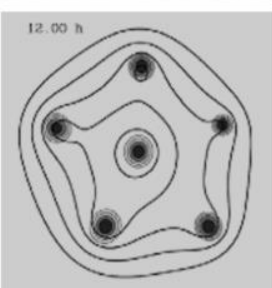
Wavenumber-2 Deep Convection in Tropical Cyclones



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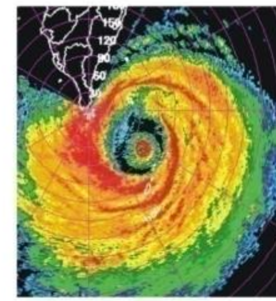
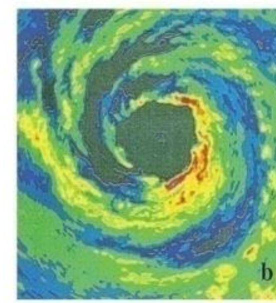
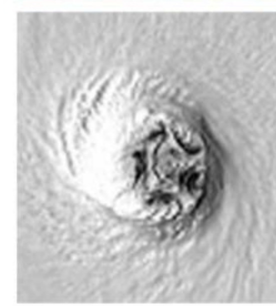


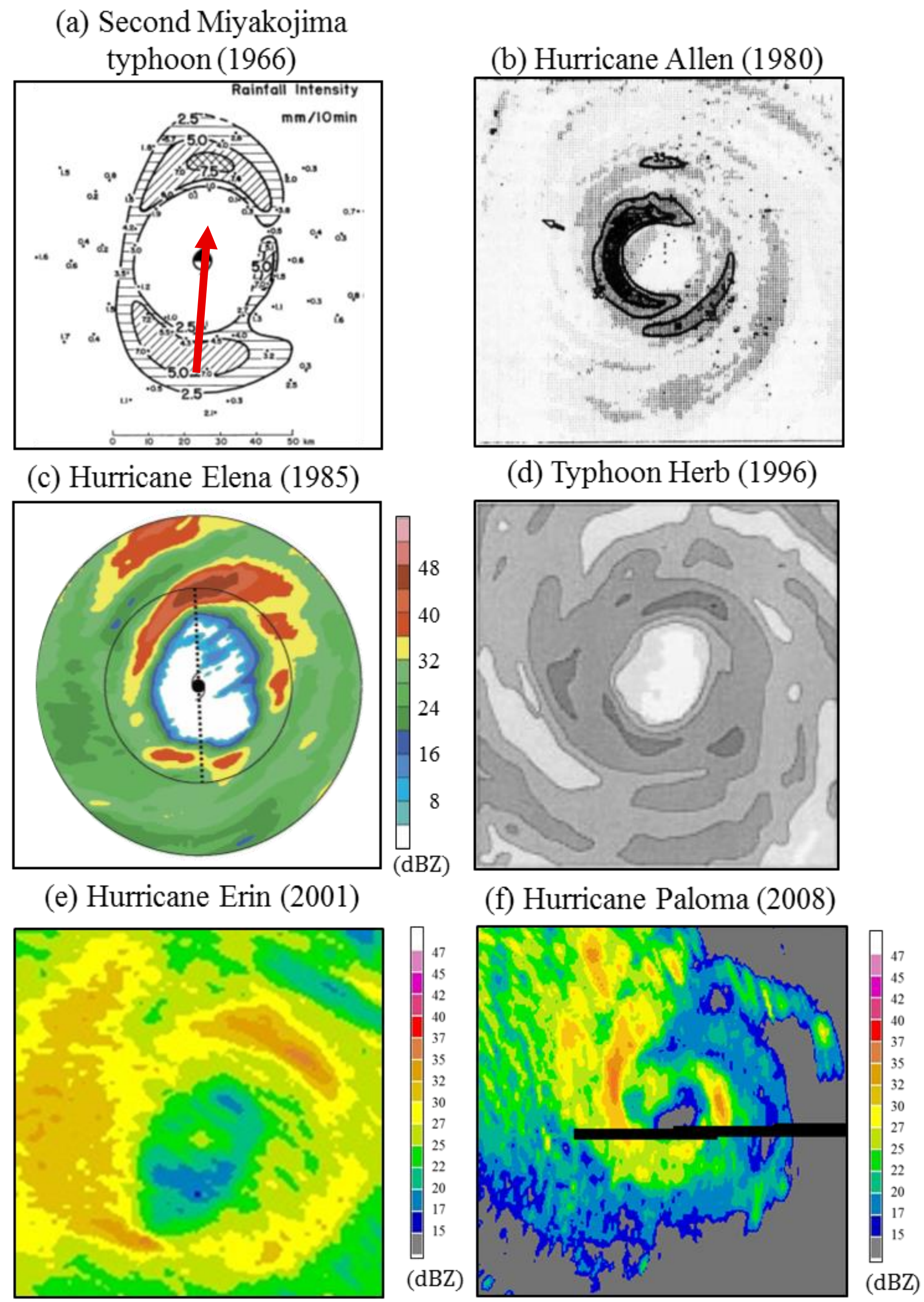




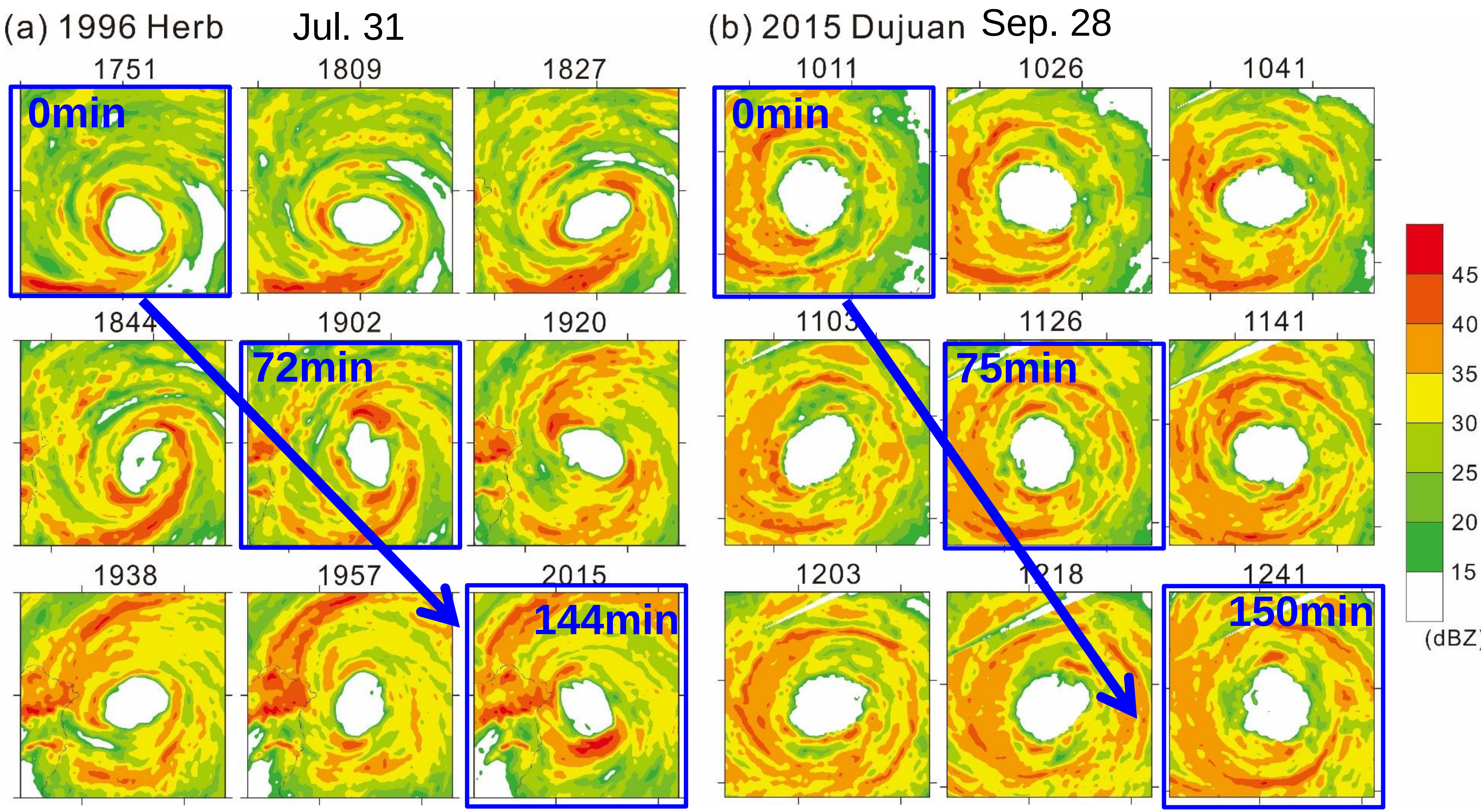
Introduction

Observations

- Deep convection occurs near the tips of the major axis
- Elliptical ring is wider on the major axis and narrower on the minor axis



(a) Mitsuta and Yoshizumi (1973)
(b) Shapiro (1983)
(c) Corbosiero et al. (2006)
(d) Kuo et al. (1999)
(e) (NOAA) WP-3D aircraft at 1749 UTC, 10 Sep. 2001
(f) (NOAA) WP-3D aircraft at 0529 UTC, 7 Nov. 2008



144 min rotation period

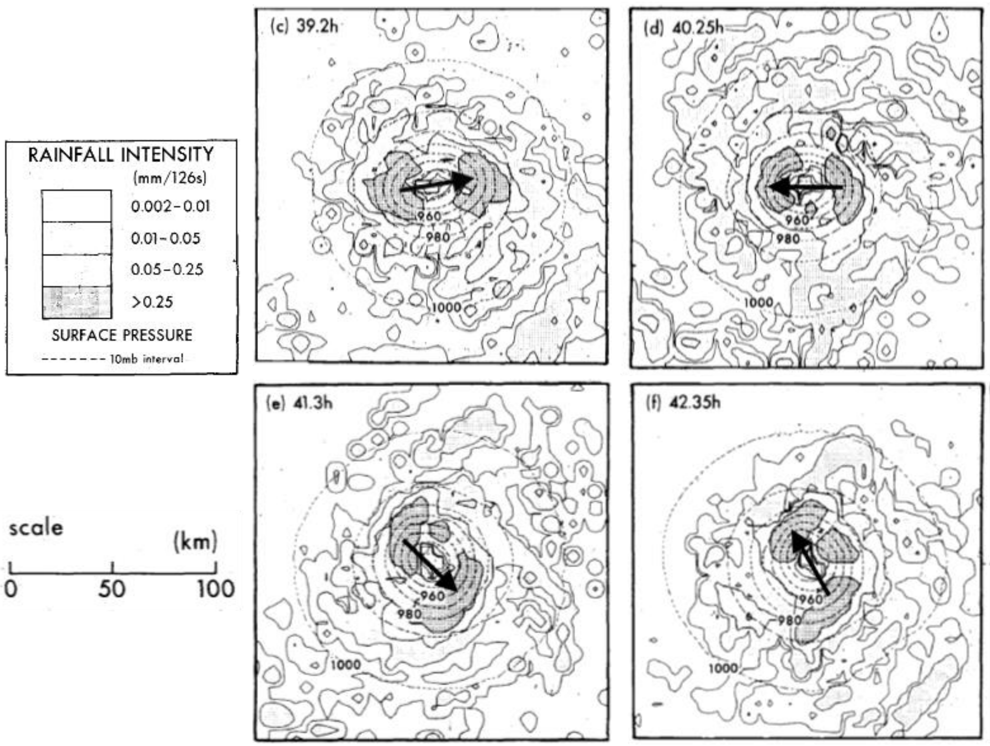
150 min rotation period

(Kuo et al. 1999)

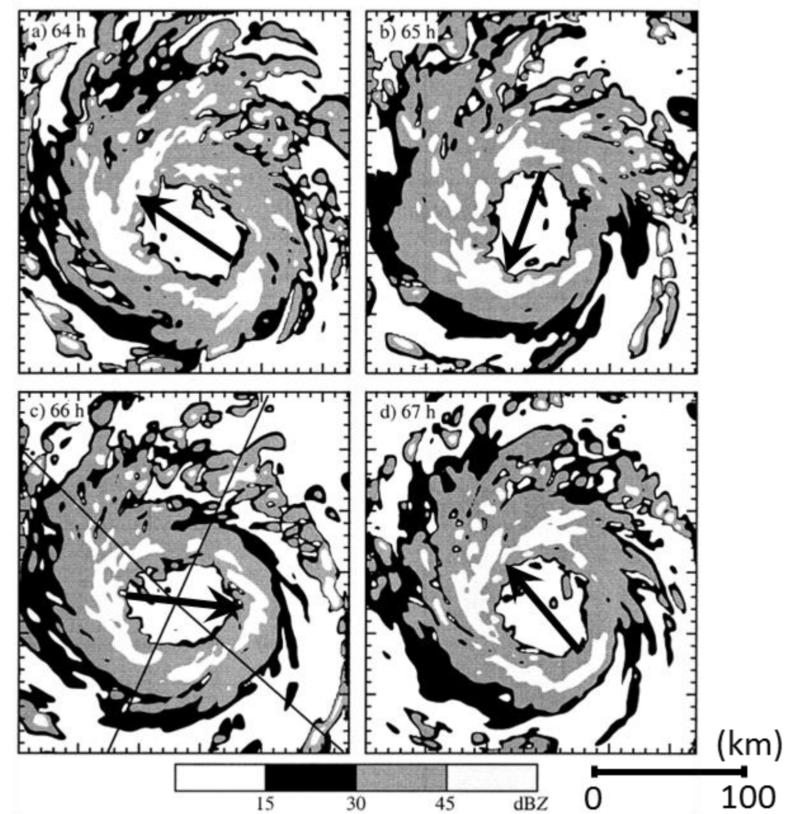
- Deep convection on the tips of major axis in the elliptical vortex
- Cyclonic rotation; slower than the mean tangential flow

Numerical model

(a)



(b)



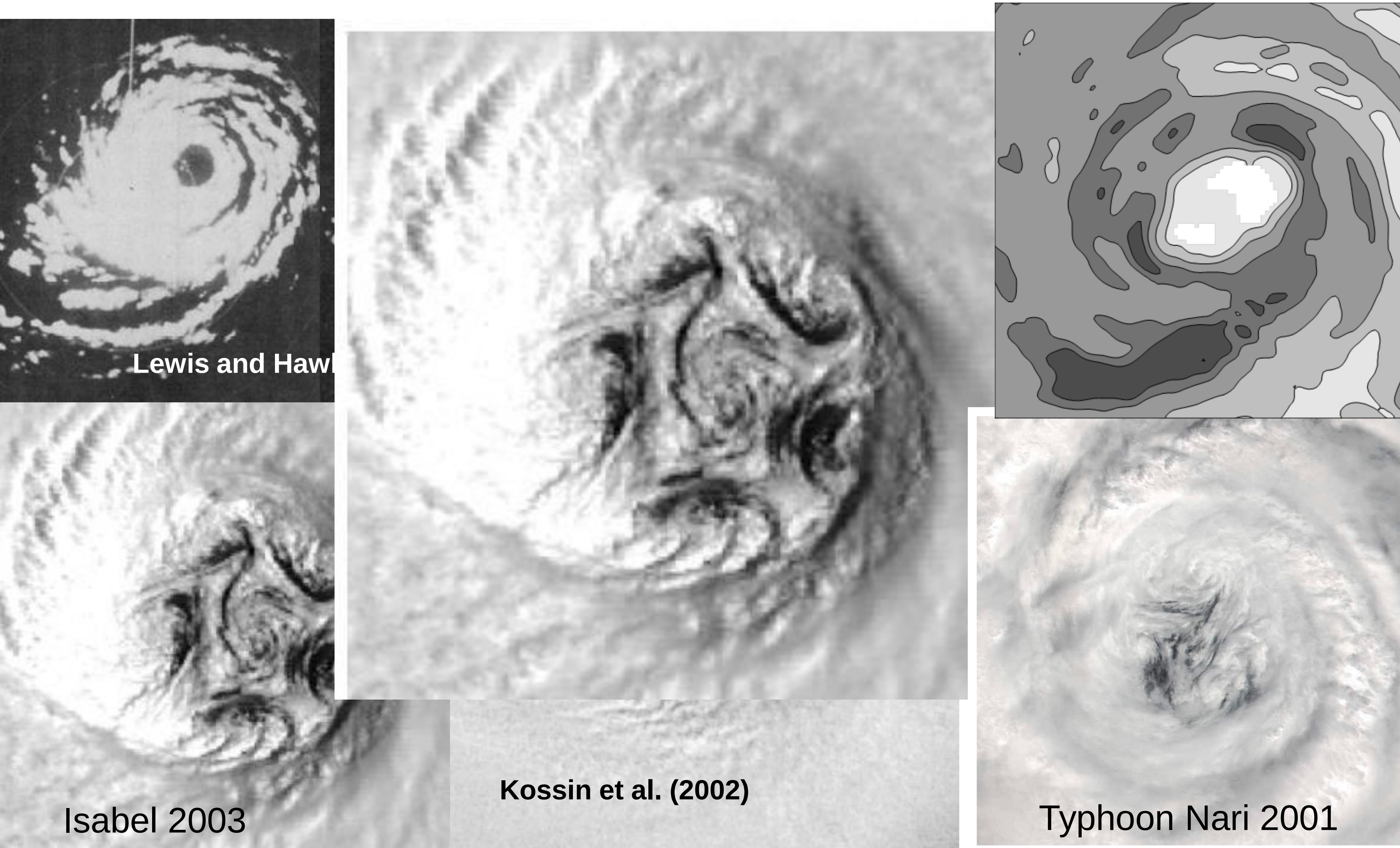
Kurihara and Bender (1982)

Braun (2002)

- Deep convection on the tips of the elliptical vortex
- Cyclonic rotation; slower than the mean tangential flow

Polygonal eyewalls and eye mesovortices in TCs

Typhoon Herb 1996



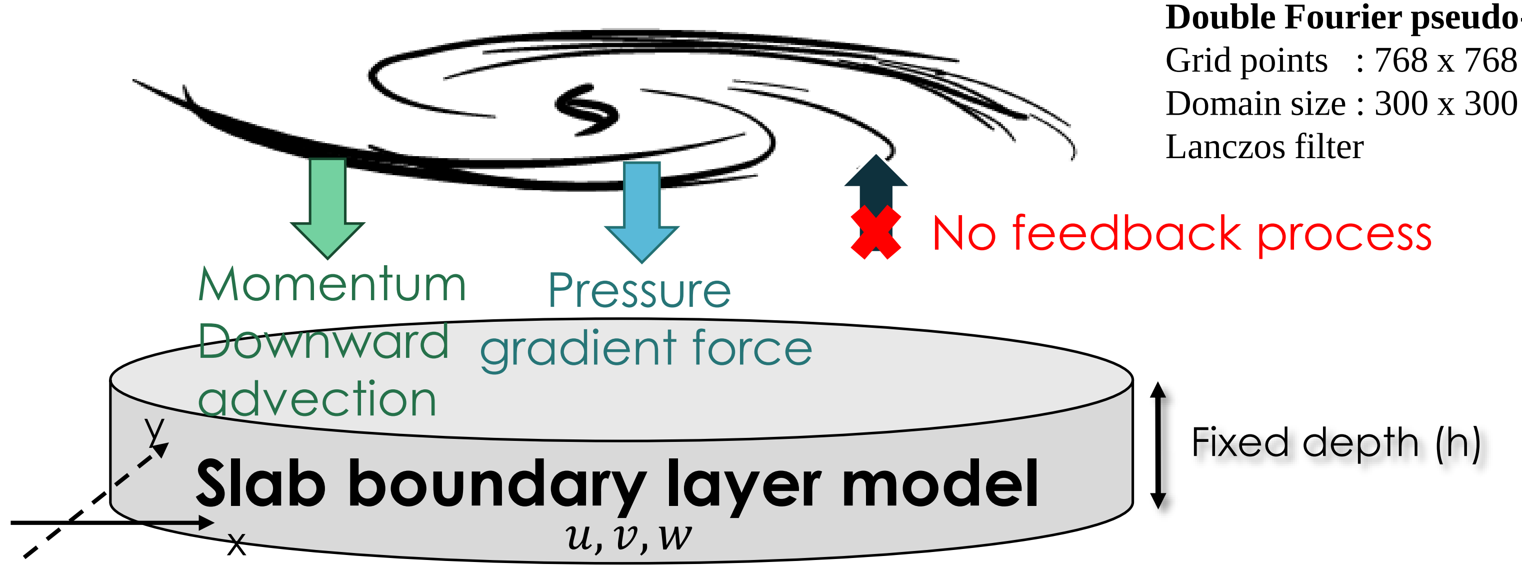
Purpose

- The structure of boundary layer pumping
- The convection in tropical cyclones that have elliptical and polygonal eyewalls

Method

Asymmetric slab boundary layer model combined with a nonlinear nondivergent barotropic model

Double Fourier pseudo-spectral method
Grid points : 768 x 768
Domain size : 300 x 300 (km^2)
Lanczos filter



Cartesian coordinate

Assumptions:
(1) u, v is independent of height
(2) depth h is constant

Barotropic Model

$$\frac{d\zeta}{dt} = \frac{\partial \zeta}{\partial x}\frac{\partial \psi}{\partial y} - \frac{\partial \zeta}{\partial y}\frac{\partial \psi}{\partial x} + \mu \nabla^2 \zeta$$

$$\frac{1}{\rho}\nabla^2 p = f\nabla^2\psi + 2[\frac{\partial^2\psi}{\partial x^2}\frac{\partial^2\psi}{\partial y^2} - \left(\frac{\partial^2\psi}{\partial x \partial y}\right)^2]$$

$$\zeta = \nabla^2 \psi$$

Slab-Boundary Layer Model

Momentum Downward advection

Pressure gradient force

Frictional effect

$$\frac{du}{dt} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w^-\left(\frac{u_{gr} - u}{h}\right) + f\left(v - \frac{1}{\rho f}\frac{\partial P}{\partial x}\right) - C_D U \frac{\mathrm{u}}{h} + K\nabla^2 u$$

$$\frac{dv}{dt} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w^-\left(\frac{v_{gr} - v}{h}\right) - f\left(u - \frac{1}{\rho f}\frac{\partial P}{\partial y}\right) - C_D U \frac{\mathrm{v}}{h} + K\nabla^2 \mathrm{v}$$

$$w = \frac{\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)}{h}, w^- = \frac{|w| - w}{2}$$

$U = 0.78(u^2 + v^2)^{1/2}$ (Williams et al. 2003)

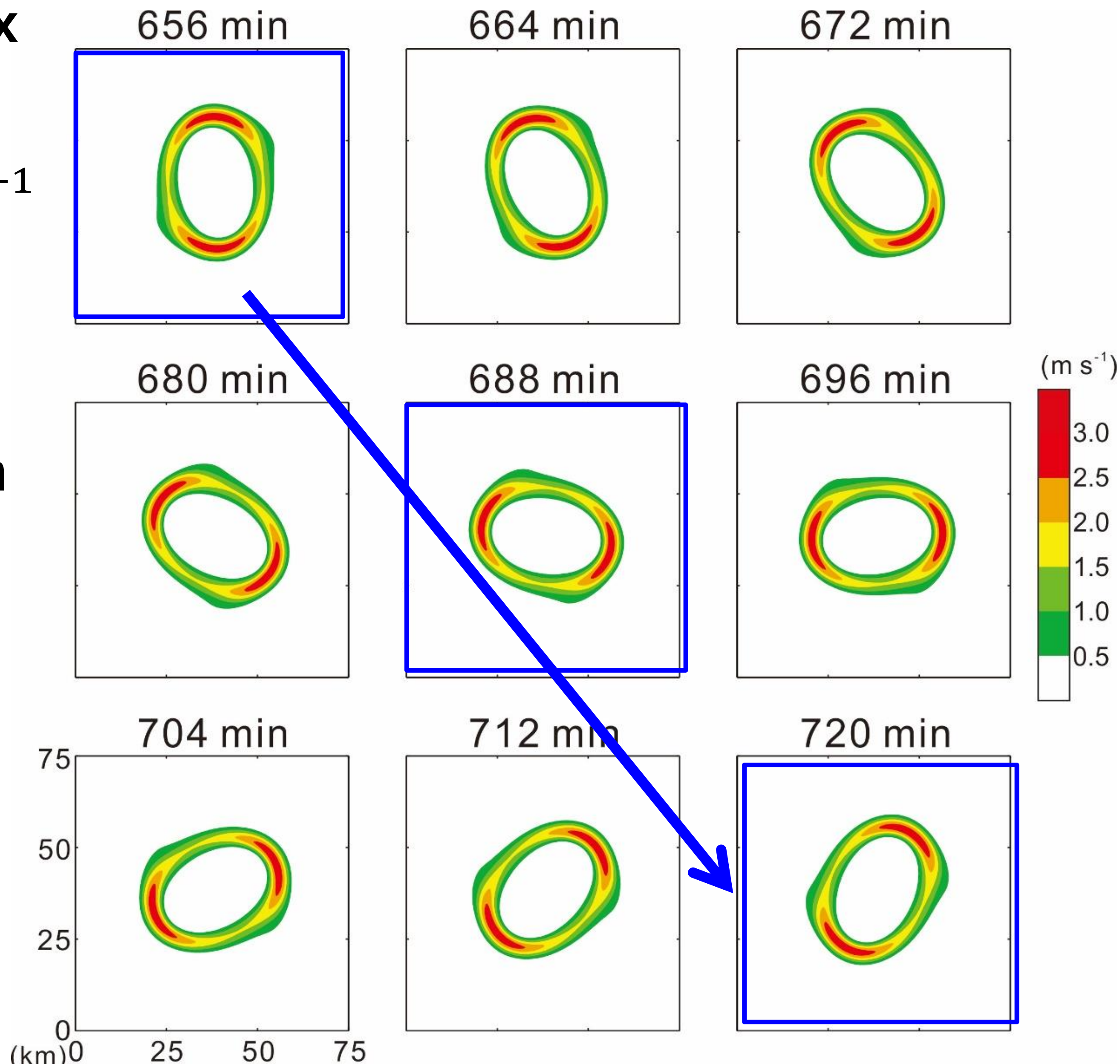
$$C_D = 10^{-3}\begin{cases} 2.70/U + 0.142 + 0.0764U & if\ U \le 25 \\ 2.16 + 0.5406\left[1 - \exp\left(-\frac{U-25}{7.5}\right)\right] & if\ U \ge 25 \end{cases}$$

(Powell et al. 2003)

Updraft of BL
Elliptical vortex

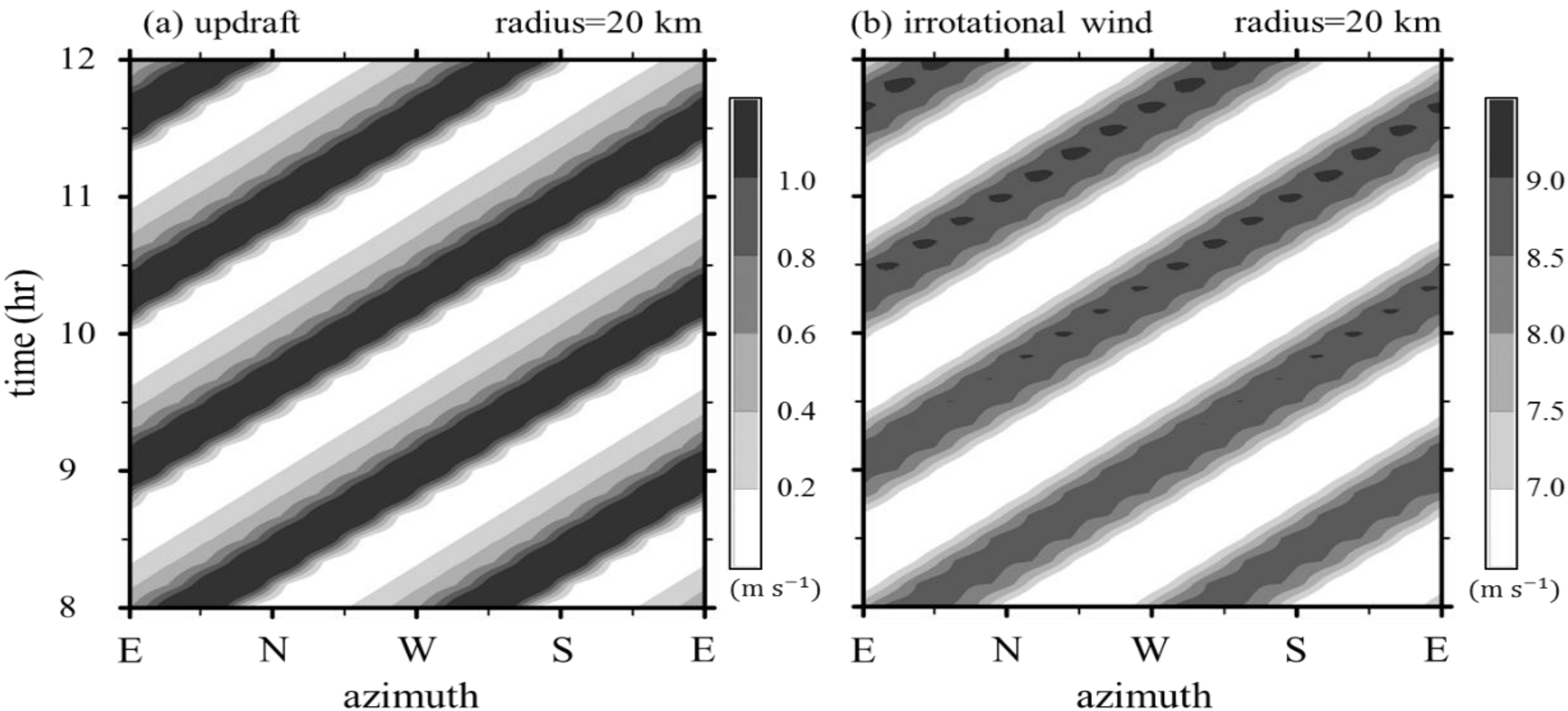
$\zeta_0 = 3 \times 10^{-3} s^{-1}$
a=40 km
b=30 km

144 min rotation period



Hovmöller diagram of BL updraft and irrotational wind at a radius of 20 km

$\zeta_0 = 3 \times 10^{-3} \mathrm{s}^{-1}$



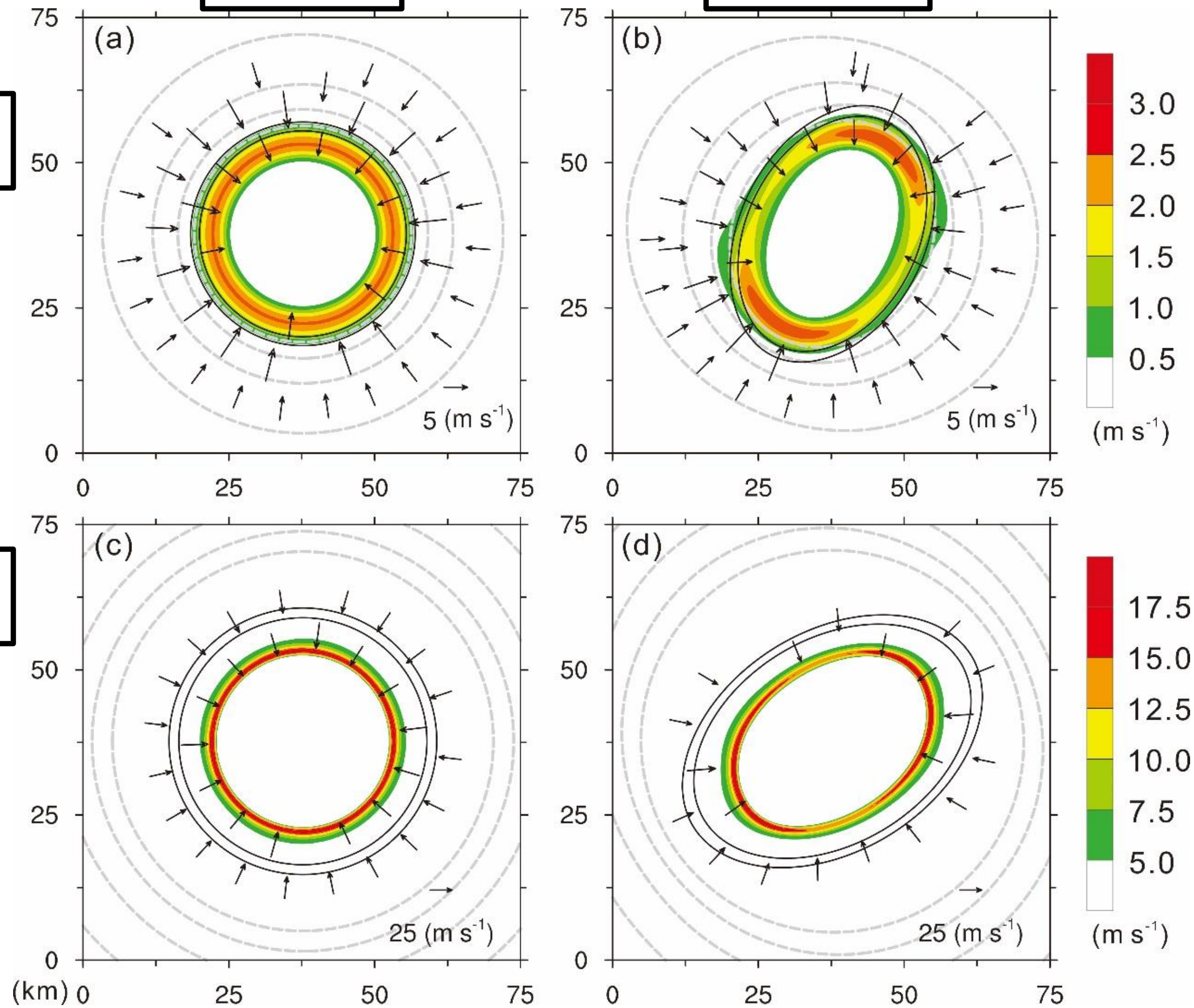
- 144 minute cyclonic rotation period
- Agreement with the observations of Typhoon Herb (1996)

Vorticity (solid lines)
Pressure (dash lines)
Updraft (shaded)
convergent wind (arrows)

Circle	Ellipse

$$\zeta_0 = 3 \times 10^{-3} s^{-1}$$

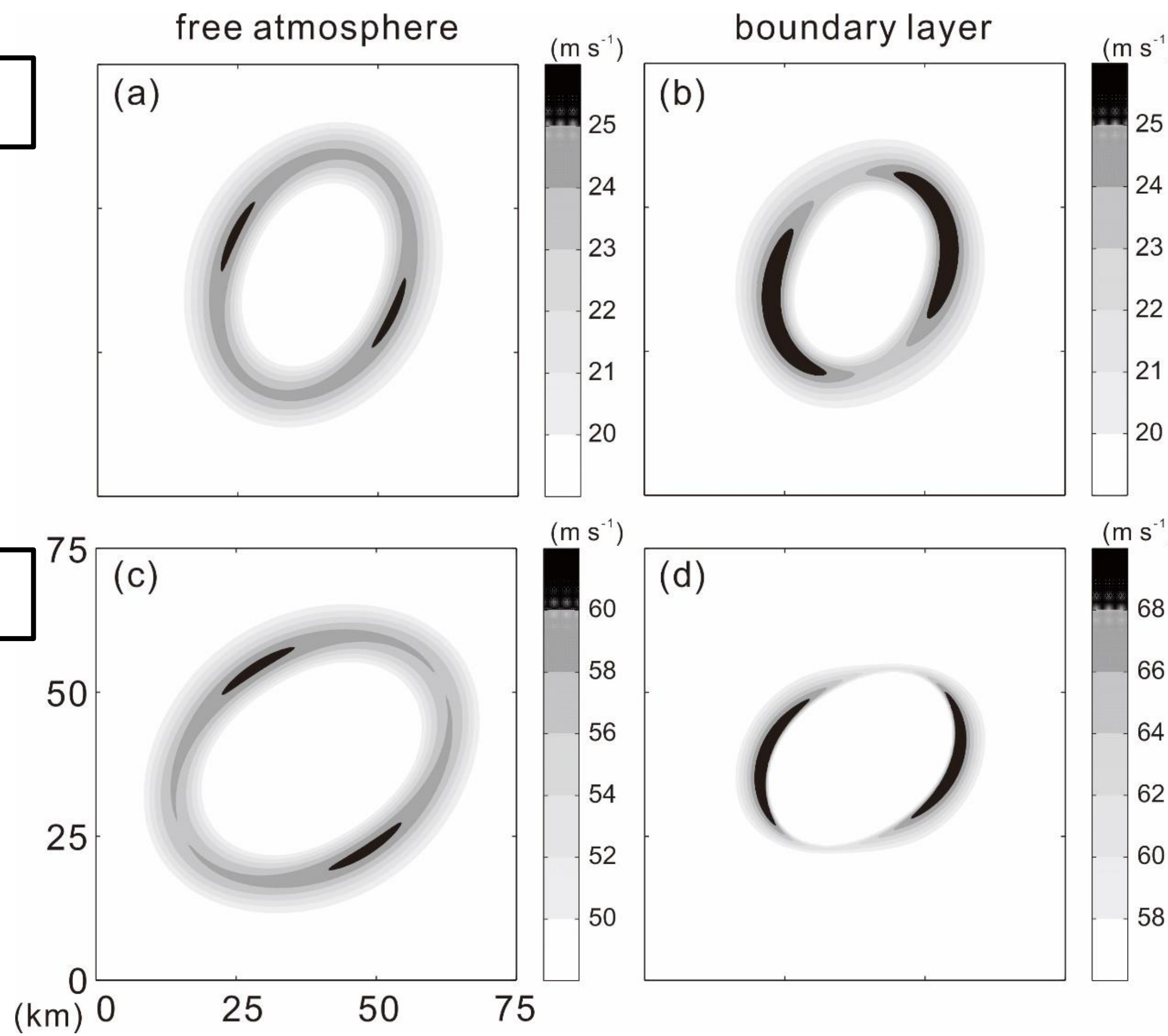
$$\zeta_0 = 6 \times 10^{-3} s^{-1}$$



Tangential wind

$\zeta_0 = 3 \times 10^{-3} s^{-1}$

$\zeta_0 = 6 \times 10^{-3} s^{-1}$



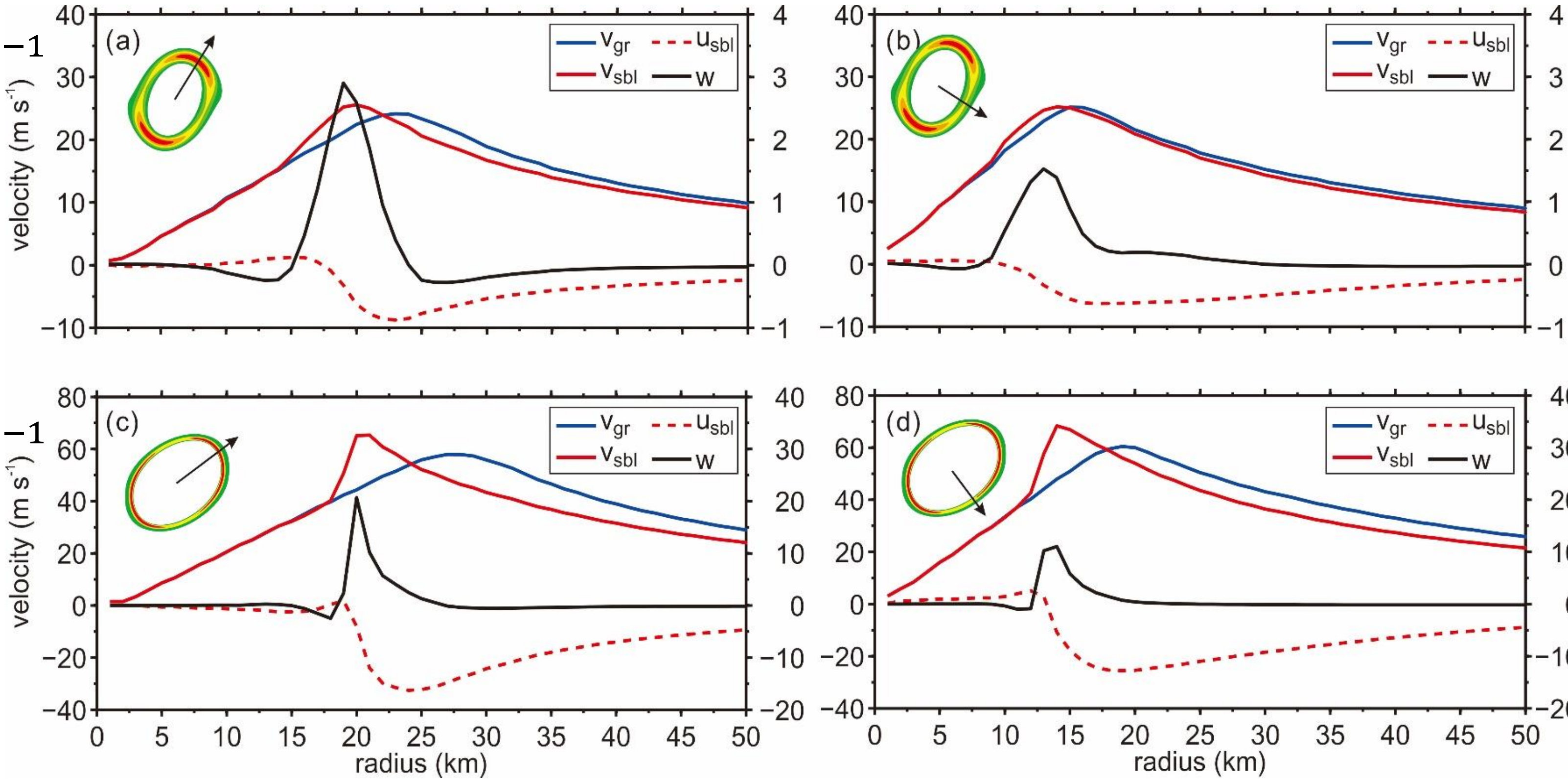
- supergradient (subgradient) winds inside (outside) the local RMW cause the convergence of the radial wind and strong updraft.

Major axis

Minor axis

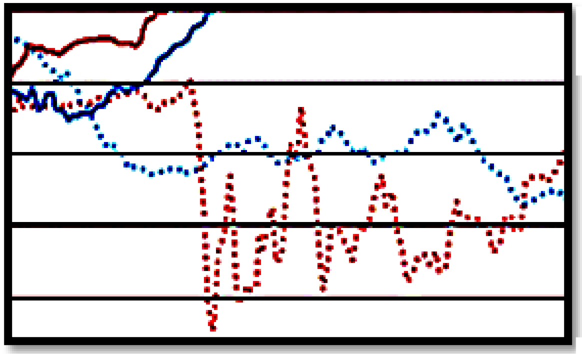
$\zeta_0 = 3 \times 10^{-3} s^{-1}$

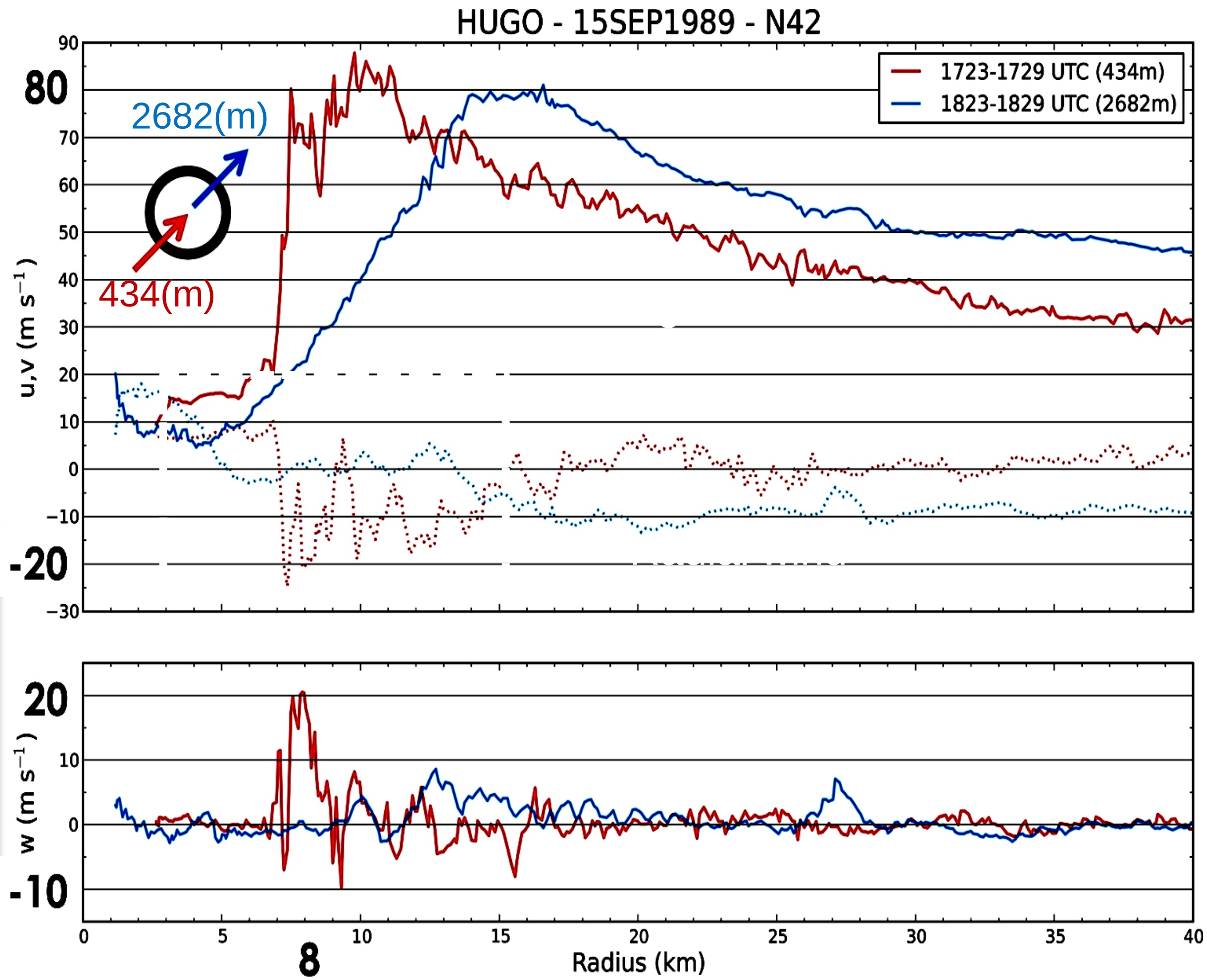
$\zeta_0 = 6 \times 10^{-3} s^{-1}$

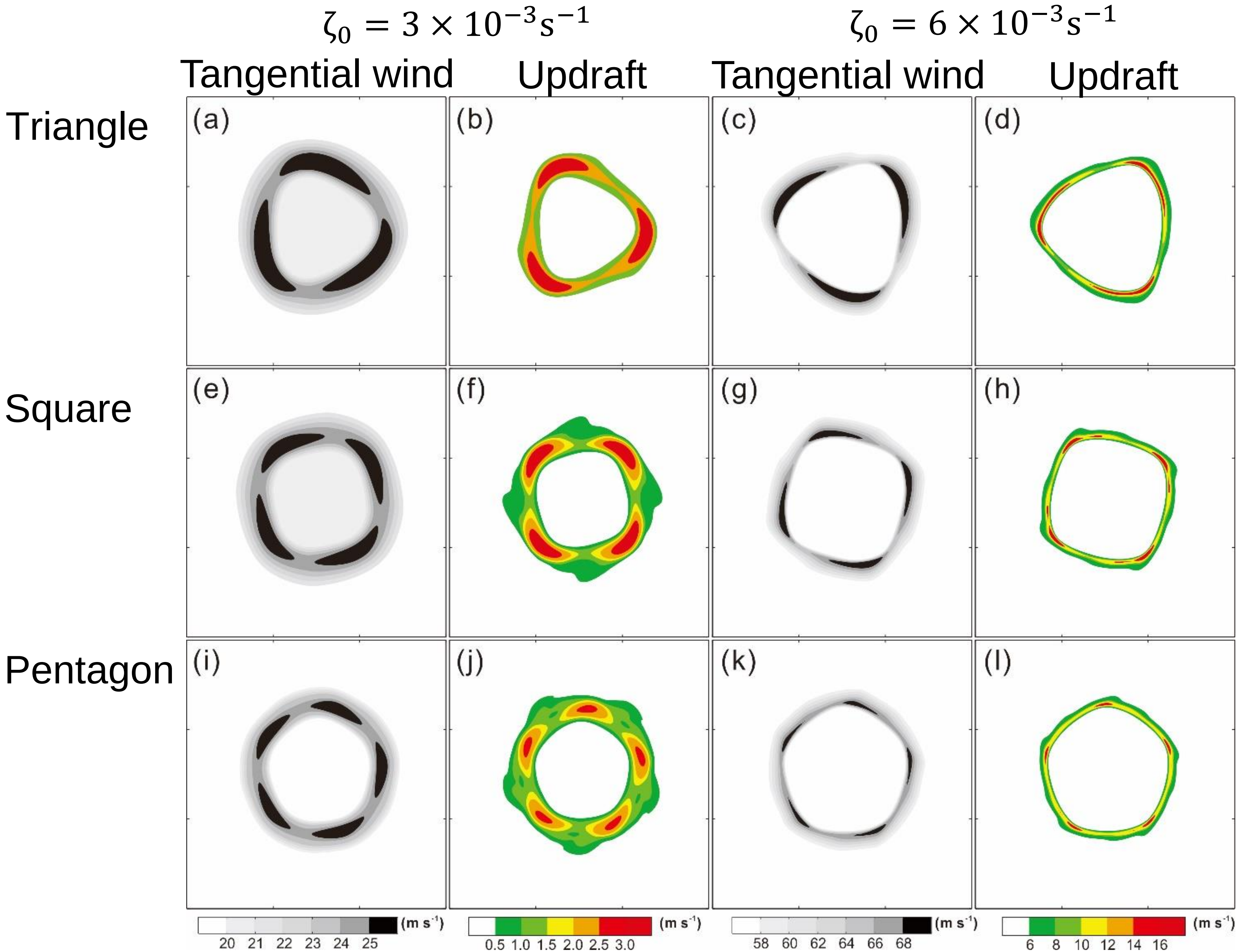


Hurricane Hugo (1989)

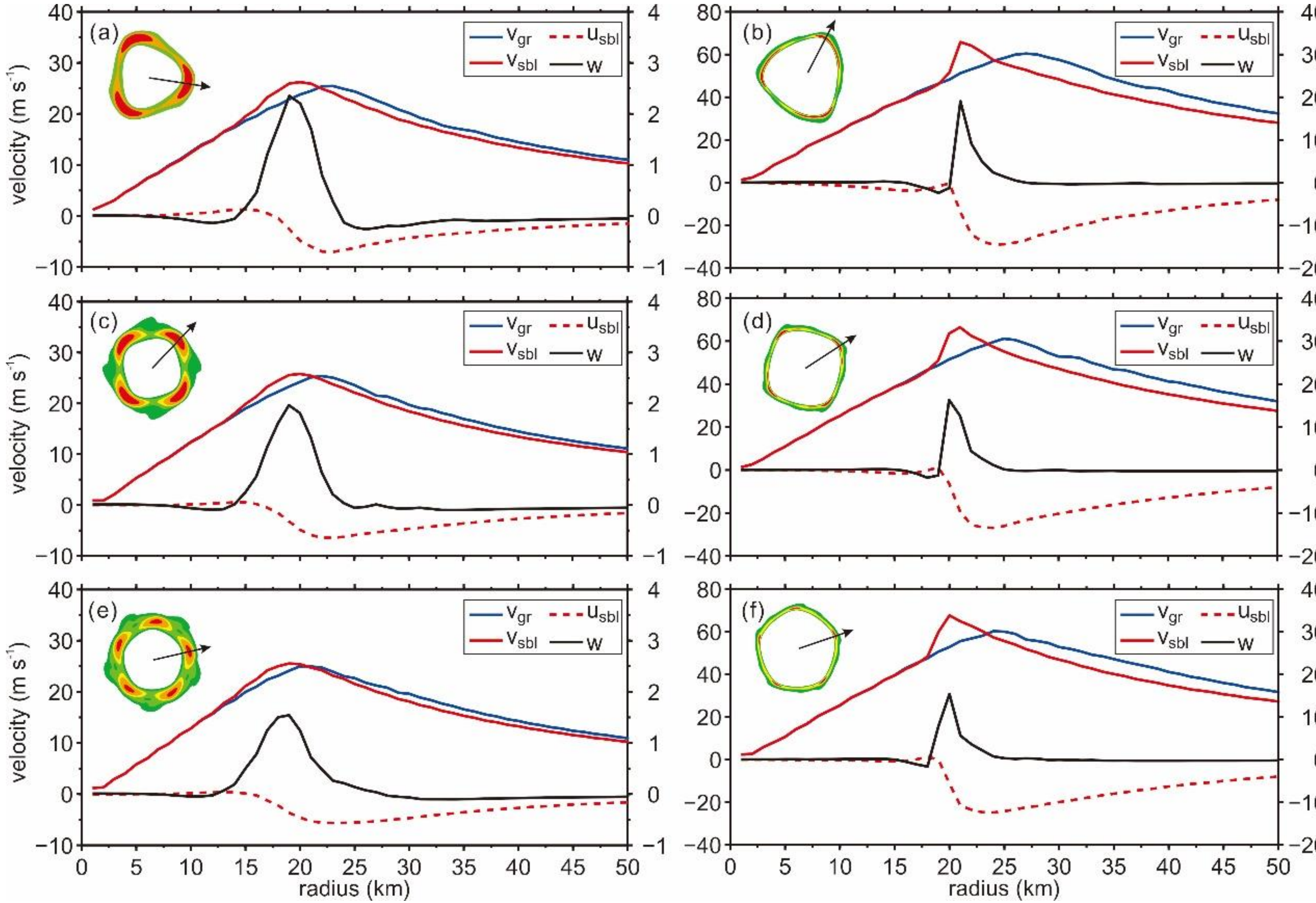
- Sharp gradient of radial inflow
- Super-/sub-gradient wind
- Sharp updraft







$\zeta_0 = 3 \times 10^{-3} s^{-1}$
$\zeta_0 = 6 \times 10^{-3} s^{-1}$
Tangential wind
Updraft
Tangential wind
Updraft
Triangle
Square
Pentagon
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
20 21 22 23 24 25 (m s-1)
0.5 1.0 1.5 2.0 2.5 3.0 (m s-1)
58 60 62 64 66 68 (m s-1)
6 8 10 12 14 16 (m s-1)



(a)
(b)
(c)
(d)
(e)
(f)
v_{gr}
v_{sbl}
u_{sbl}
w
velocity (m s^{-1})
radius (km)

Summary

- Observations
  - Deep convection with cyclonic rotation occurs on the tips of the major axis in an elliptical eyewall
- Asymmetric SBL model combined with a nonlinear nondivergent barotropic model
  - asymmetric tangential and radial wind
  - large convergence and strong updrafts
  - cyclonic rotation
  - jet-like high speed tangential winds upstream the major axis

Tangential momentum equation $\frac{D\boldsymbol{v}}{Dt} = -\left(\frac{v}{r} + f\right)u$

- ✓ tangential wind deceleration ($\frac{Dv}{Dt} < 0$) when the air parcels experience as they enter the tip of the major axis region can only be provided by a positive radial wind
- ✓ The tips of the major axis are in the BL jet exit zone and thus supergradient winds are produced.
- ✓ The dynamics of midlatitude upper level super-geostrophic westerly wind in the jet exit region.