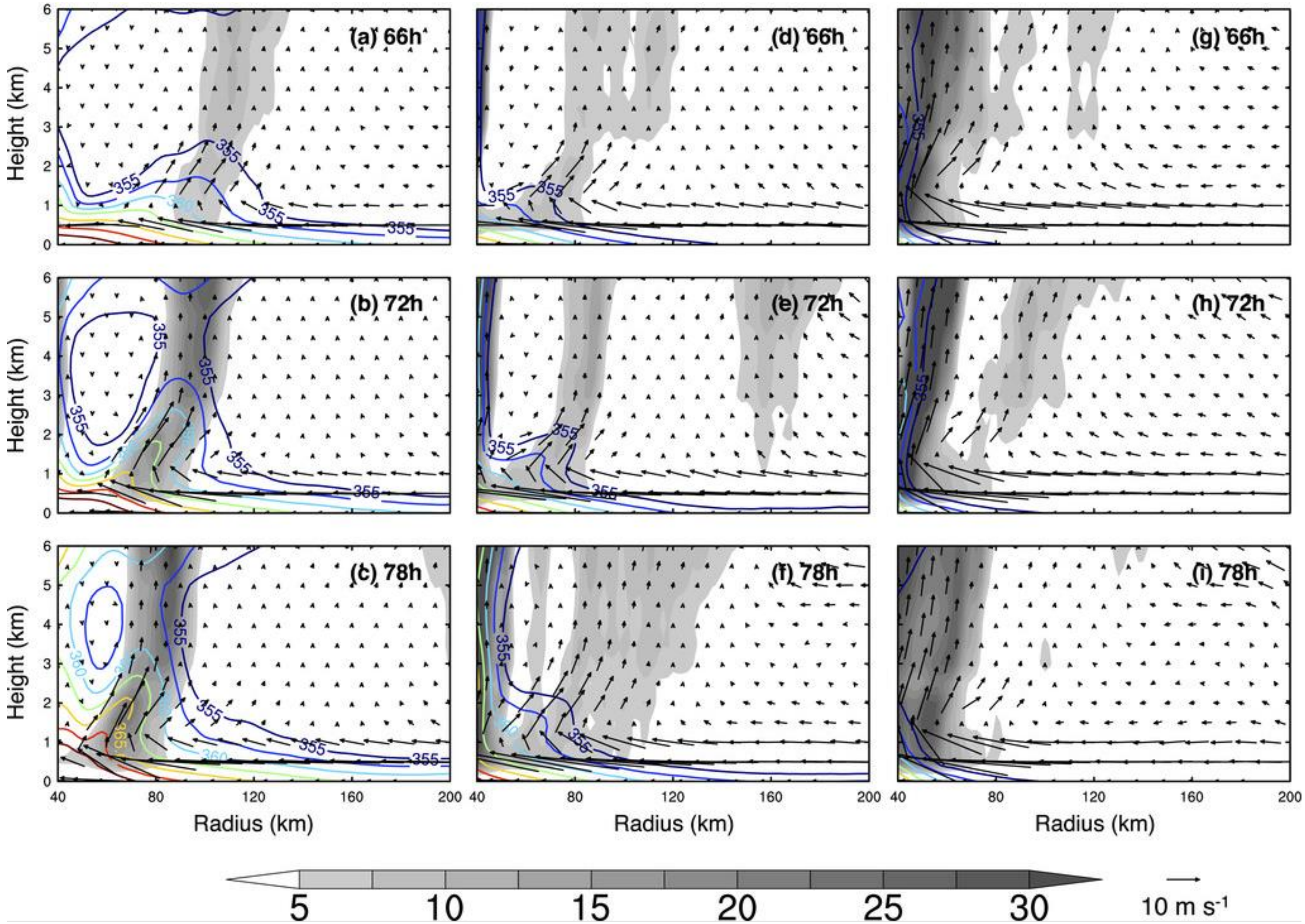
Azimuthal-mean

B02 B05 B08

66 hr

72 hr

78 hr

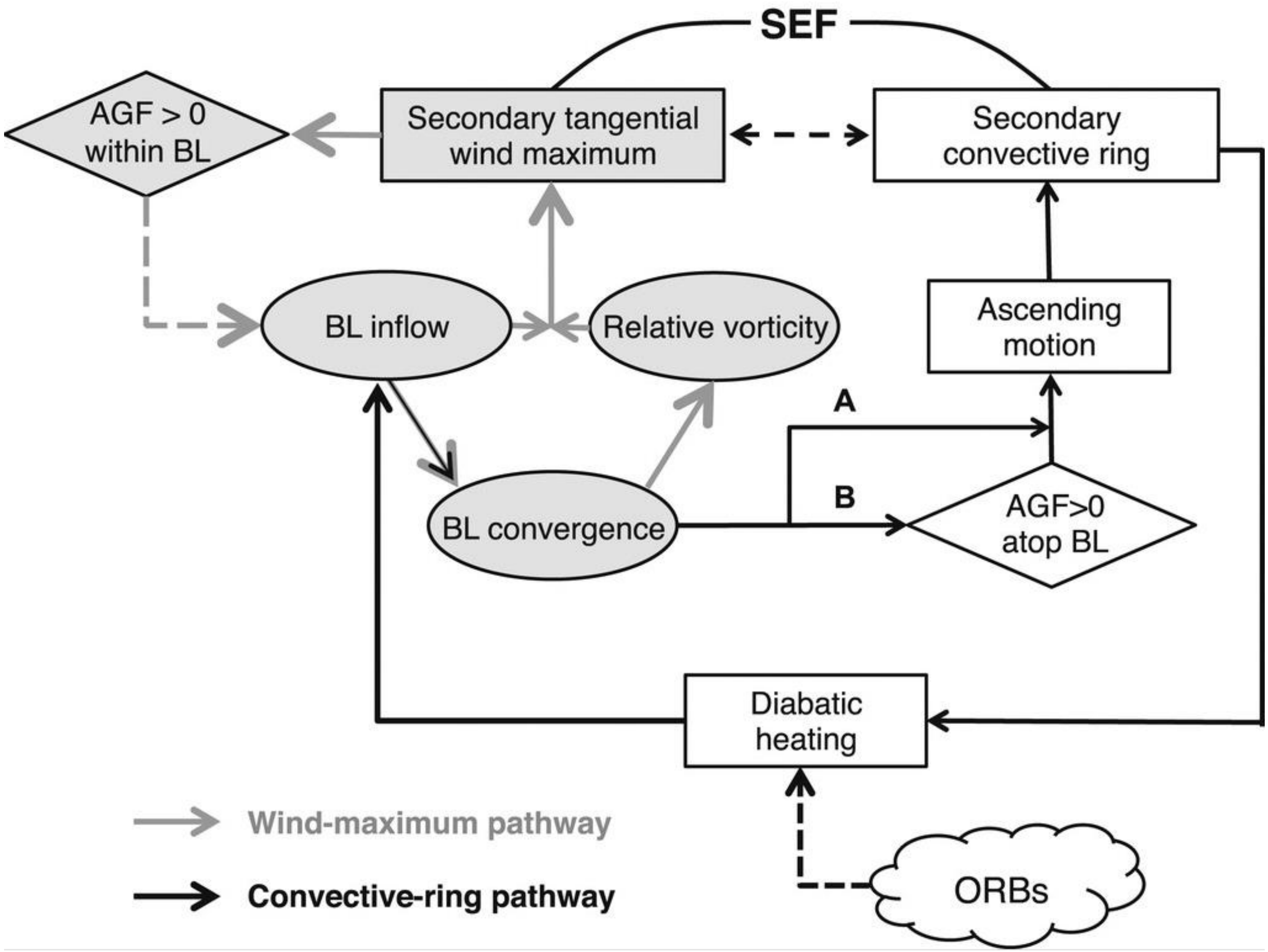



Contour: $\theta_e$

Quiver: $u, w$

Shading: heating

# Discussion


SEF
AGF > 0
within BL
Secondary tangential
wind maximum
Secondary
convective ring
BL inflow
Relative vorticity
Ascending
motion
A
B
BL convergence
AGF>0
atop BL
Diabatic
heating
Wind-maximum pathway
Convective-ring pathway
ORBs

# Conclusions

- This paper investigated SEF process by idealized simulations with altering the decaying rate of initial tangential wind only.

| Initial v | SEF | features |
|---|---|---|
| strong | canonical | v max, convective ring |
| medium | fake | convective ring |
| weak | X | single eyewall |

- The canonical SEF can occur only driven by ORBs. The stratiform heating at the downwind end of ORBs can cause descending inflow and converge in boundary layer, staring the process of SEF which was described above.

- In the case of fake SEF, BL convergence driven by IRBs is weaker, and radial advection of vorticity can not overtake the diffusion. Tangential wind maximum can not be established and convergence can not be enhanced.