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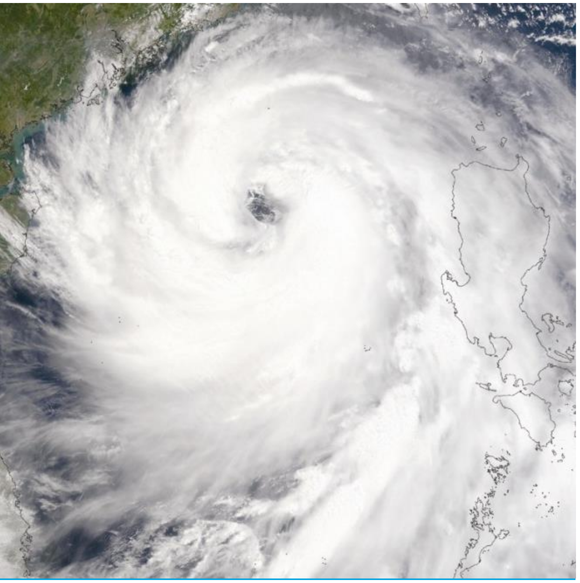

Lectures on Tropical Cyclone Motion

Johnny Chan

School of Energy and Environment
City University of Hong Kong

Four lectures

- Fundamental concepts of tropical cyclone motion
- Application of the tropical cyclone motion concepts I
- Application of the tropical cyclone motion concepts II
- Tropical cyclone forecast errors

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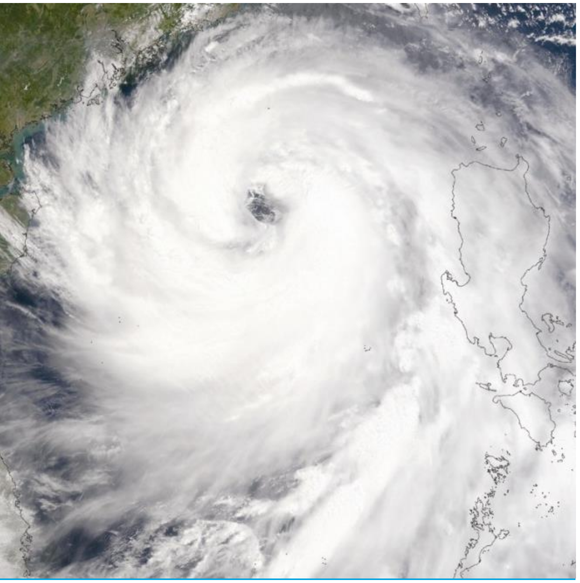

Fundamental Concepts of Tropical Cyclone Motion

Johnny Chan

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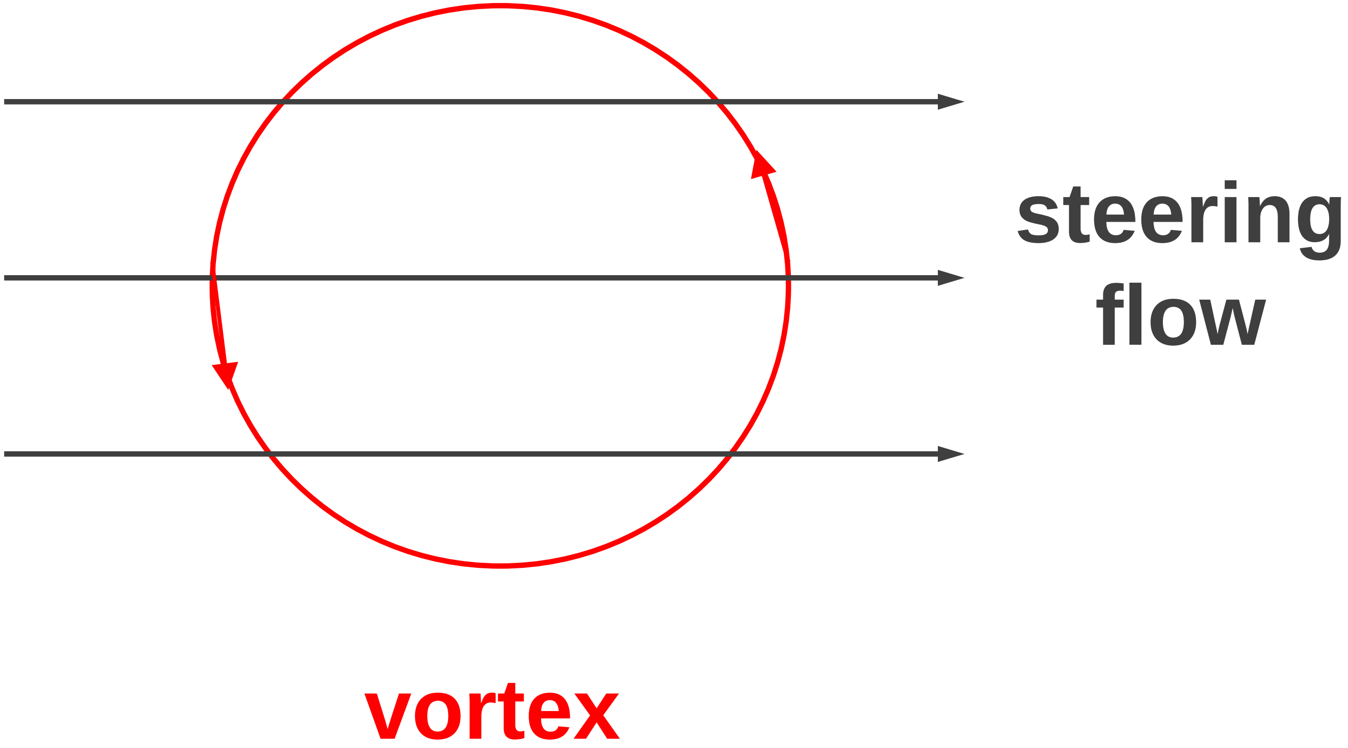
City University of Hong Kong

Outline

- Barotropic concepts
  - ☐ Steering
  - ☐ Beta effect
- Baroclinic processes

Steering Flow

The Concept of Steering Flow



Questions

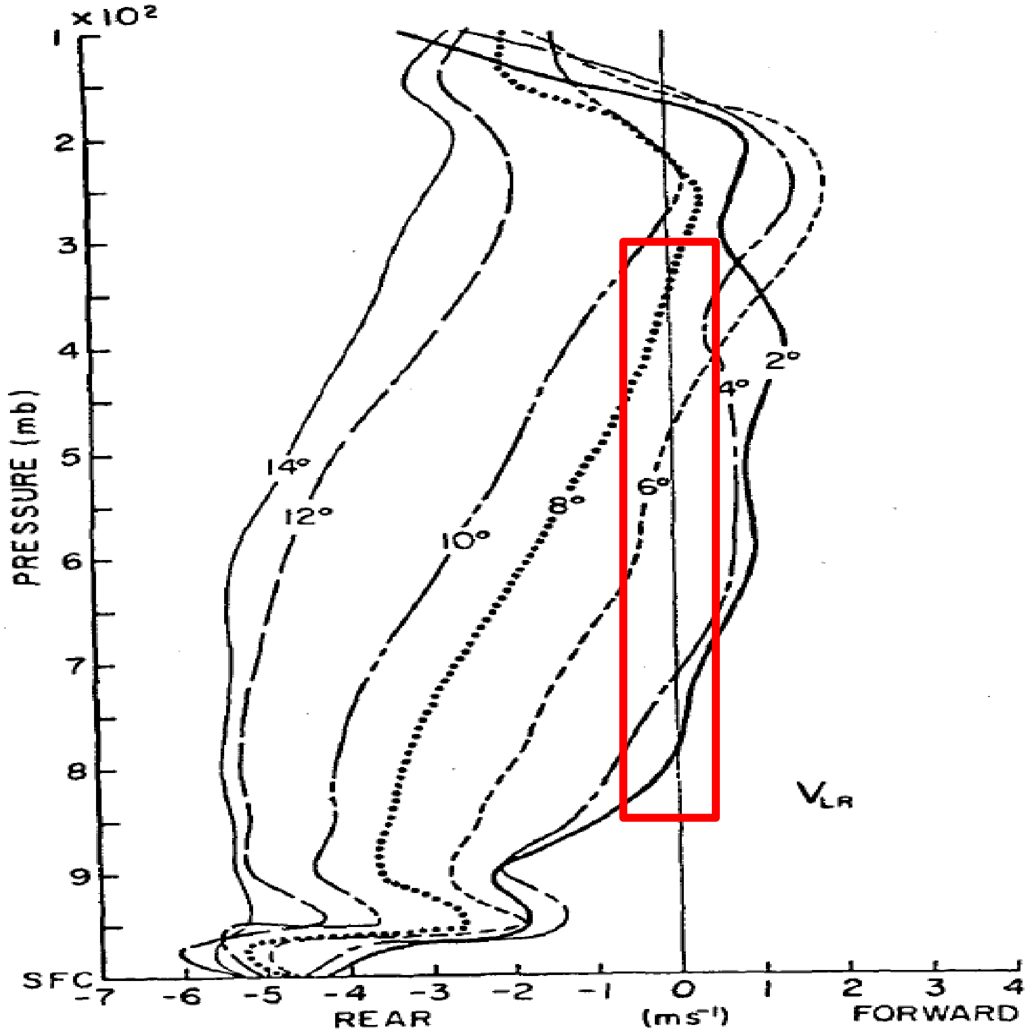
- Where is the steering flow within the TC vortex?
  - At what level or within which layer?
  - Within what radii from the TC centre?

George and Gray (1976)

Azimuthally-averaged flow at different radii parallel and relative to TC motion Western North Pacific

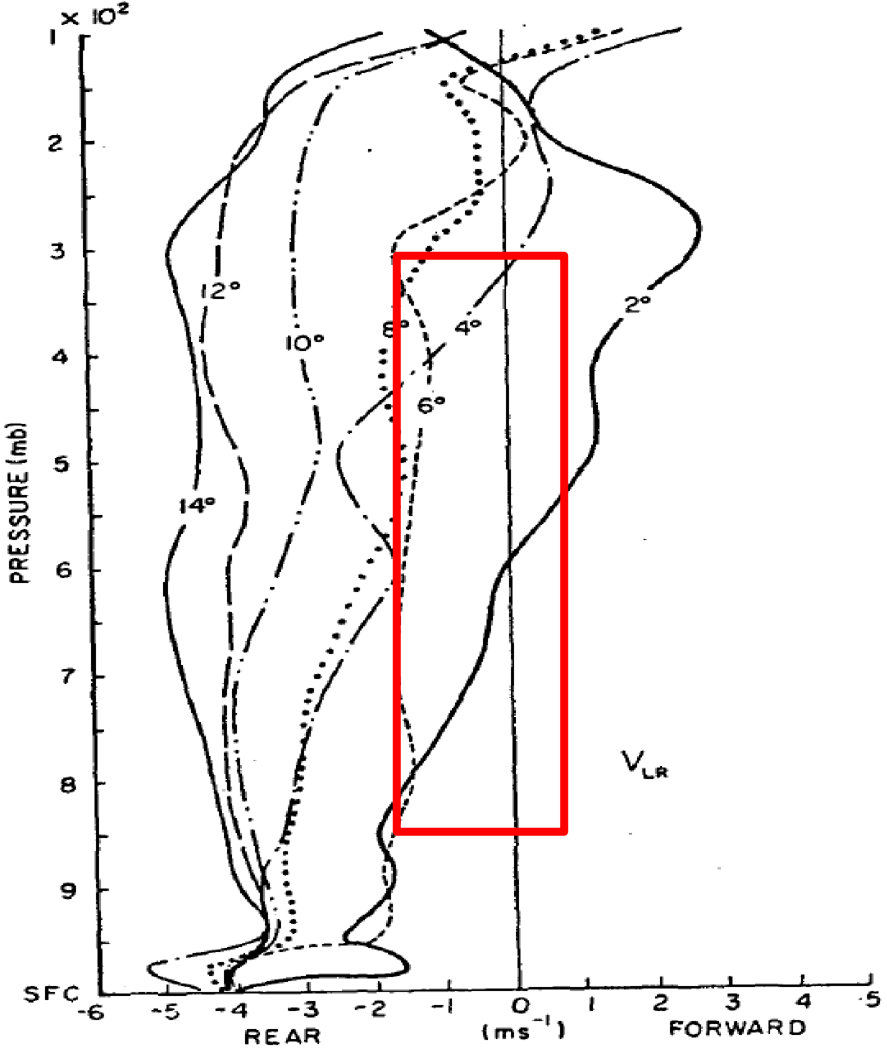
Latitude > 20ºN

TC moving faster TC moving slower



Latitude < 20ºN

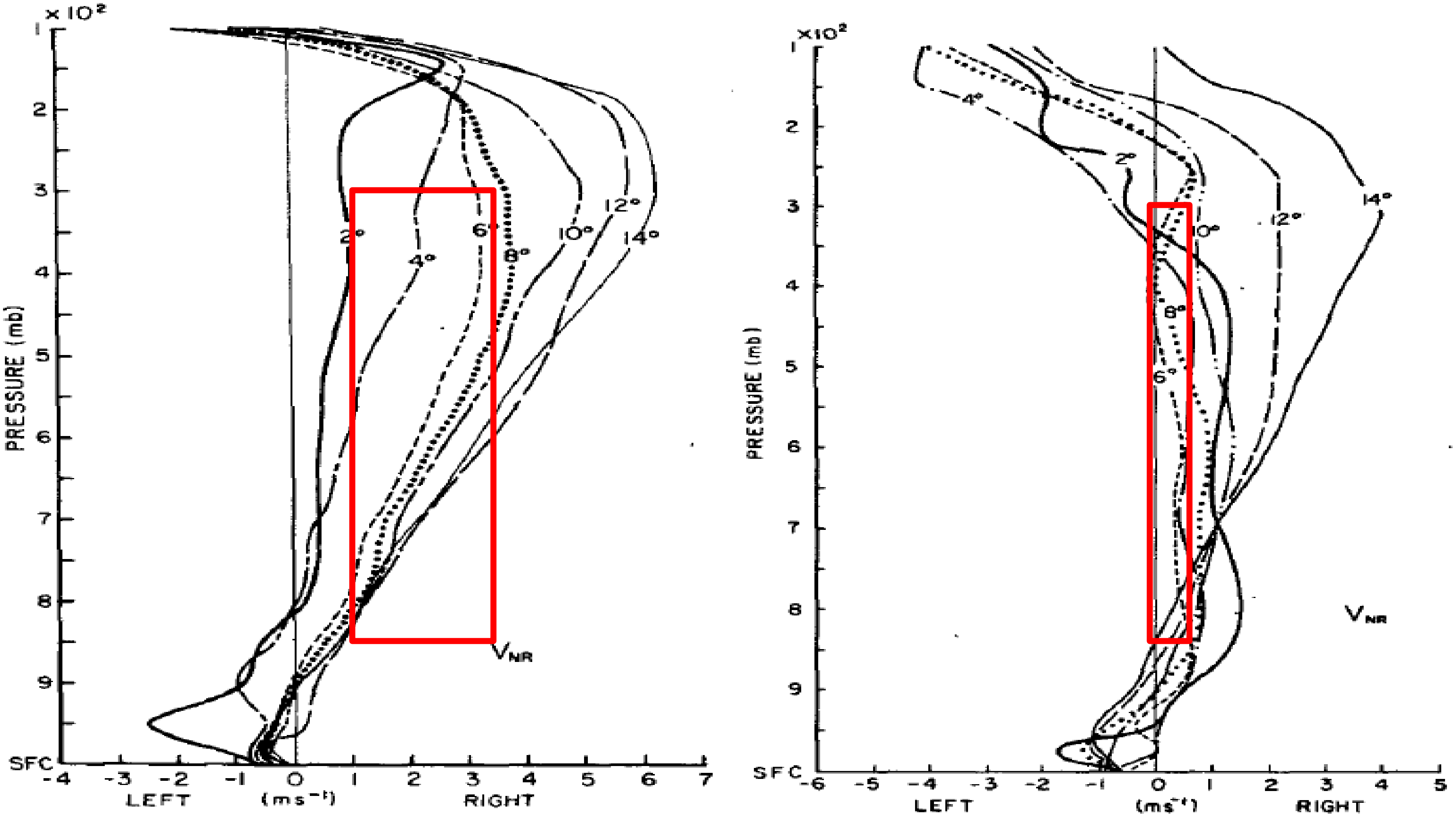
TC moving faster TC moving slower



George and Gray (1976)

Azimuthally-averaged flow at different radii normal to TC motion

Western North Pacific

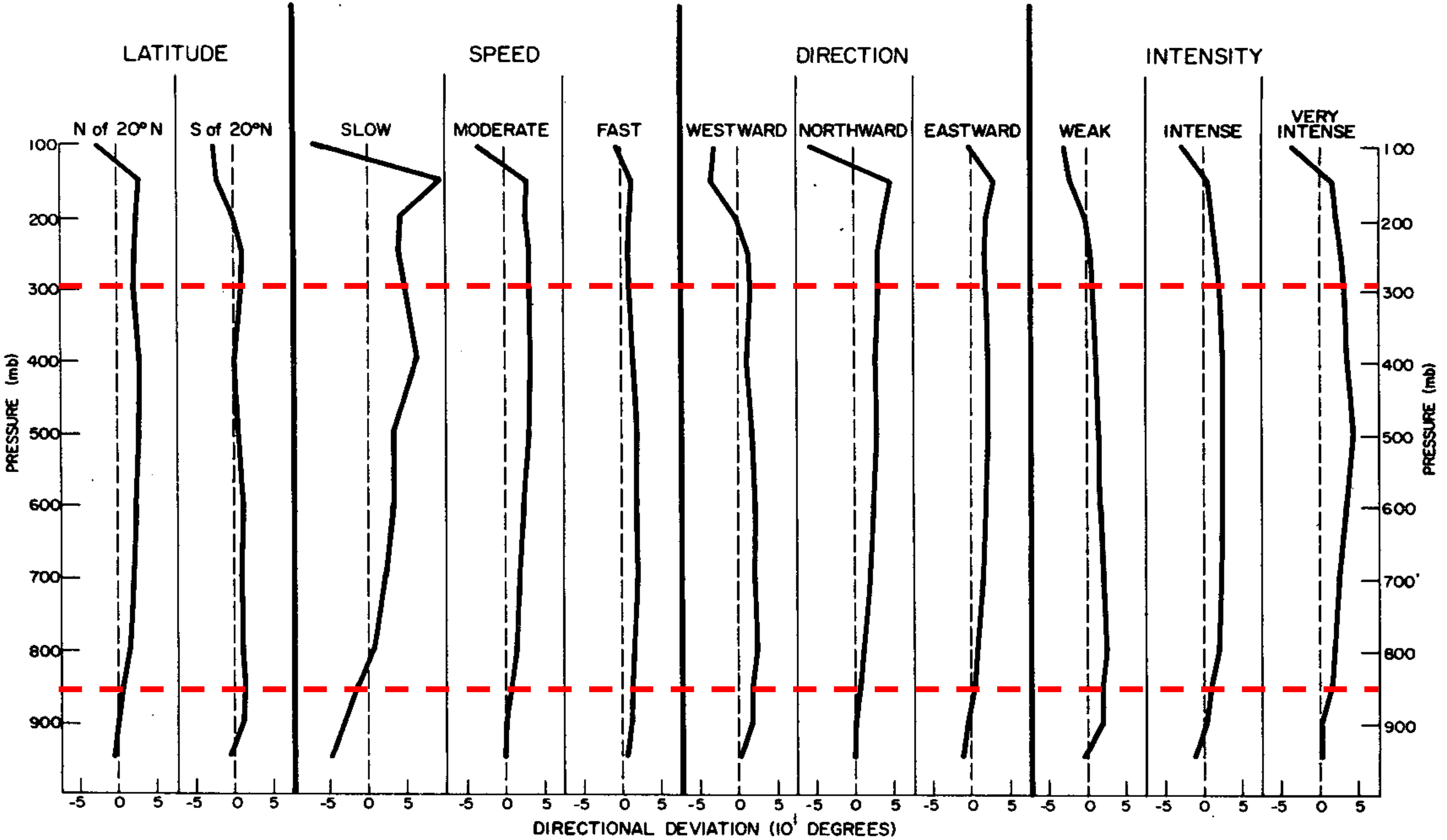


Latitude > 20°N

Latitude < 20°N

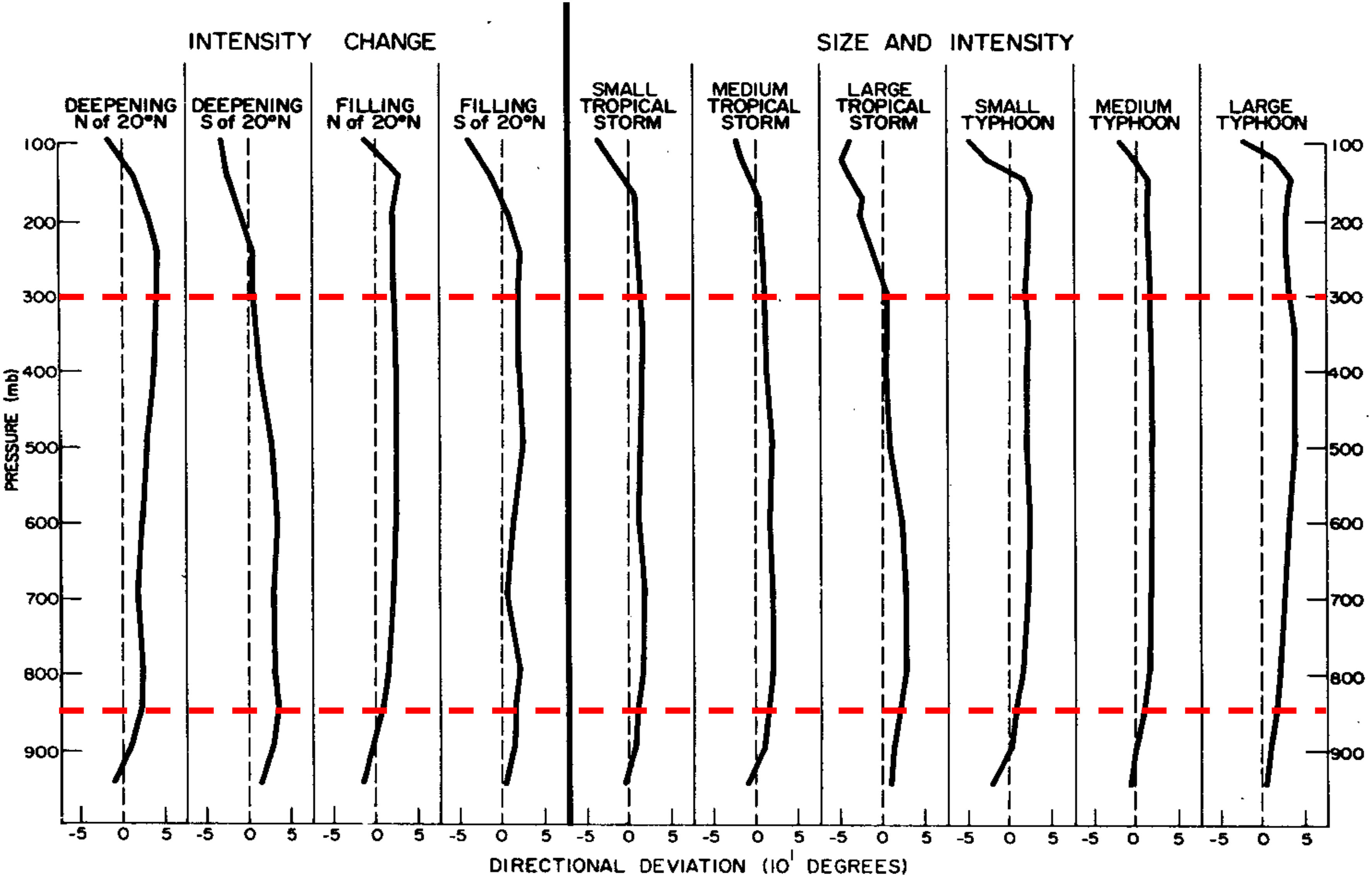
Chan and Gray (1982)

5-7^o azimuthally-averaged ***directional*** deviation from TC motion vector Western North Pacific



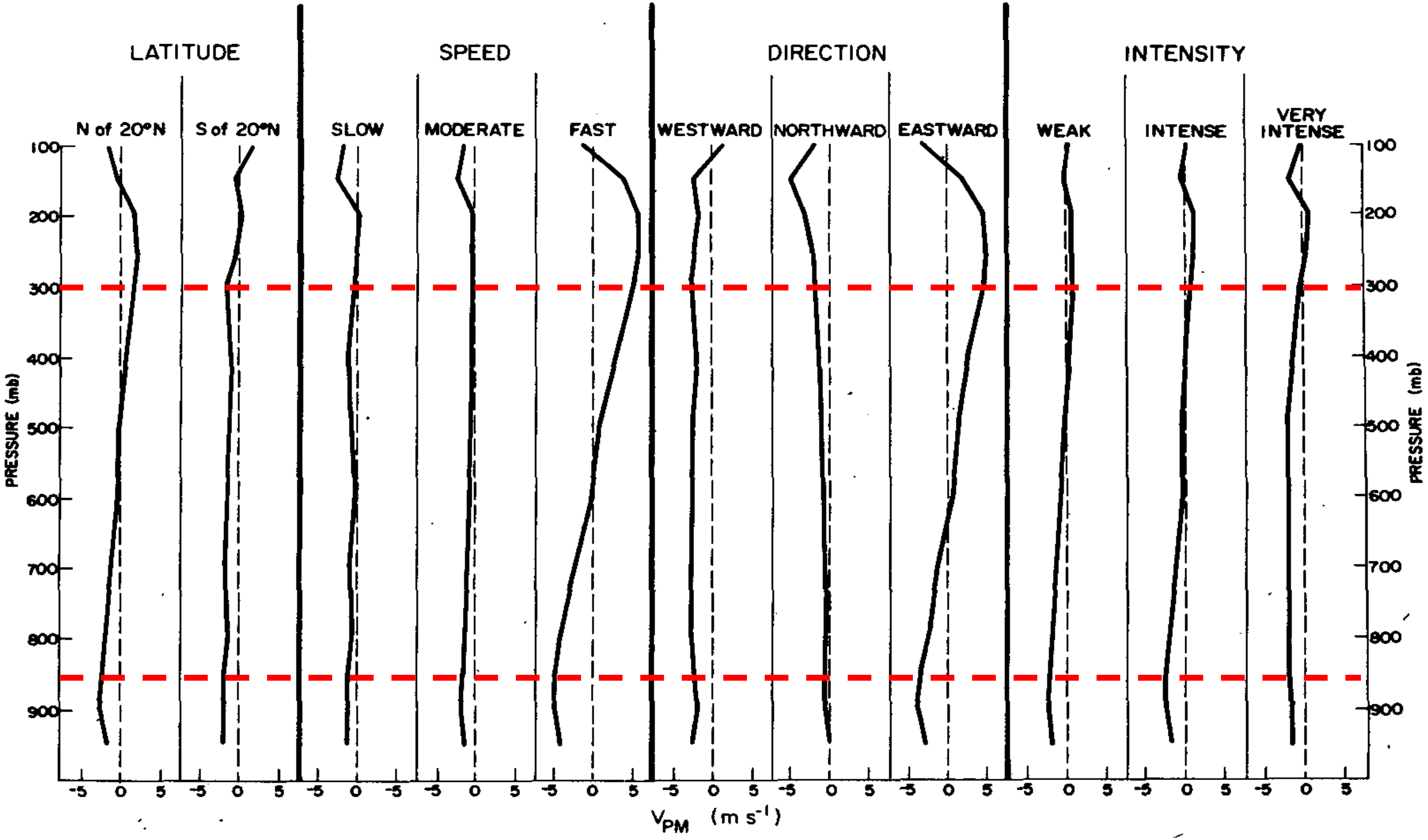
Chan and Gray (1982)

5-7º azimuthally-averaged ***directional*** deviation from TC motion vector Western North Pacific



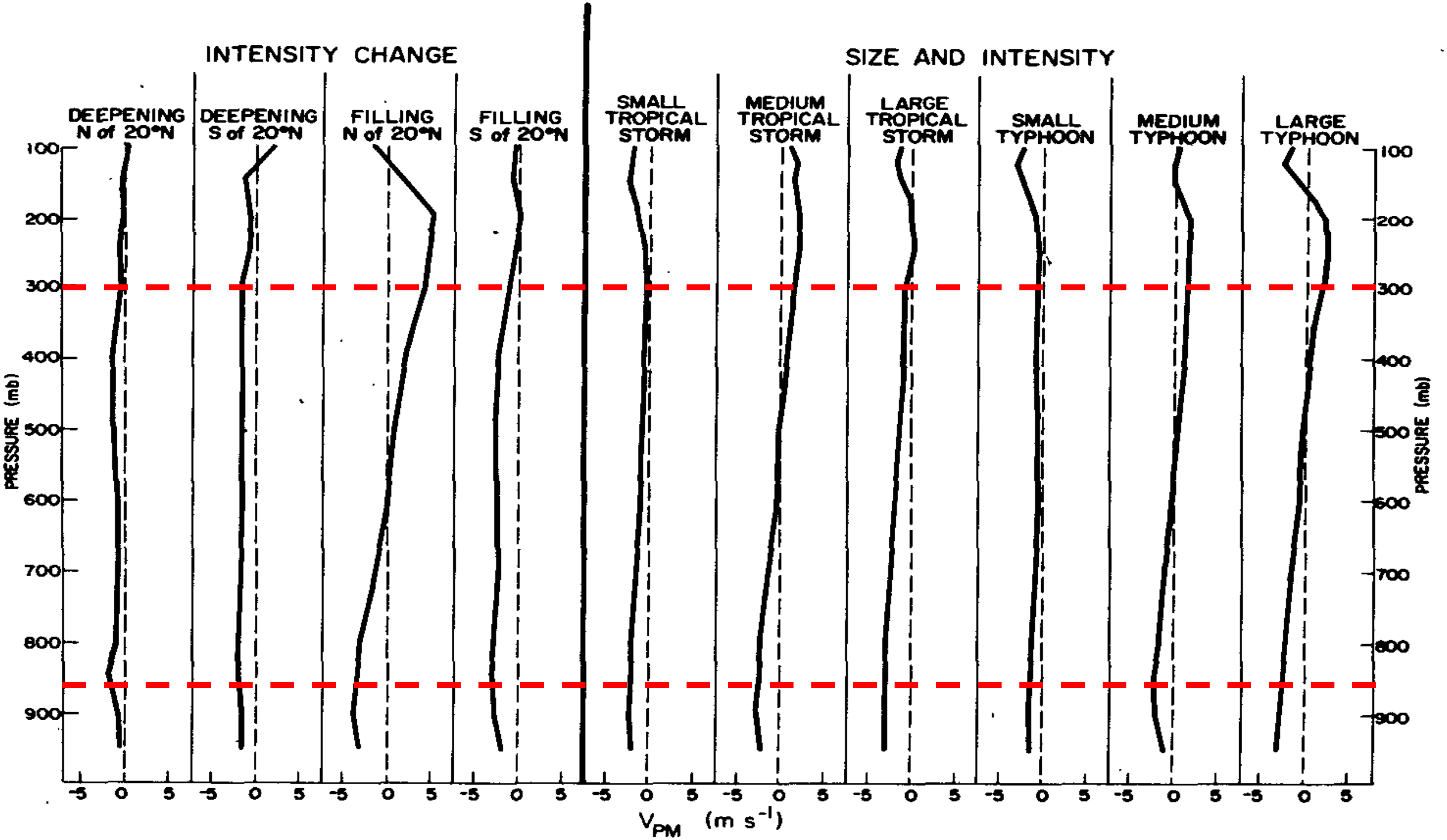
Chan and Gray (1982)

5-7° azimuthally-averaged *speed* deviation from TC motion vector
Western North Pacific



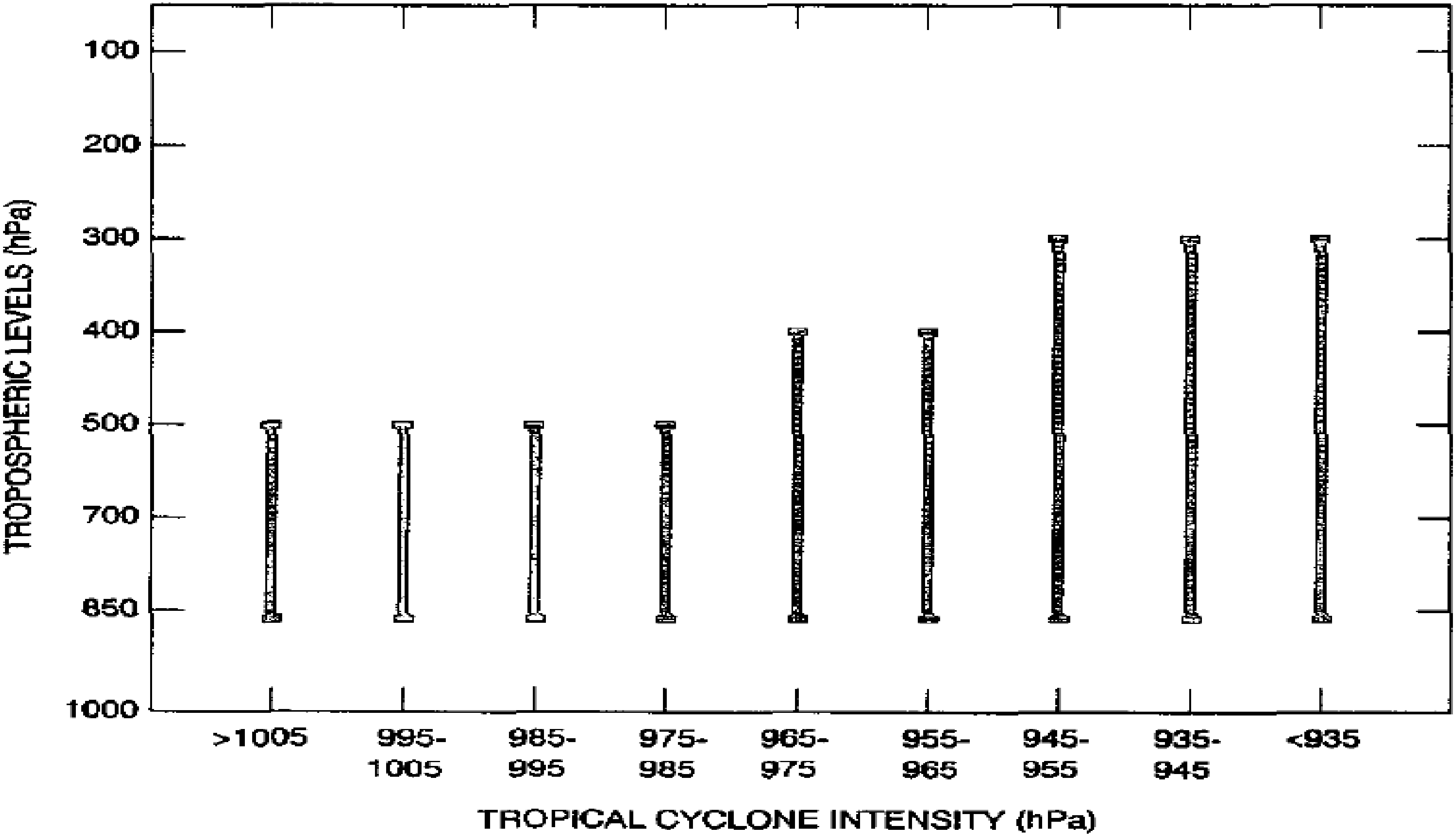
Chan and Gray (1982)

5-7^o azimuthally-averaged ***speed*** deviation from TC motion vector Western North Pacific



Velden and Leslie (1991)

Optimum steering flow layer for different TC intensities in the Australian region



Answers

- Where is the steering flow within the TC vortex?
  - ☐ At what level or within which layer?

    The best relationship with TC motion appears to be in the mid troposphere (500 or 700 hPa) or averaged within the main part of the troposphere (850-300 hPa); but might also depend on the TC intensity, with a deeper layer for a more intense TC

  - ☐ Within what radii from the TC centre?

    The best relationship is within the 5-7^o latitude radial band (to reduce the impact of the TC circulation but not too far away from the TC centre)

Important results

- Irrespective of how the steering flow is defined, a TC tends to move
  - to the ***left*** (in the Northern Hemisphere), or to the ***right*** (in the Southern Hemisphere) of the steering flow
  - with a ***speed larger than*** that of the steering flow

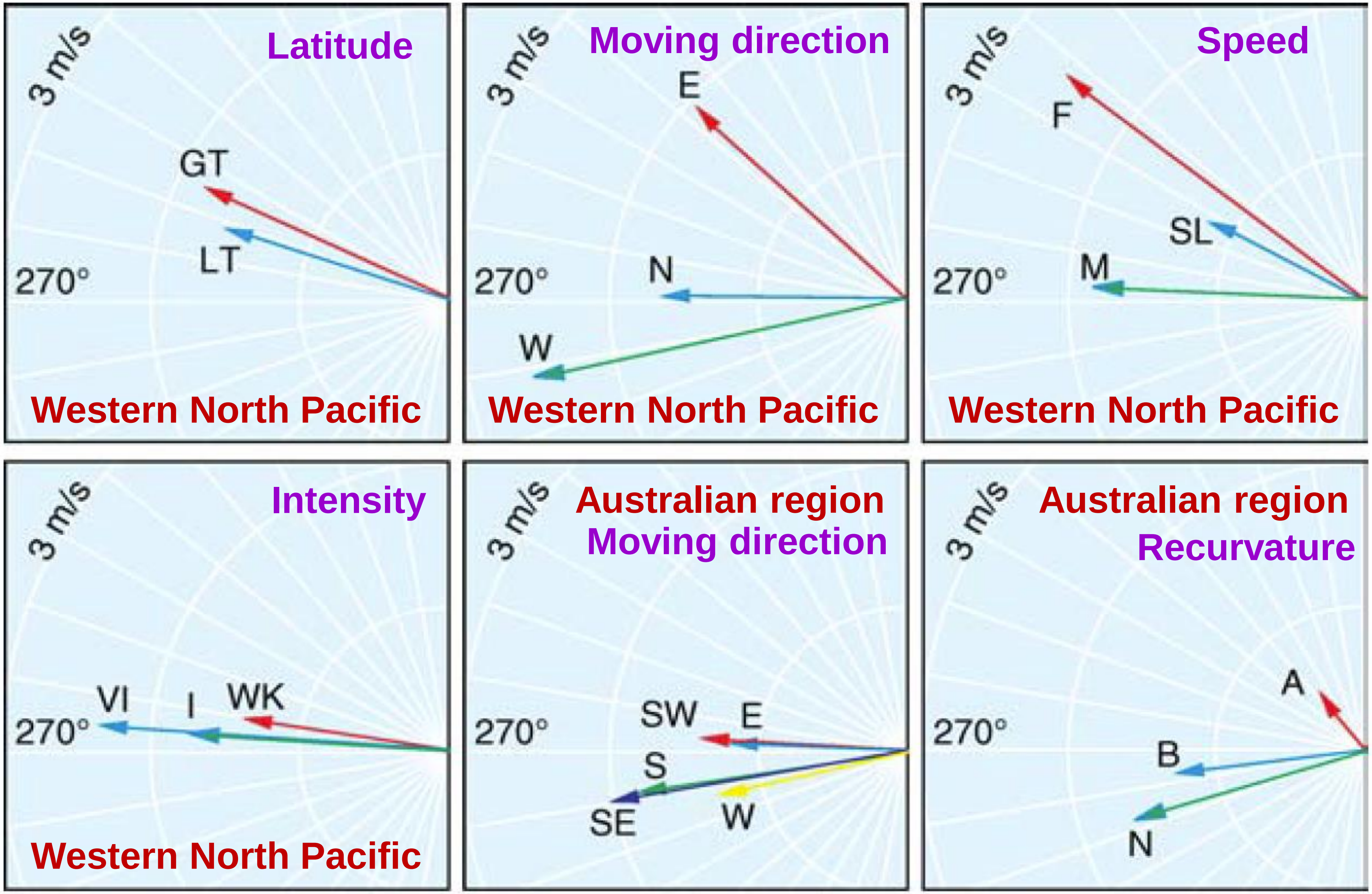
Historical perspective

Riehl (1954):

- Tropical storms move under the influence of **external** and **internal** forces
  - ☐ **External forces** are applied by the currents that surround a storm on all sides and carry it along, which is the steering current.
  - ☐ **Internal forces** arise within the tropical cyclone circulation because of the variation of Coriolis force across the cyclone
- In the mean, tropical storms move in the direction and with the speed of the steering current, defined as the pressure-weighted mean flow from the surface to 300 mb over a band of 8°latitude radius from the cyclone centre
- Internal forces cannot produce displacements averaging more than 1-2 knots

Carr and Elsberry (1990)

TC motion vector minus 5-7° azimuthally-averaged flow vector



The vorticity equation

$$\underbrace{\frac{\partial \zeta}{\partial t}}_{\text{LC}} = \underbrace{-\mathbf{V}_H \cdot \nabla(\zeta + f)}_{\text{HA}} \underbrace{-\omega \frac{\partial \zeta}{\partial p}}_{\text{VA}} \underbrace{-(\zeta + f)\nabla \cdot \mathbf{V}}_{\text{DIV}} - \left\{ \begin{matrix} \text{tilting} \\ \text{term} \end{matrix} \right\}$$

ζ = relative vorticity; f = Coriolis parameter;

$\mathbf{V}_H$ = horizontal velocity vector; ω = vertical p velocity

$\mathbf{V}$ = 3-dimensional velocity vector

LC – local change of relative vorticity

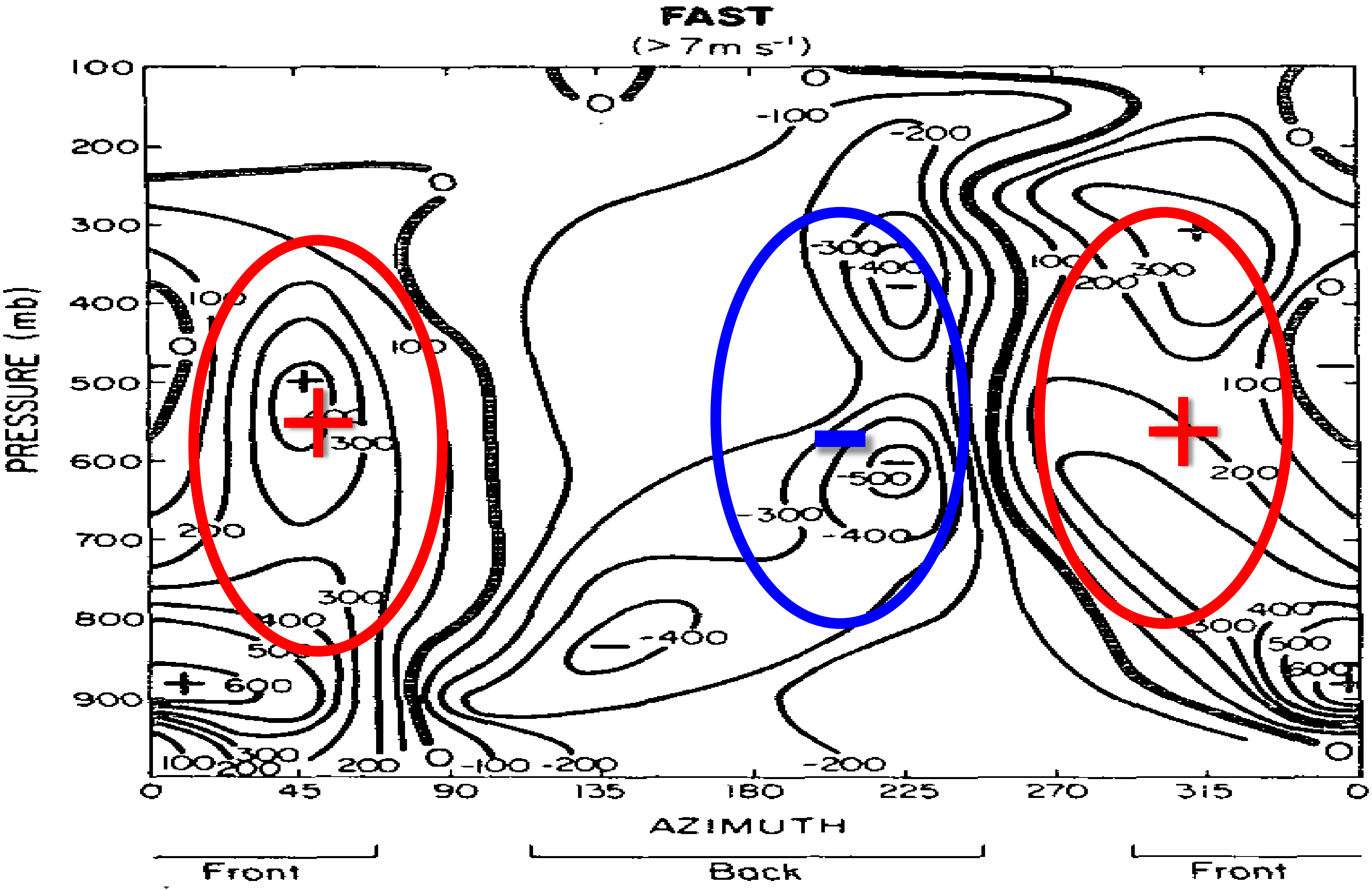
HA – horizontal advection of absolute vorticity

VA – vertical advection of relative vorticity

DIV – divergence or stretching term

Chan (1984)

Vertical variations of LC around the TC at 2ºlatitude radius



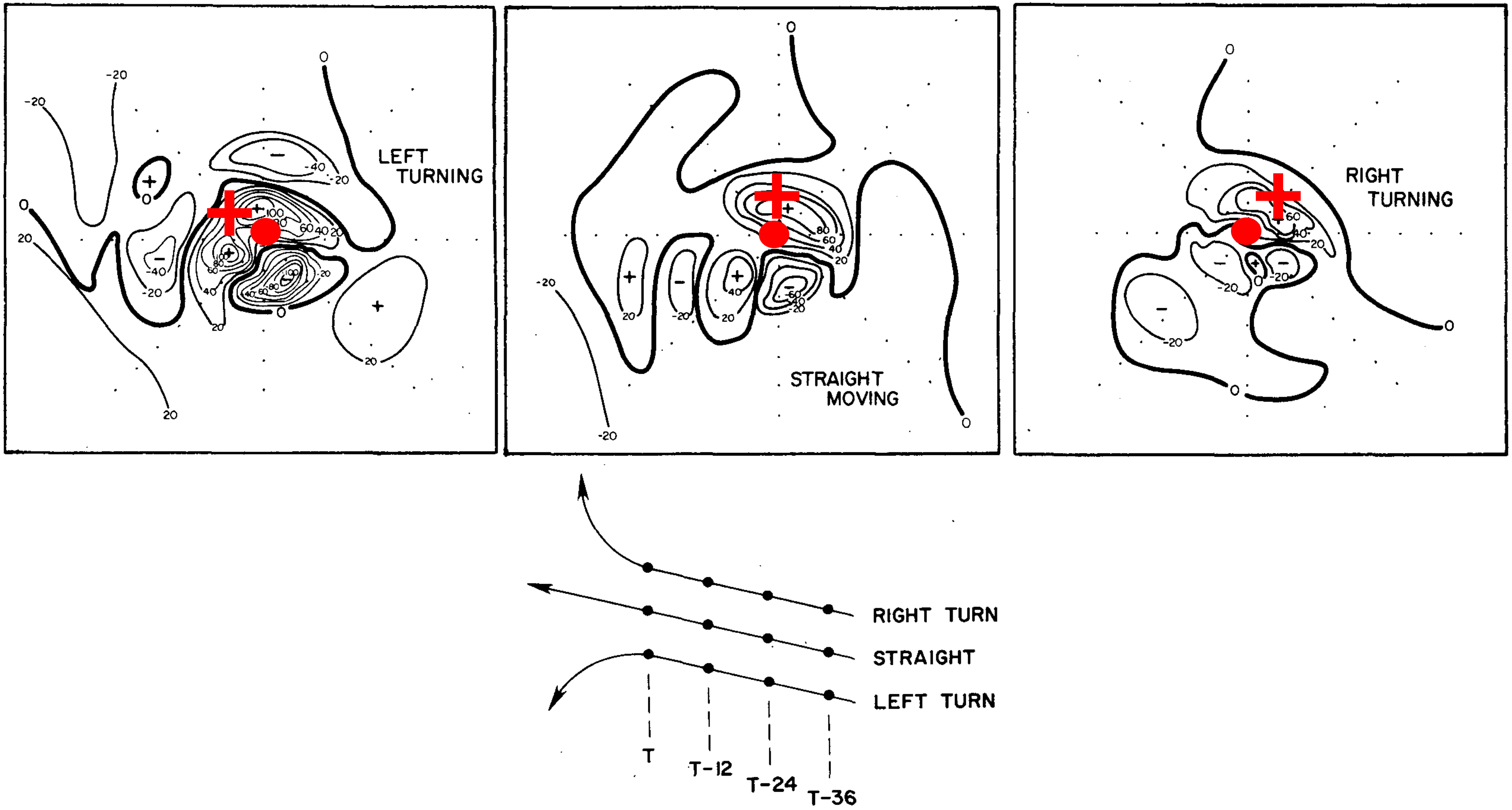
Observations

- LC is maximum in front of the TC motion, and minimum in the rear
- An increase in relative vorticity implies a spinup of the air, which through geostrophic adjustment, leads to a lowering of the surface pressure

⇒ ***TC movement can be viewed as a continuous increase in relative vorticity in front of the TC***

Chan (1984)

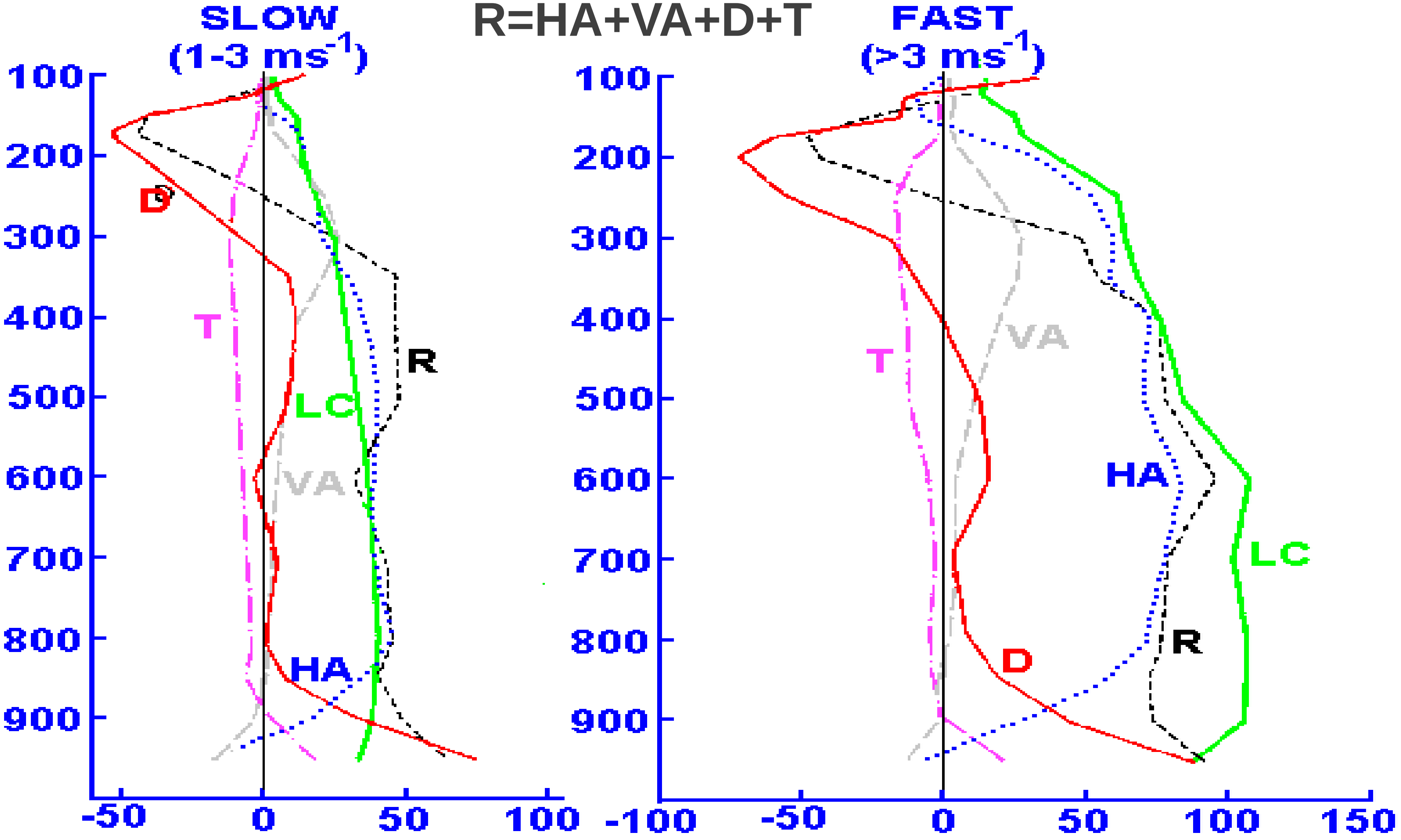
LC between turn time and 12 hours before



Chan (1984)

Vertical variations of the various terms ahead of TC motion vector

R=HA+VA+D+T



Observations

- VA and tilting terms are generally small.
- DIV term is only significant in the lower and upper troposphere
- LC is mainly contributed by the HA term, especially in the mid troposphere
- Integrated over the entire troposphere, HA term still dominates

So, to a first approximation,

$$\frac{\partial \zeta}{\partial t} = -\mathbf{V}_H \cdot \nabla(\zeta + f)$$

which is the barotropic vorticity equation.

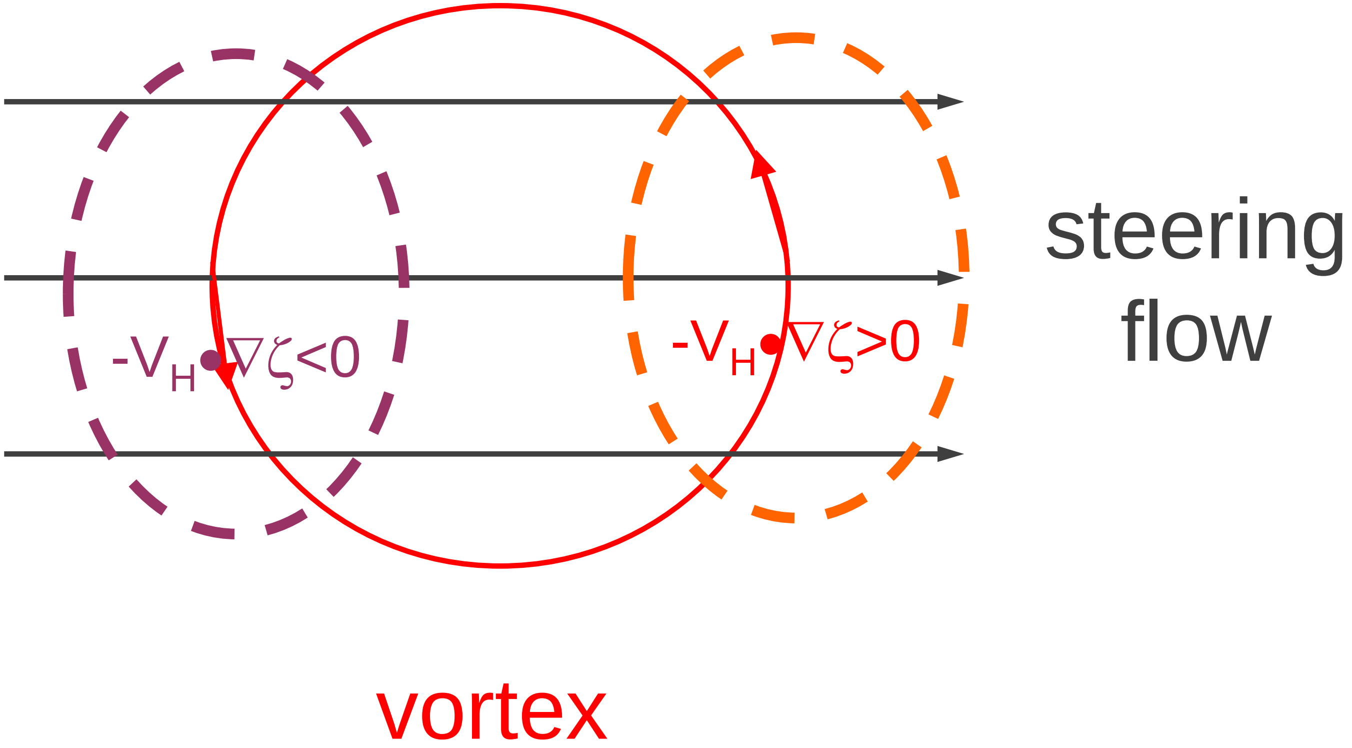
The barotropic vorticity equation

$$\frac{\partial \zeta}{\partial t} = -\mathbf{V}_{\mathrm{H}} \cdot \nabla(\zeta + f) = \underbrace{\boxed{-\mathbf{V}_{\mathrm{H}} \cdot \nabla \zeta}}_{\text{steering flow}} \underbrace{\boxed{-\beta v}}_{\beta \text{ effect}}$$

steering flow

β effect

Dynamic view of TC motion due to the steering flow



Beta Effect

The beta effect

- In general, the steering flow dominates $\partial\zeta/\partial t$ so that TC motion is dominated by the steering flow.

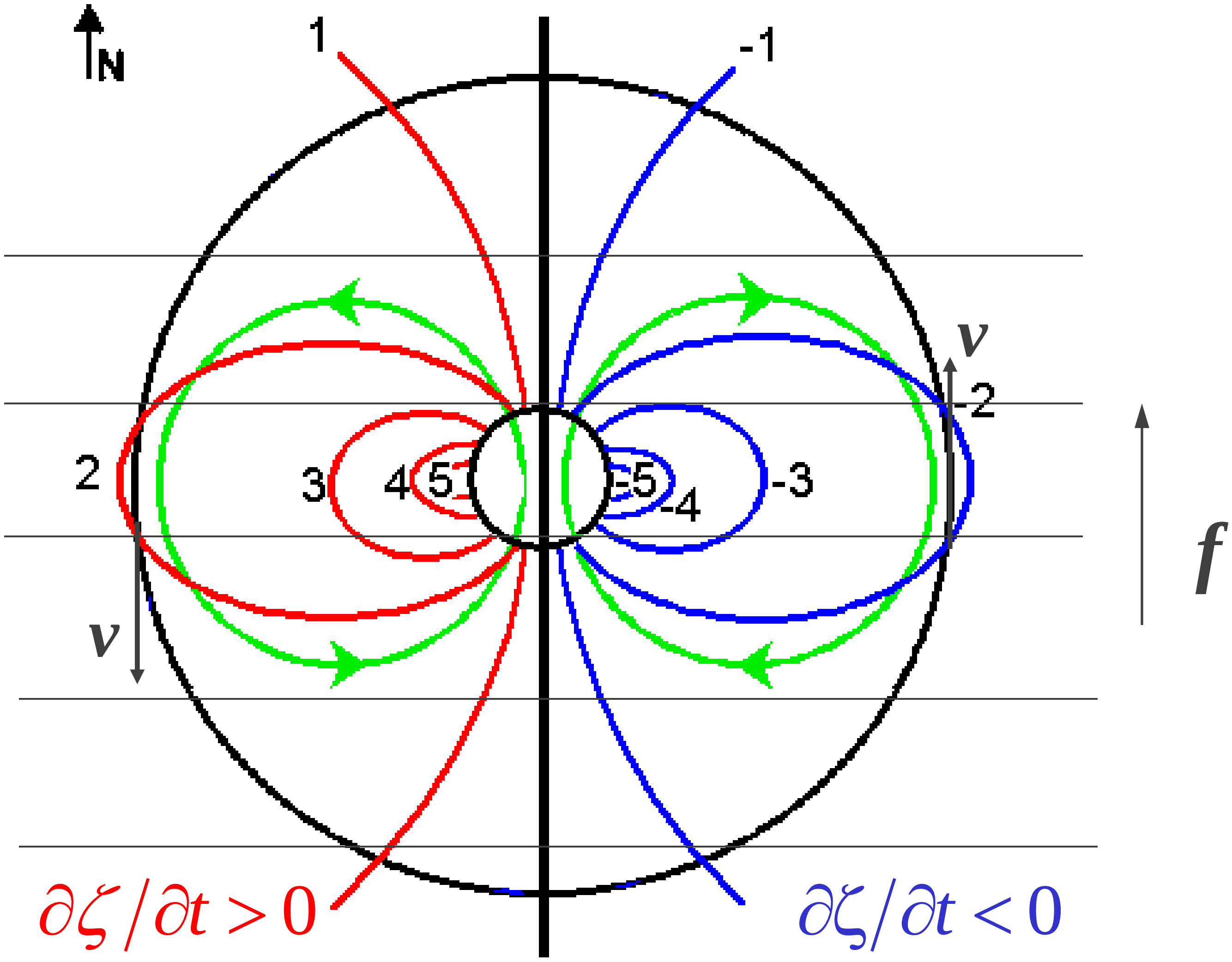
- In an environment with a weak flow, the advection of planetary vorticity βv becomes important. This is known as the **β effect** ($\beta = df/dy = \nabla f$).

- If the environmental flow is zero, the barotropic vorticity equation becomes

$$\partial\zeta/\partial t = - \beta v$$

where v is the meridional wind of the TC, so that the max $\partial\zeta/\partial t$ is to the west of the cyclone:

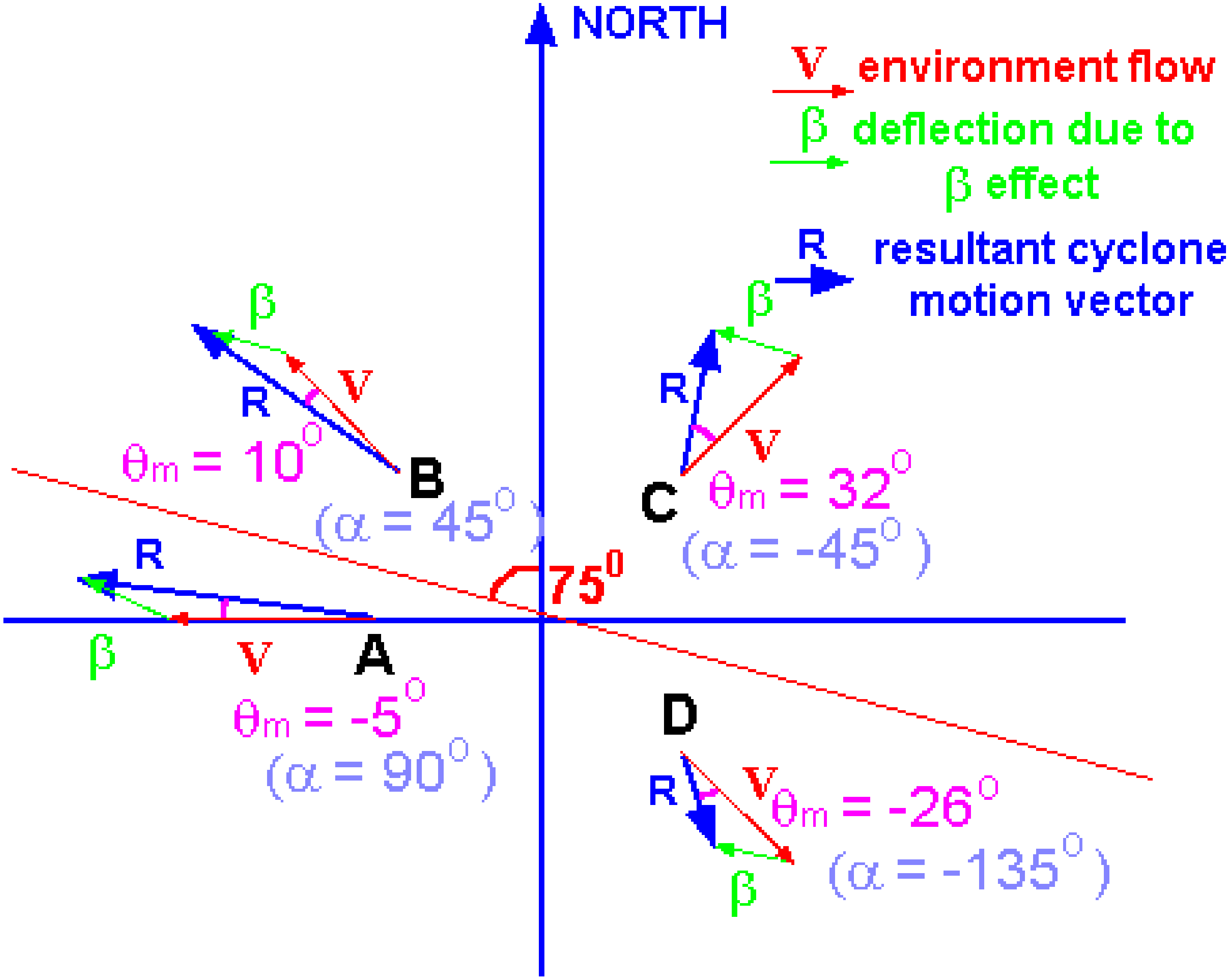
The Linear Beta Effect



- Physically, this is because β (= df/dy) is constant and the meridional component is maximum to the west of the cyclone.
- However, an increase in ζ to the west and a decrease to the east will induce a secondary circulation → northward motion.
- The combined effect therefore produces a northwestward motion. In the Southern Hemisphere, the motion is towards the southwest.

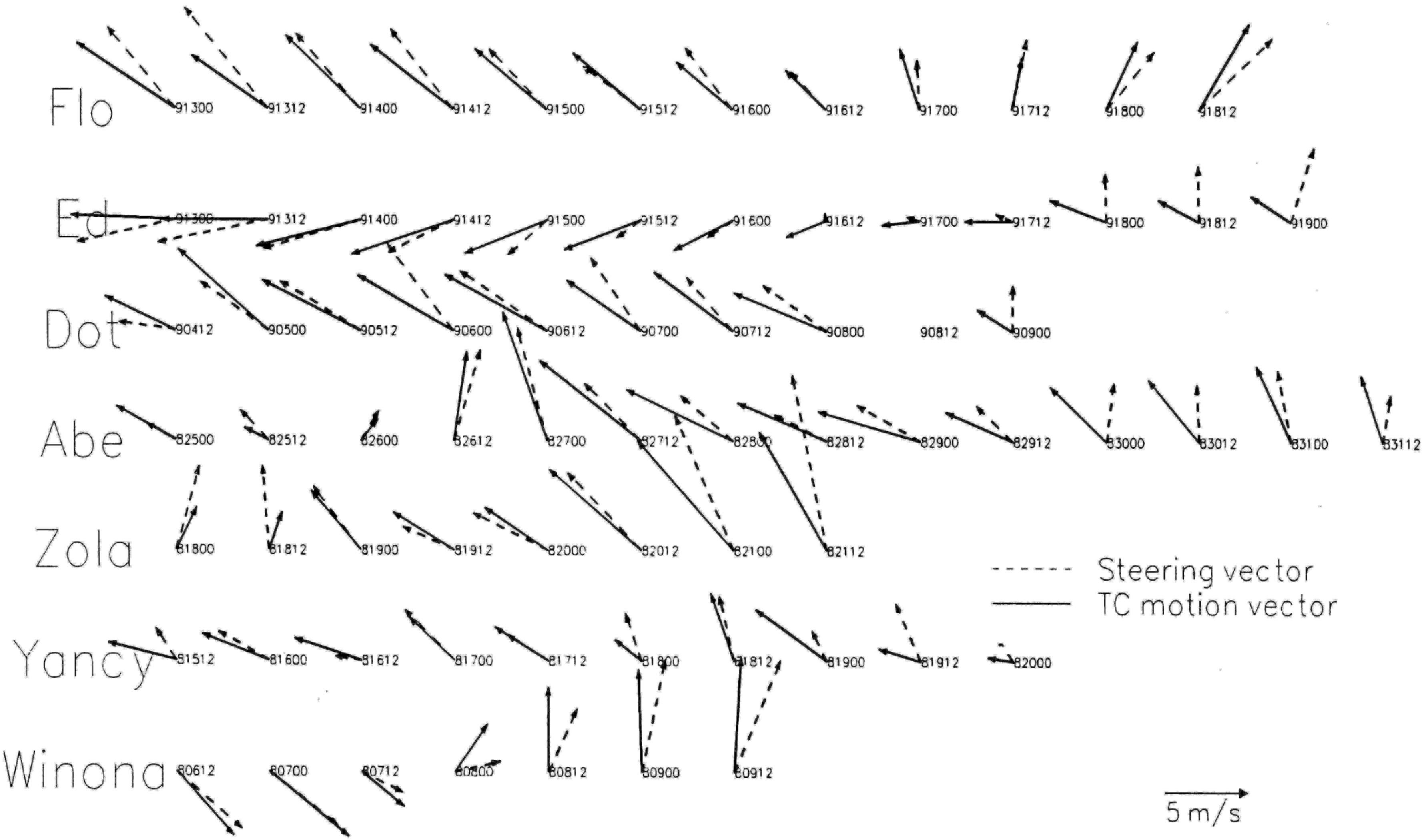
- Because the Coriolis force is always present, this westward and poleward motion is present in ***all*** tropical cyclones
- If we now include the steering flow, the movement of a TC is then a combination of the steering flow and this westward and poleward motion.

Steering + beta effect



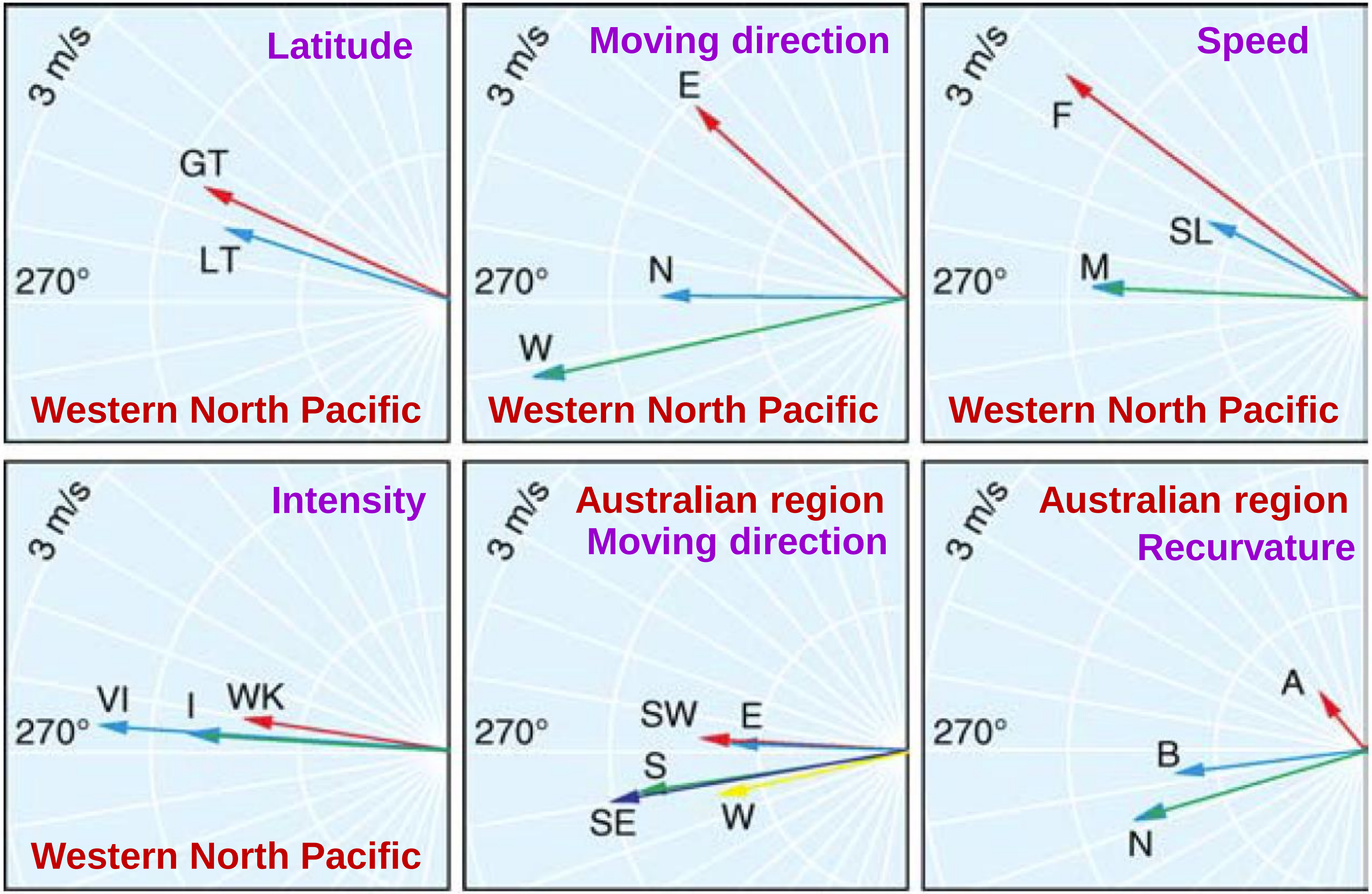
Ngan and Chan (1995)

Steering vs TC motion (Observed)



Carr and Elsberry (1990)

TC motion vector minus 5-7° azimuthally-averaged flow vector

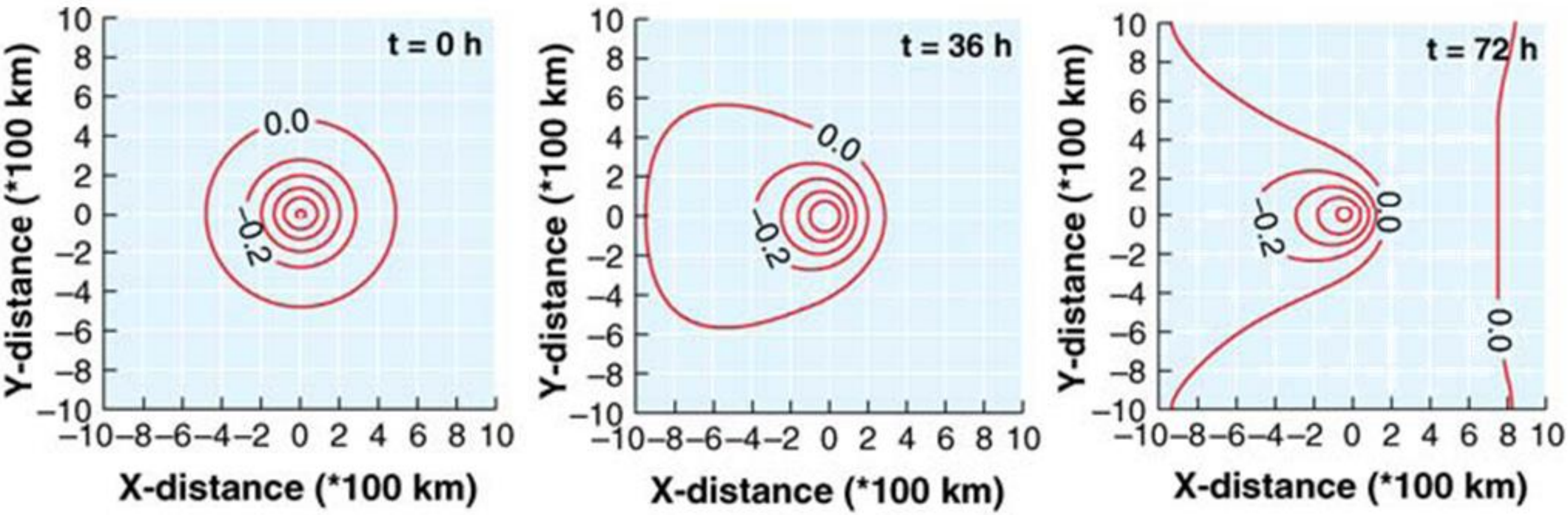


Thus, ***a tropical cyclone will move in a direction and with a speed different from those of the steering flow. This deviation depends on the direction of the steering flow.***

Chan and Williams (1987)

The linear beta effect

Integrating the linear barotropic vorticity equation in time with an idealized vortex (i.e. assuming the changing relative vorticity will not feed back to the meridional wind) yields the following results (contours are the streamfunction):



Observations

- Instead of a northwestward motion, the vortex remains almost stationary but is stretched westward.
- The westward stretch is due to Rossby wave dispersion, with longer waves dispersing faster, and thus the outer circulation propagating more, leading to the "stretch" of the vortex

$\Rightarrow$ ***The linear beta effect cannot explain the observed beta effect.***

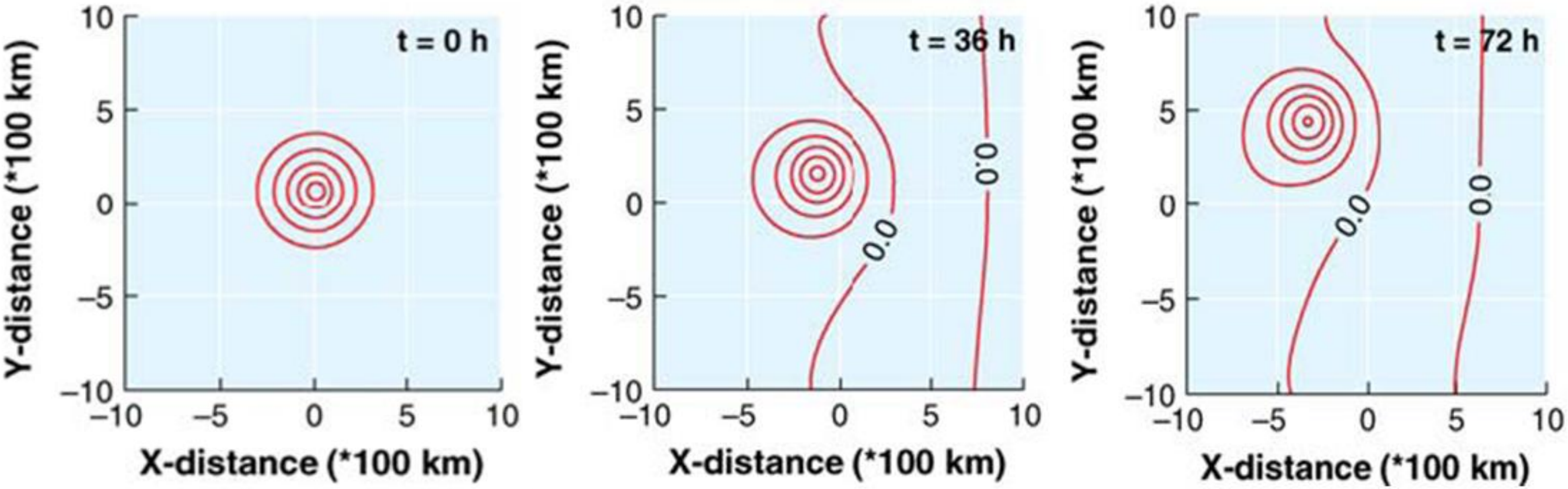
The nonlinear beta effect

Chan and Williams (1987)

$$\frac{\partial \zeta}{\partial t} = -\mathbf{V}_{\mathrm{H}} \cdot \nabla(\zeta + f) = -\mathbf{V}_{\mathrm{H}} \cdot \nabla \zeta - \beta v$$

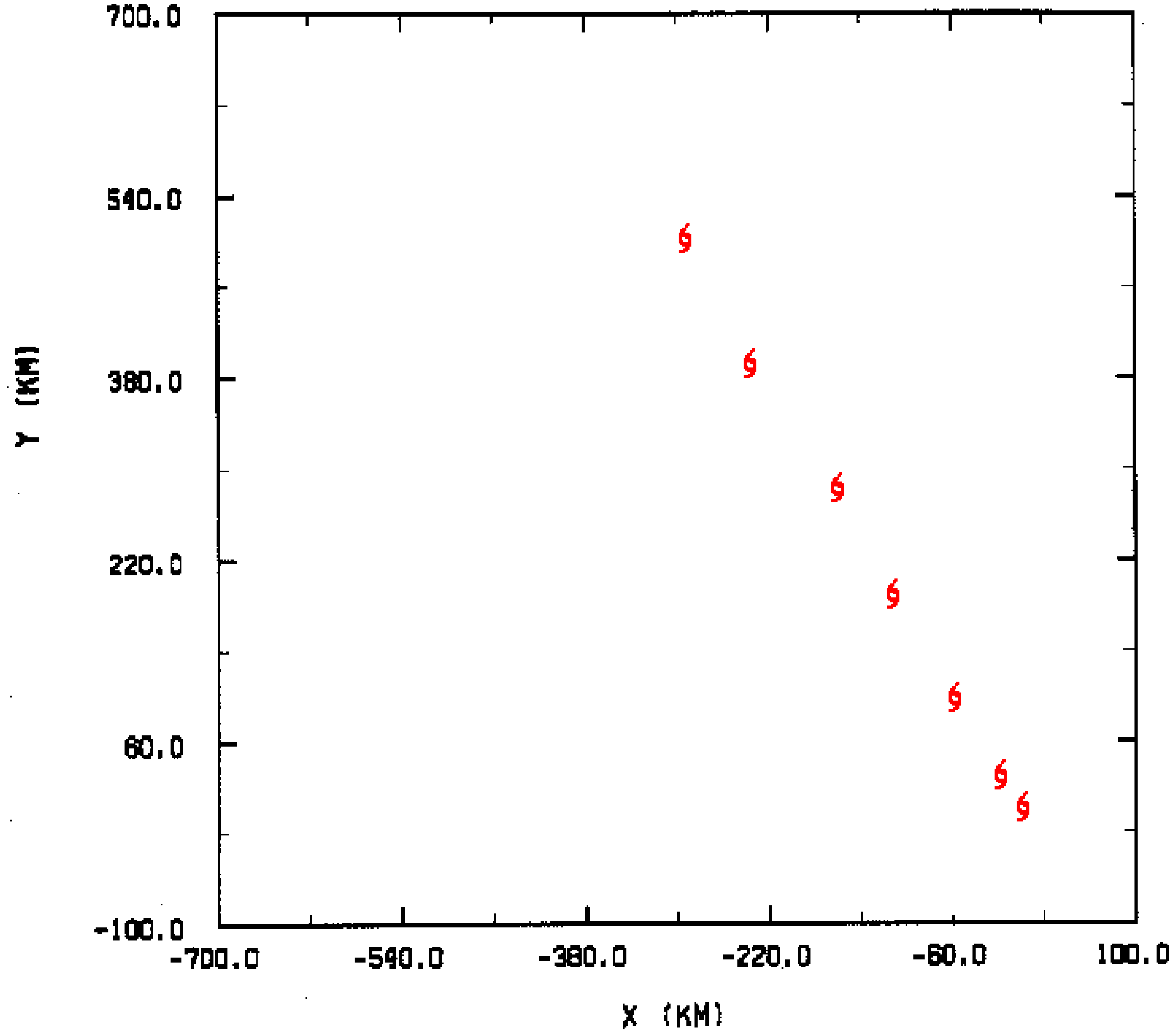
$$\nabla^2 \psi = \zeta$$

$$\mathbf{V} = \mathbf{k} \times \nabla \psi$$



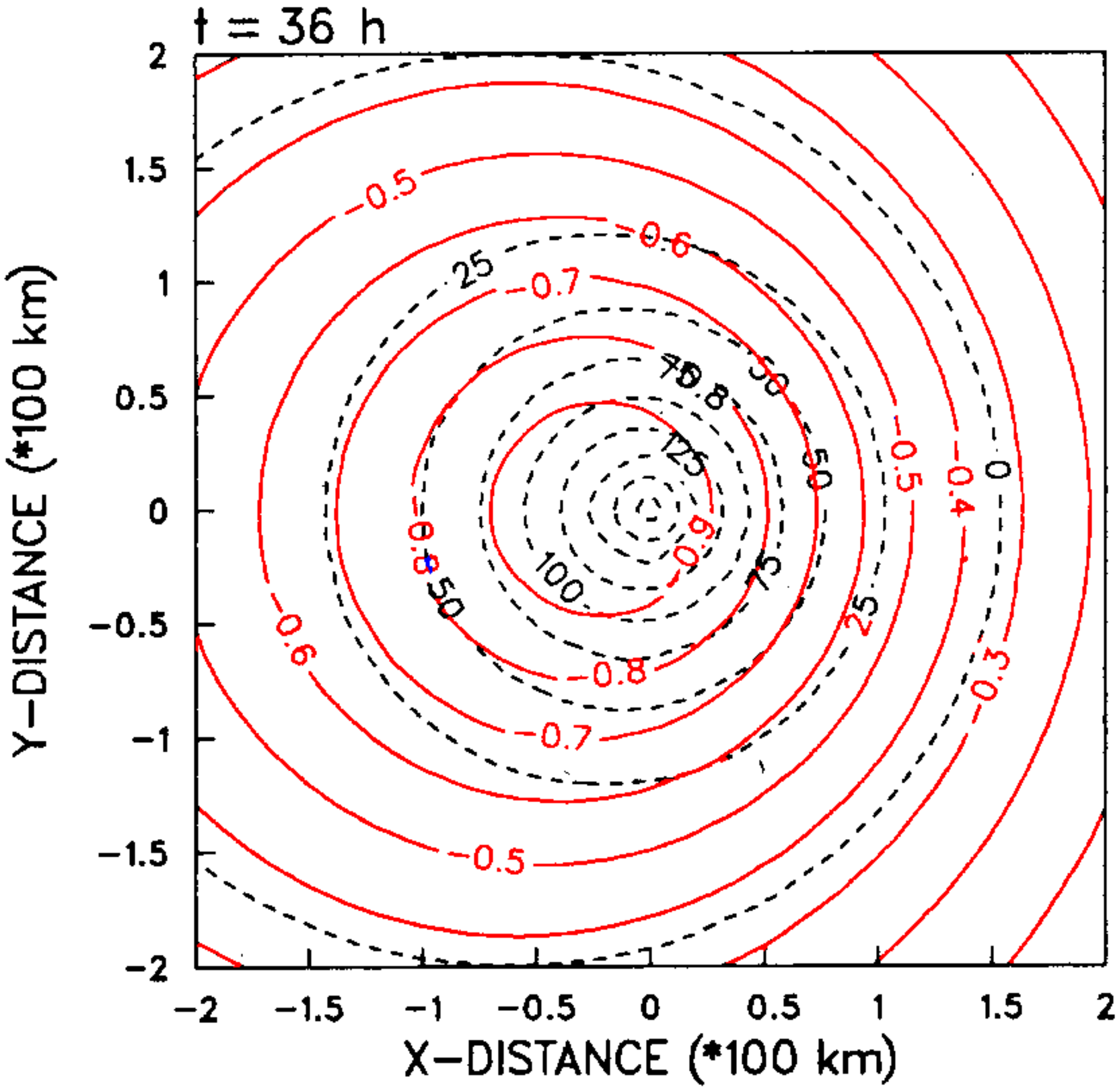
Trajectory of the Vortex

Chan and Williams (1987)



Chan and Williams (1987)

Streamfunction and Vorticity



b = 1.0

r_m = 100 km

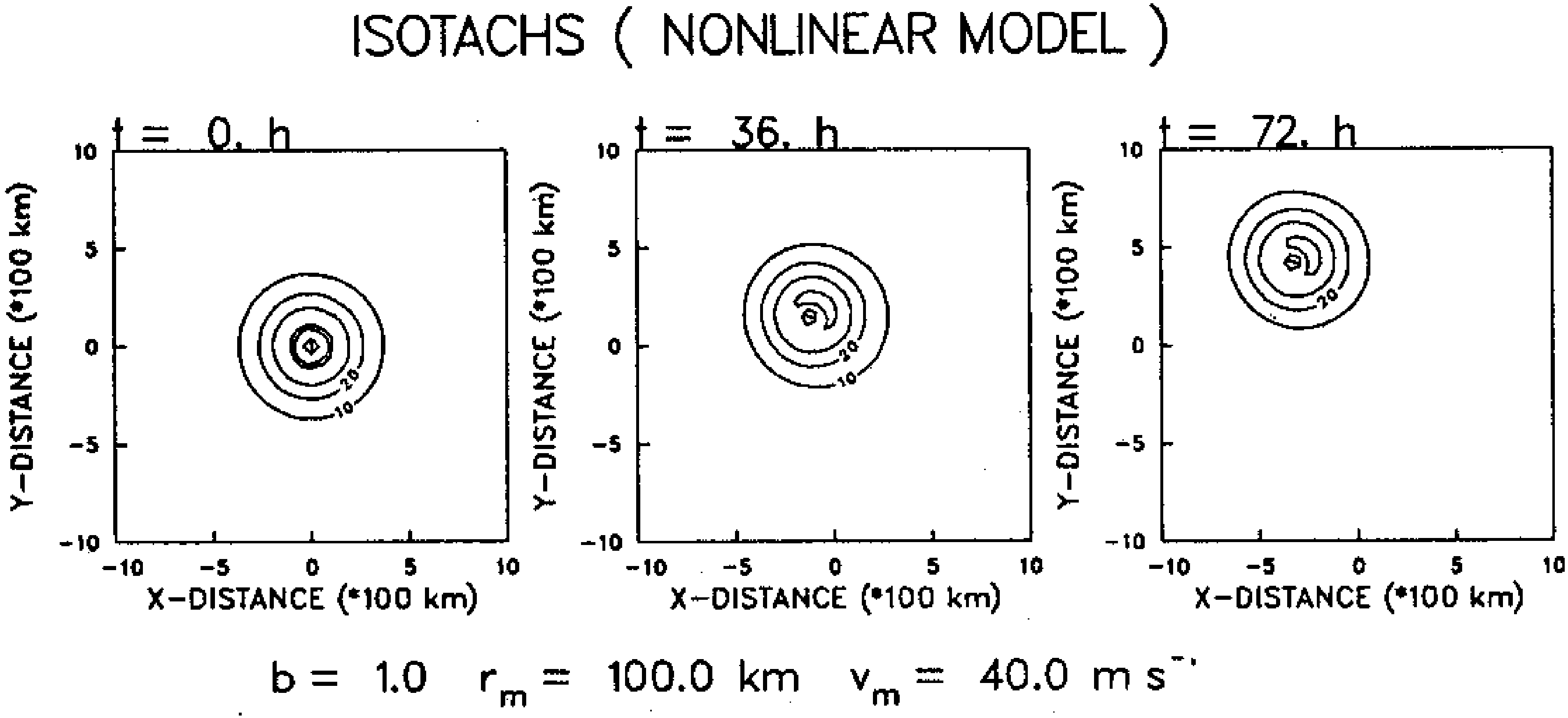
v_m = 40 m s^{-1}

- - - - streamfunction

—— vorticity

Chan and Williams (1987)

Total wind speed



Fiorino and Elsberry (1989)

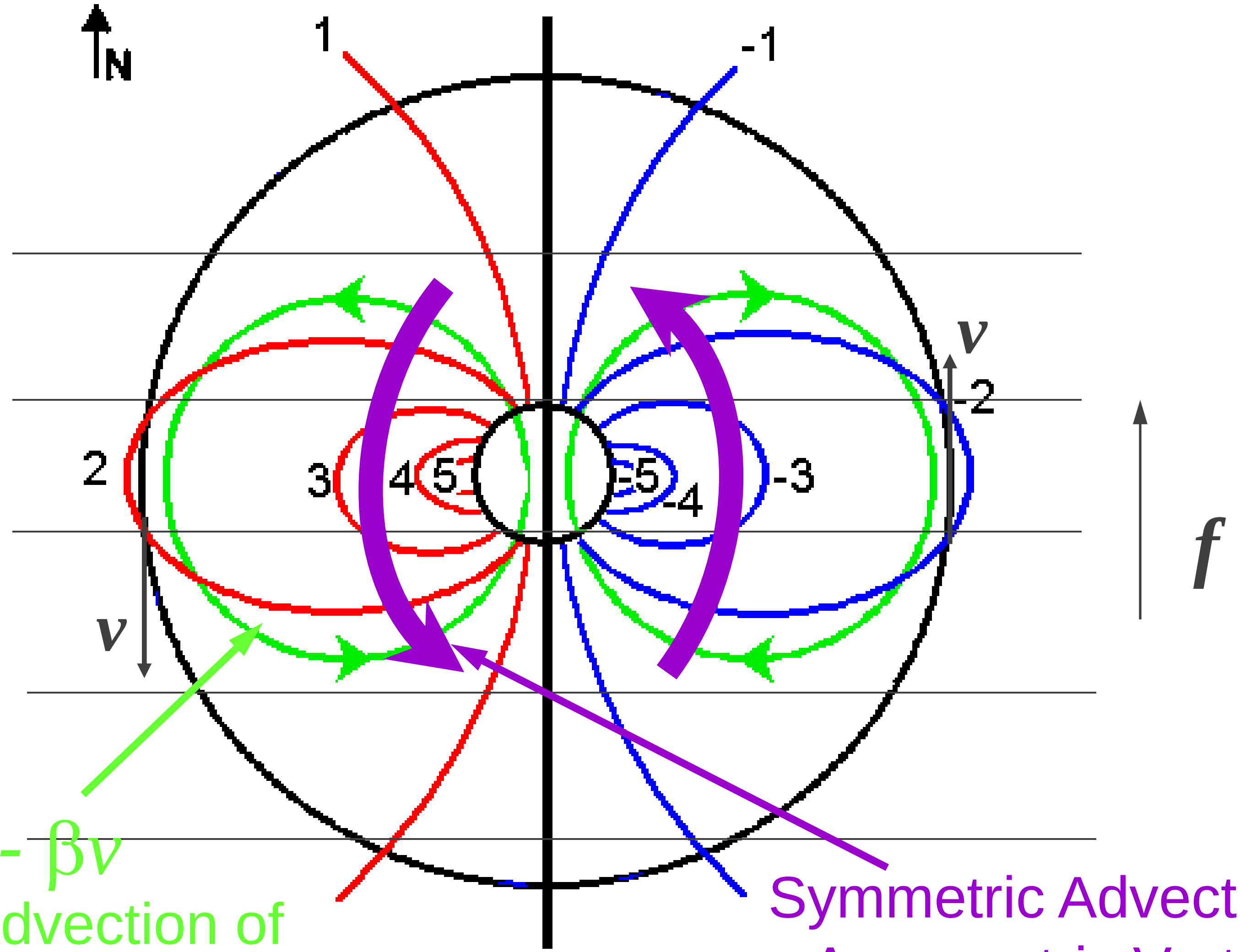
$$\frac{\partial \zeta}{\partial t} = \underbrace{-\mathbf{V}_{\mathbf{a}} \bullet \nabla \zeta_{\mathbf{s}}}_{\text{AASV}} \underbrace{-\mathbf{V}_{\mathbf{s}} \bullet \nabla \zeta_{\mathbf{a}}}_{\text{SAAV}} \underbrace{-\mathbf{V}_{\mathbf{a}} \bullet \nabla \zeta_{\mathbf{a}}}_{\text{AAAV}}$$

Asymmetric Advection of Symmetric Vorticity

Symmetric Advection of Asymmetric Vorticity

Asymmetric Advection of Asymmetric Vorticity

The nonlinear beta effect



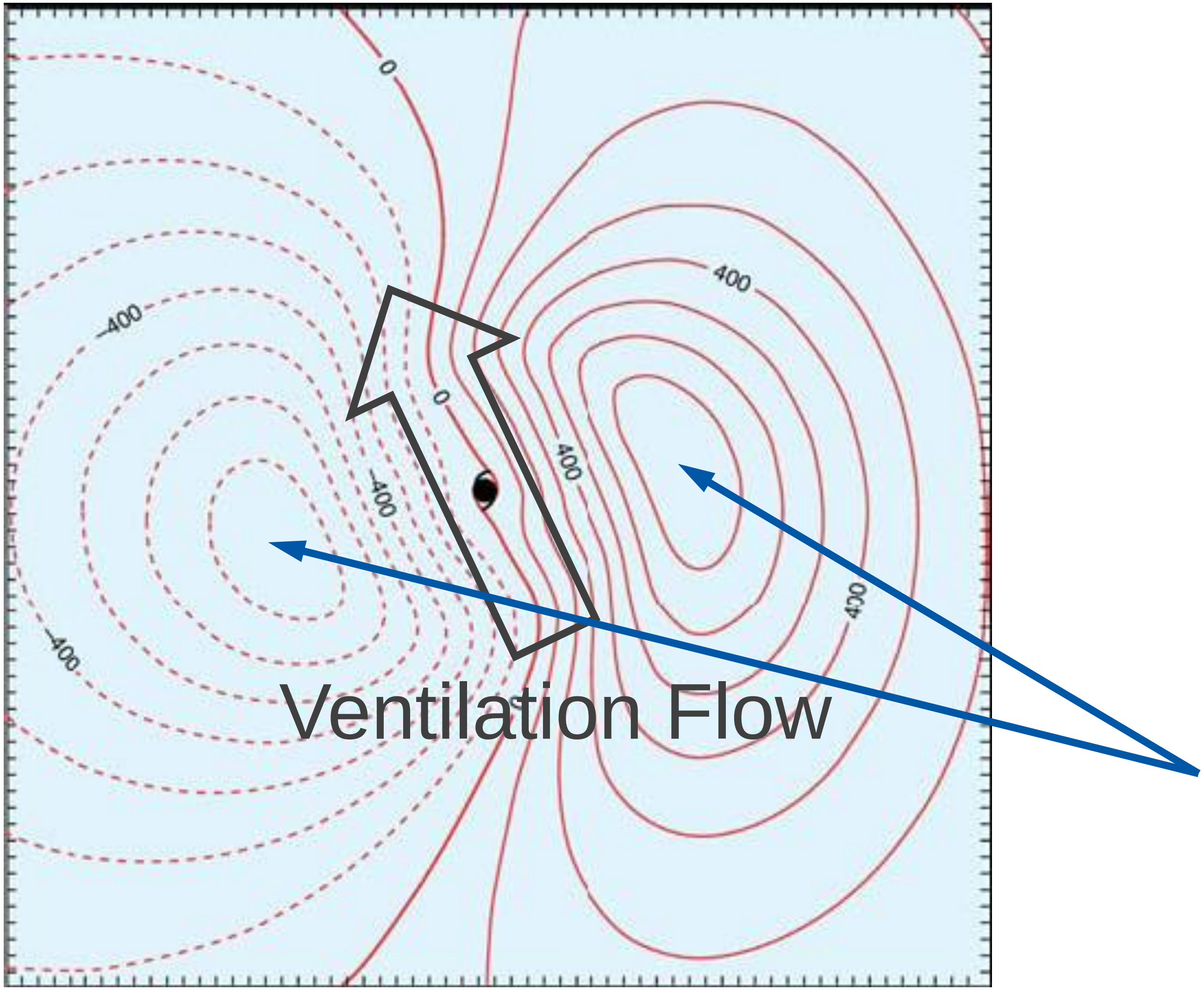
$\partial\zeta/\partial t = -\beta v$

Asymmetric Advection of Symmetric Vorticity

Symmetric Advection of Asymmetric Vorticity

Fiorino and Elsberry (1989)

Asymmetric Streamfunction



Ventilation Flow

beta gyres

Barotropic concept of tropical cyclone motion

A tropical cyclone will move in a direction and with a speed different from those of the steering flow due to the nonlinear beta effect.

Questions

- How does the beta effect vary with
  - ☐ intensity
  - ☐ size
- What if the steering flow is not uniform
  - ☐ in the horizontal
  - ☐ in the vertical?

Chan and Williams (1987)

Variation of direction of movement with intensity and radius of maximum wind

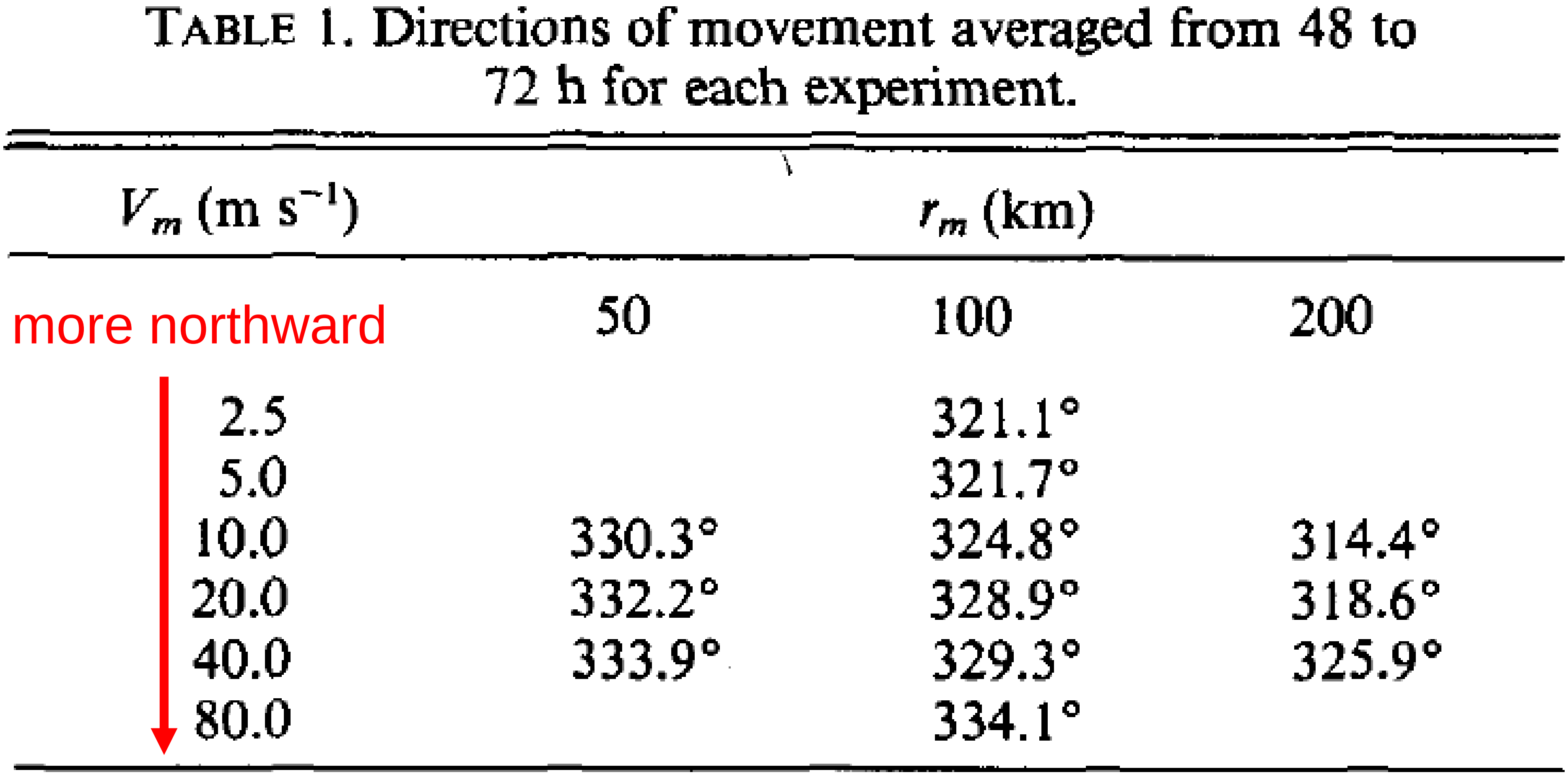


TABLE 1. Directions of movement averaged from 48 to 72 h for each experiment.

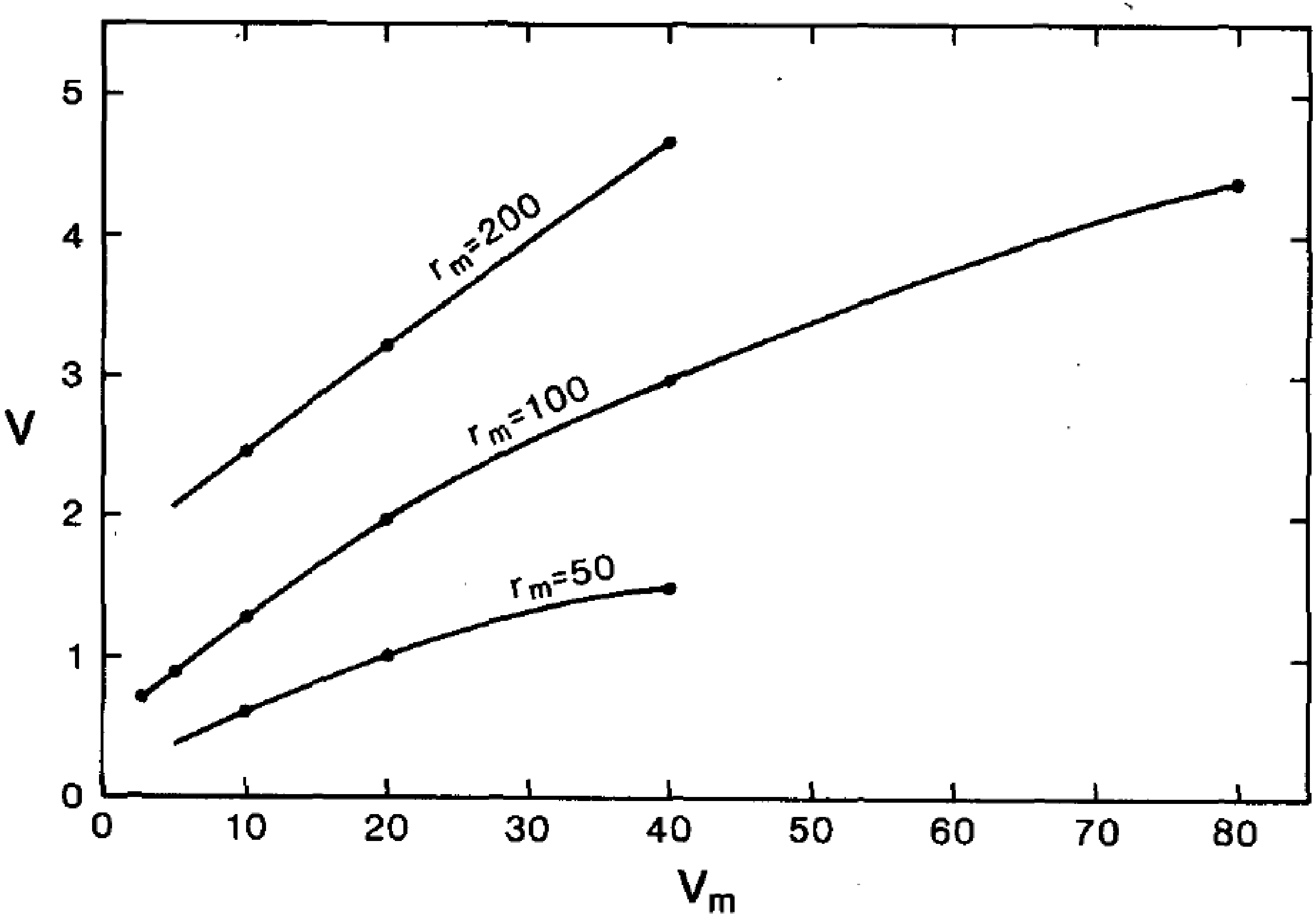
V_m (m s^{-1})	r_m (km)		
	50	100	200
2.5		321.1°	
5.0		321.7°	
10.0	330.3°	324.8°	314.4°
20.0	332.2°	328.9°	318.6°
40.0	333.9°	329.3°	325.9°
80.0		334.1°	

more northward

more westward

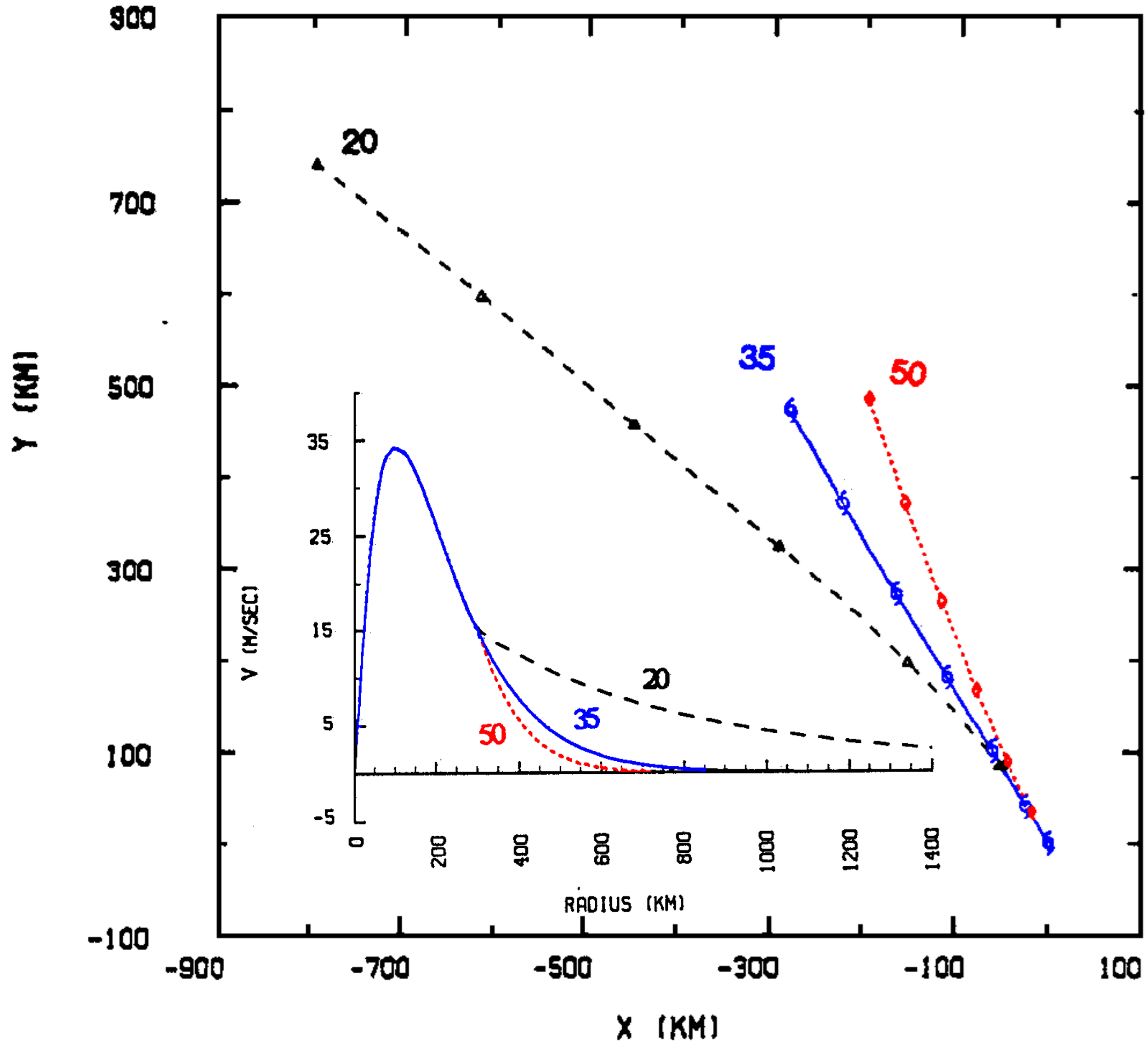
Chan and Williams (1987)

Variation of speed with intensity and radius of maximum wind



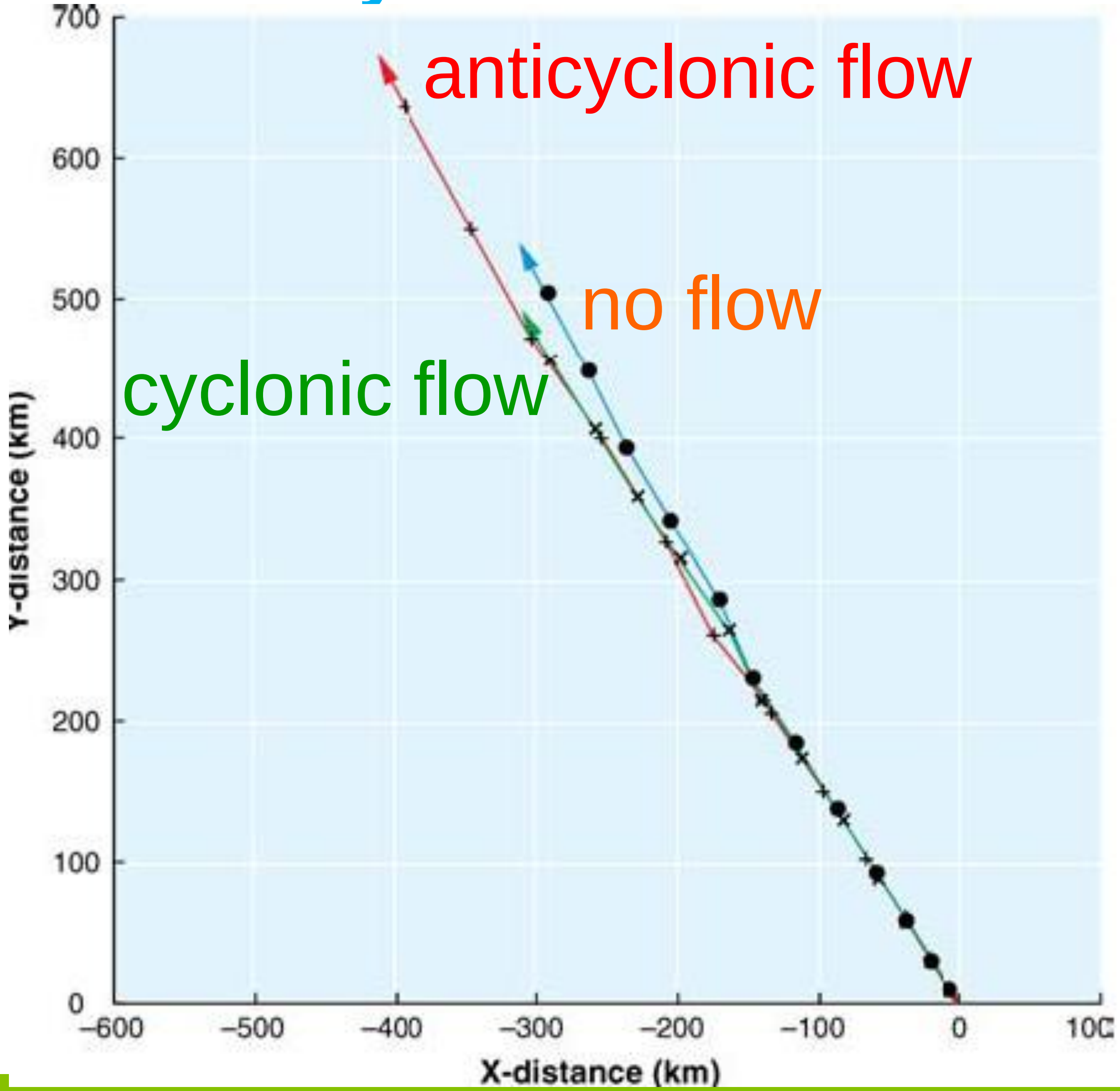
Fiorino and Elsberry (1989)

Variation of track with size



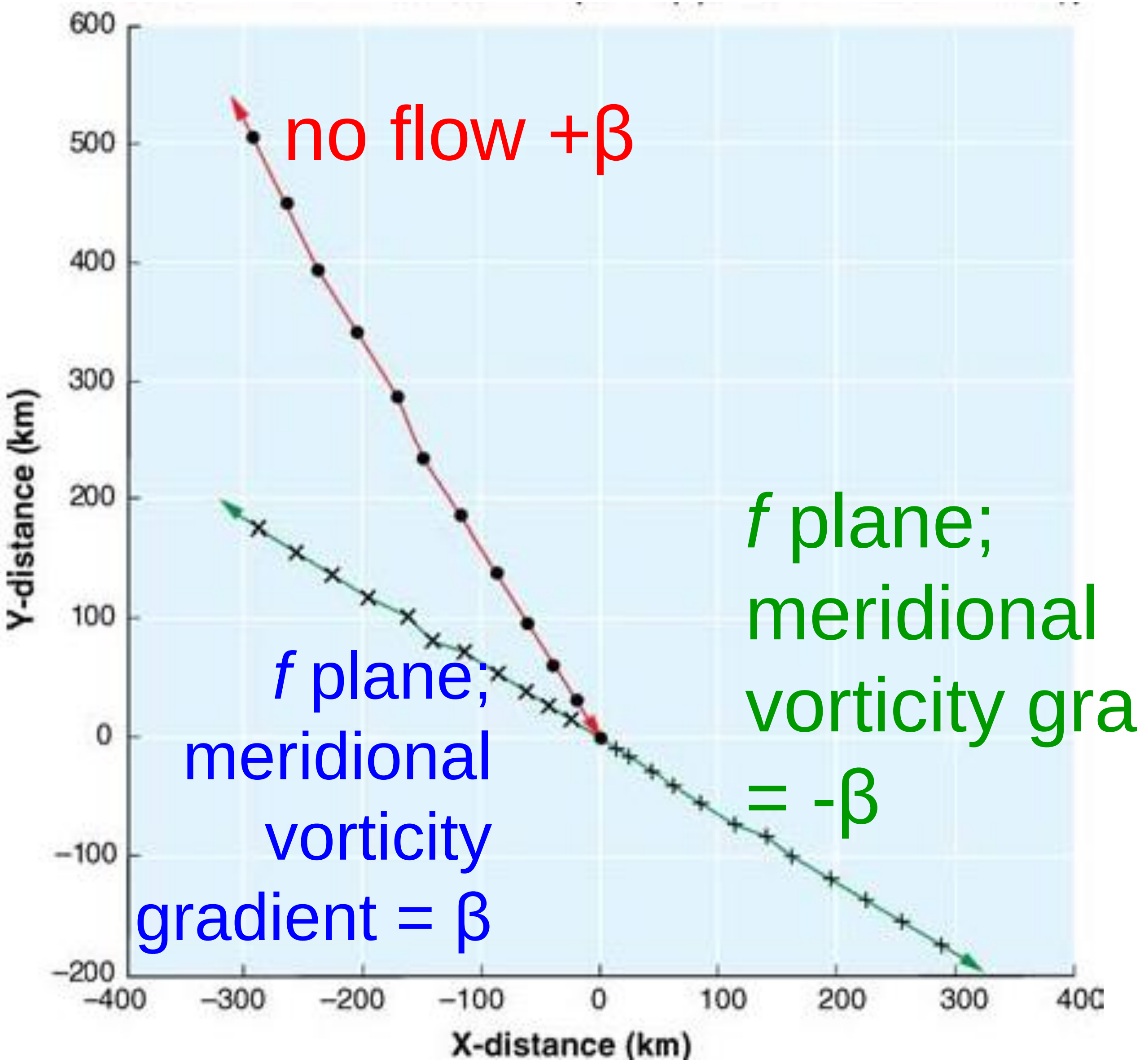
Williams and Chan (1994)

Effect of linearly sheared flow



Williams and Chan (1994)

Effect of meridional vorticity gradient



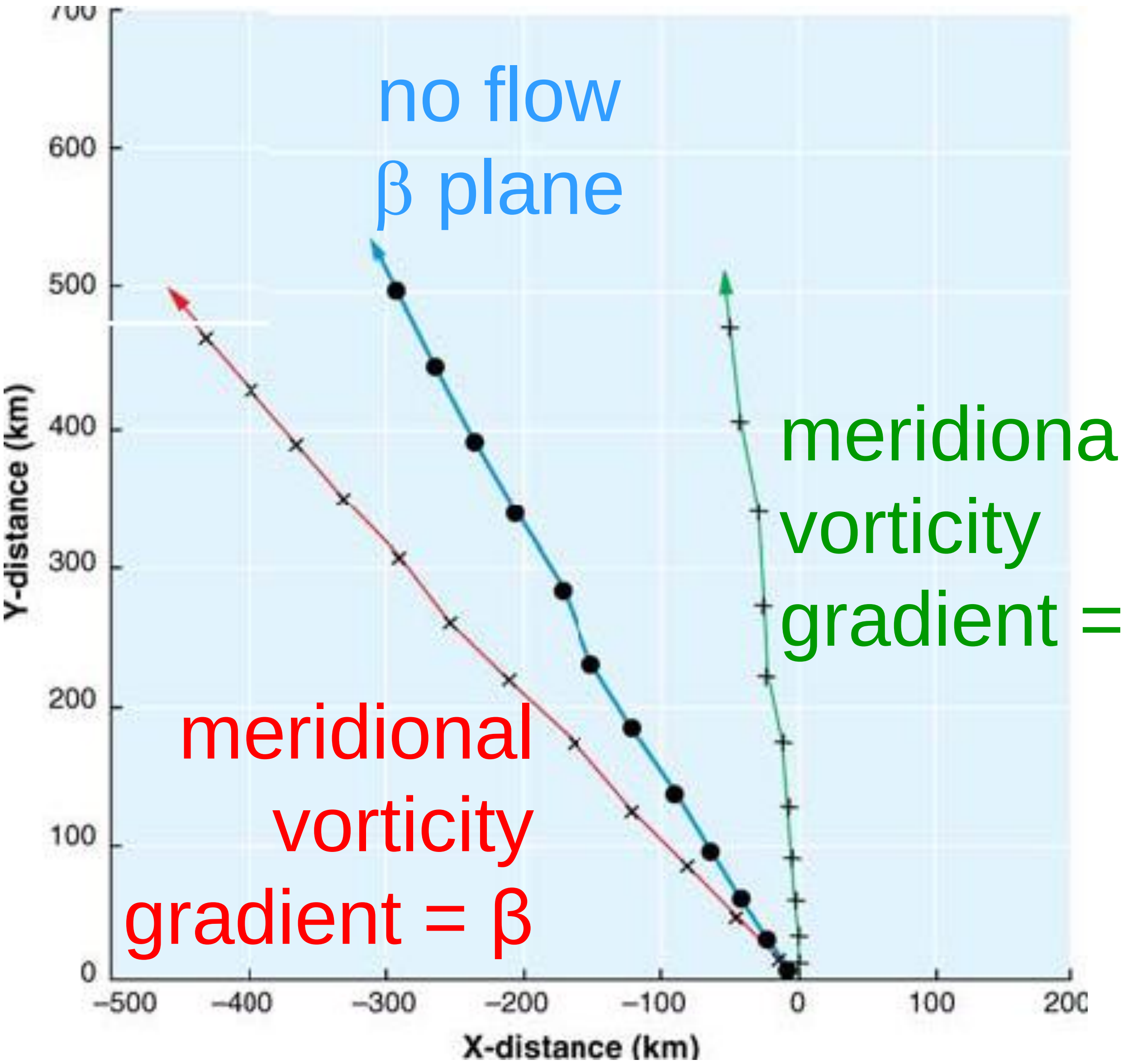
no flow +β

f plane; meridional vorticity gradient = β

f plane; meridional vorticity gradient = -β

Williams and Chan (1994)

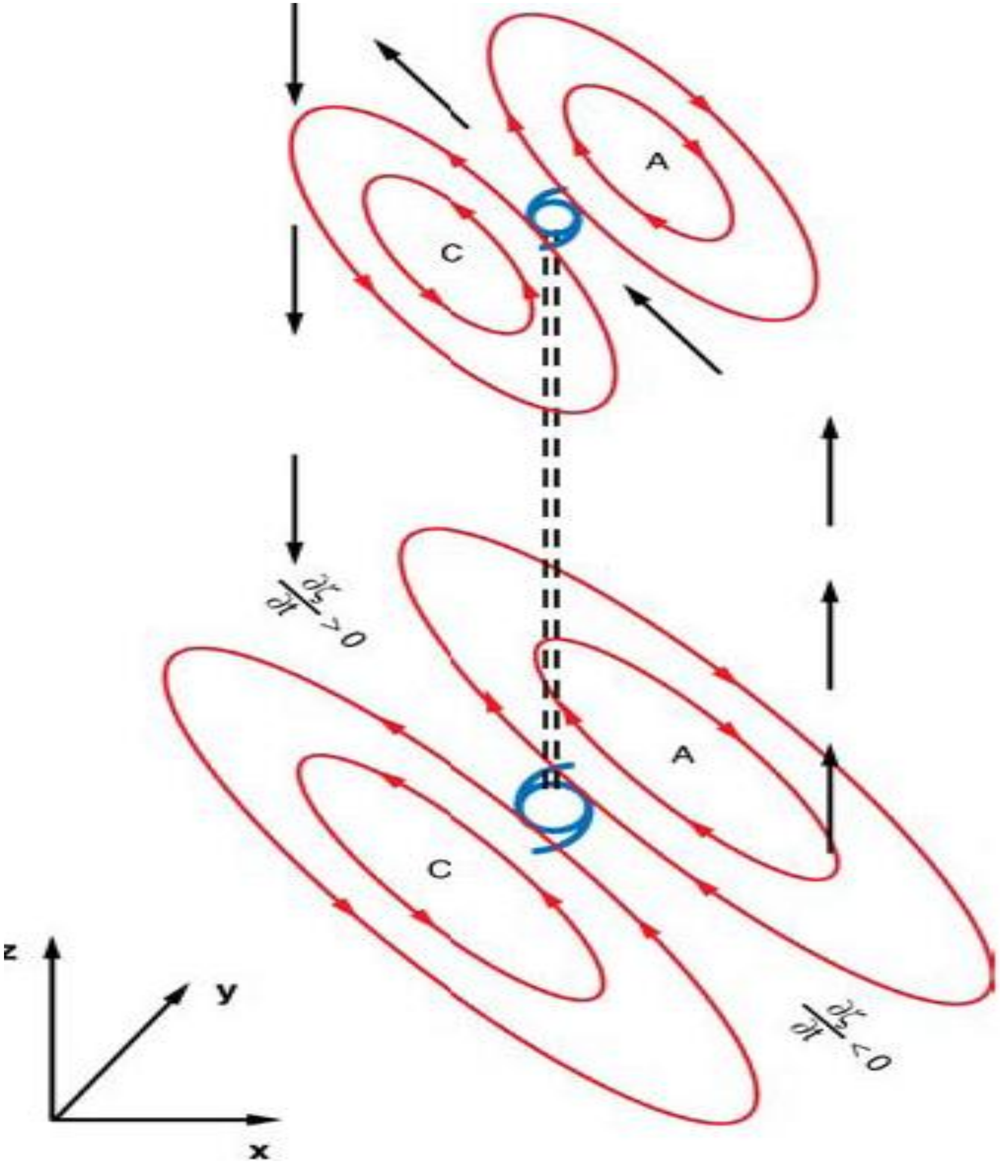
Effect of meridional vorticity gradient + β



Baroclinic Processes: The Potential Vorticity Approach

Elsberry (1995)

Effect of differential β in the vertical



Wu and Wang (2000)'s potential vorticity diagnostic approach:

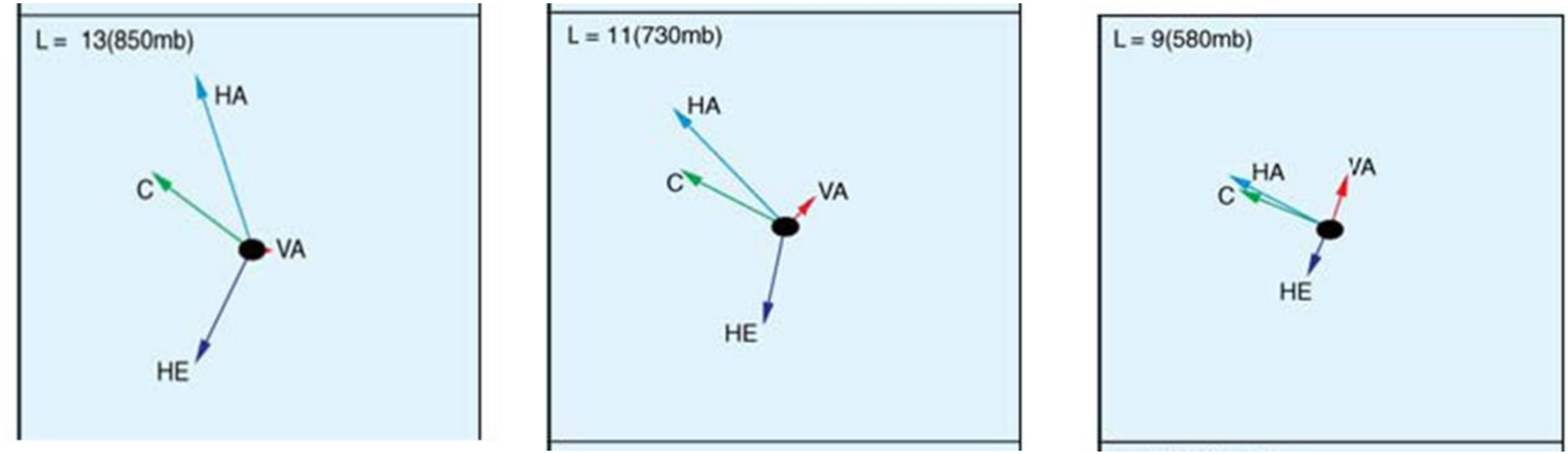
TC moves towards area of max PV tendency

$$\frac{\partial P_1}{\partial t} = \Lambda_1 \left[\begin{Bmatrix} \text{Horizontal} \\ \text{advection} \end{Bmatrix} + \underbrace{\begin{Bmatrix} \text{Vertical} \\ \text{advection} \end{Bmatrix}}_{\text{important near eye and tropopause}} + \begin{Bmatrix} \text{Diabatic} \\ \text{heating} \end{Bmatrix} + \underbrace{\left\{ \text{Friction} \right\}}_{\text{important only in PBL}} \right]$$

Λ_1 - wavenumber 1 (WN-1) operator

Wu and Wang (2000)

Modeling results



C – cyclone motion

HA – horizontal advection

VA – vertical advection

HE – diabatic heating

Chan et al. (2002)

$$\Lambda_1\{\mathrm{HA}\} = \underbrace{-\mathbf{V}_1 \cdot \nabla P_s}_{\mathrm{A}} \; \underbrace{-\mathbf{V}_s \cdot \nabla P_1}_{\mathrm{B}}$$

advection of symmetric PV by asymmetric flow

advection of asymmetric PV by symmetric flow

asymmetric flow:

- environmental (steering) flow
- ventilation flow due to β effect
- flow associated with asymmetric convection

symmetric PV:

- vortex PV
- symmetric part of environmental flow
- PV associated with symmetric convection

symmetric flow:

- vortex flow
- symmetric part of environmental flow

asymmetric PV:

- β gyres
- PV associated with asymmetric convection
- PV associated with asymmetric component of environmental flow

Diabatic Heating

$$DH = g\left[-(f+\zeta)\frac{\partial Q}{\partial p} - \frac{\partial u}{\partial p}\frac{\partial Q}{\partial y} + \frac{\partial v}{\partial p}\frac{\partial Q}{\partial x}\right]$$

Q – heating rate

ζ – relative vorticity

f – Coriolis parameter

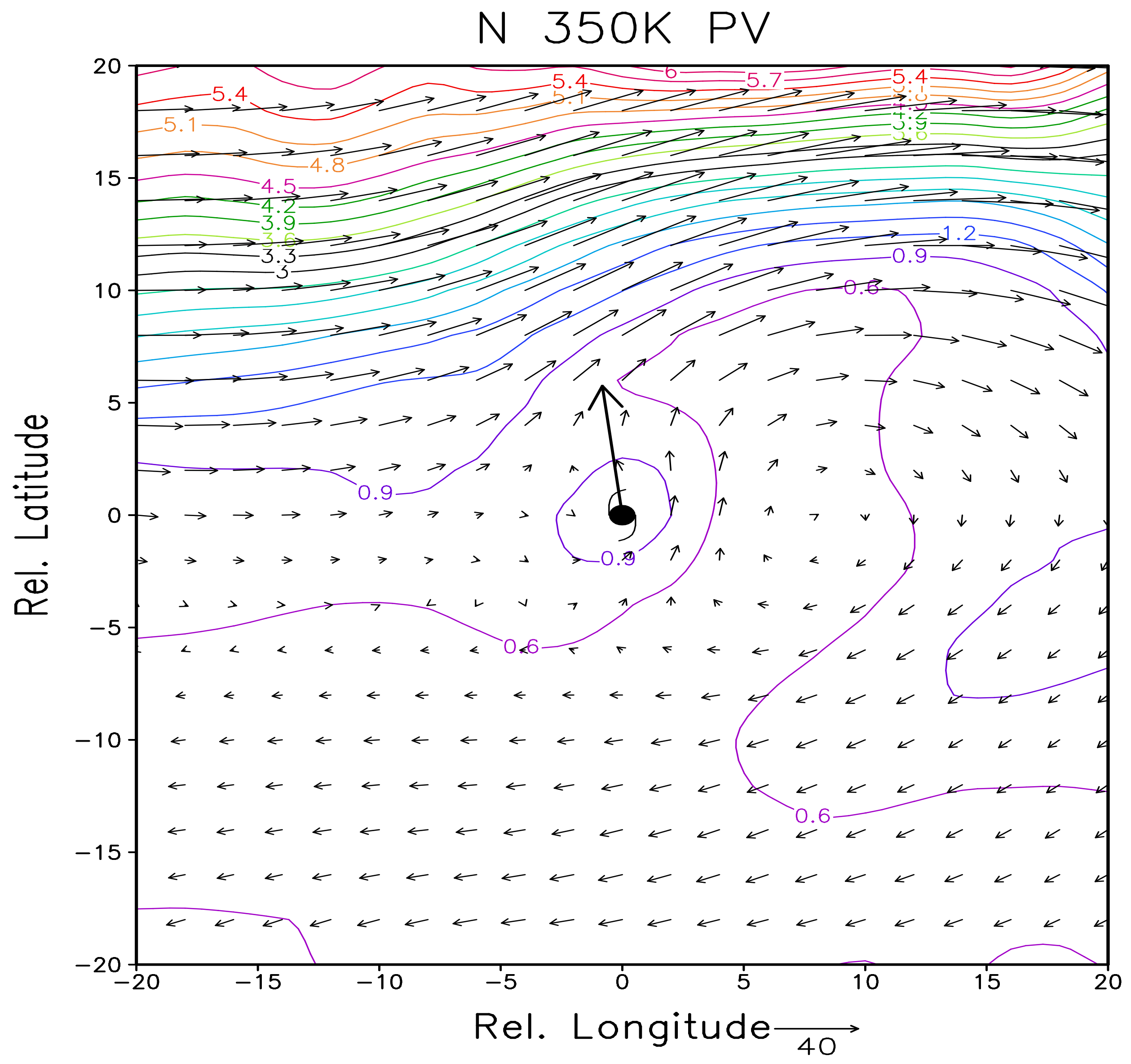
u, v – zonal and meridional wind

p – pressure (vertical coordinate)

$$\frac{\partial P_1}{\partial t} = \begin{Bmatrix} \text{asymmetric advection} \\ \text{of symmetric PV} \end{Bmatrix} + \begin{Bmatrix} \text{symmetric advection} \\ \text{of asymmetric PV} \end{Bmatrix} + \begin{Bmatrix} \text{WN} - 1 \\ \text{Heating} \end{Bmatrix}$$

Example - northward case

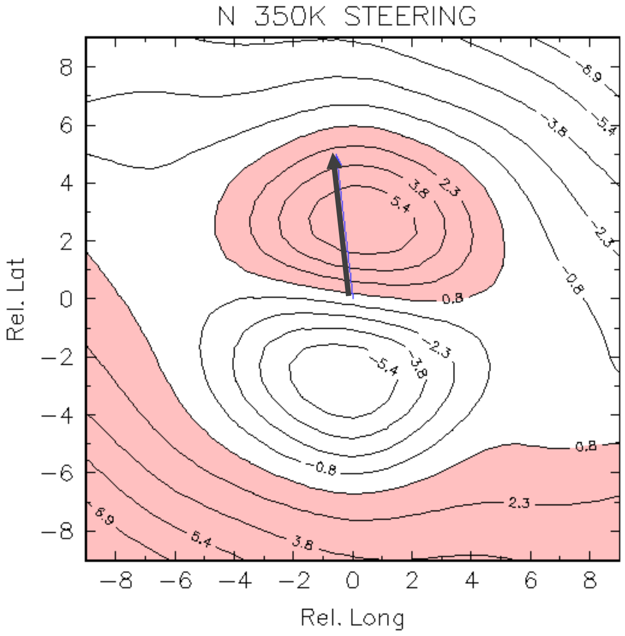
Chan et al. (2002)



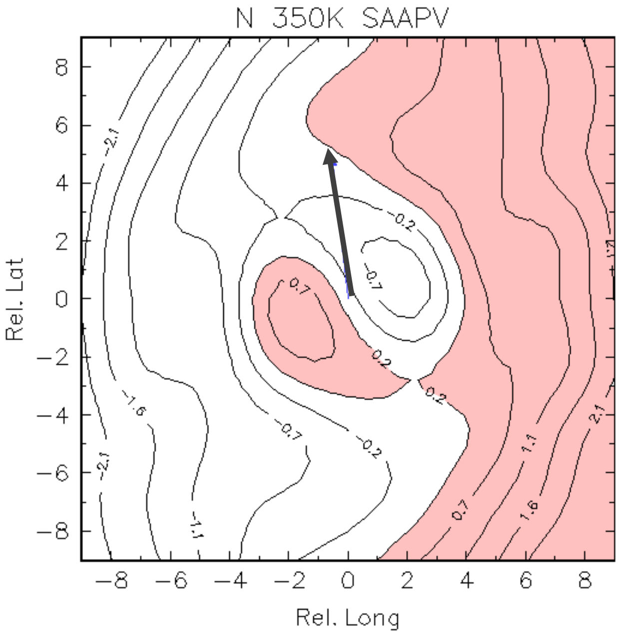
Example - northward case

Chan et al. (2002)

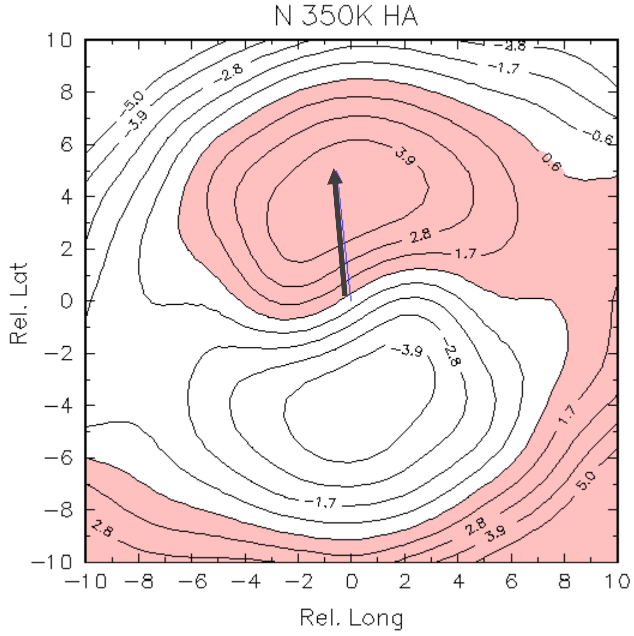
AASPV



SAAPV



Total PV advection



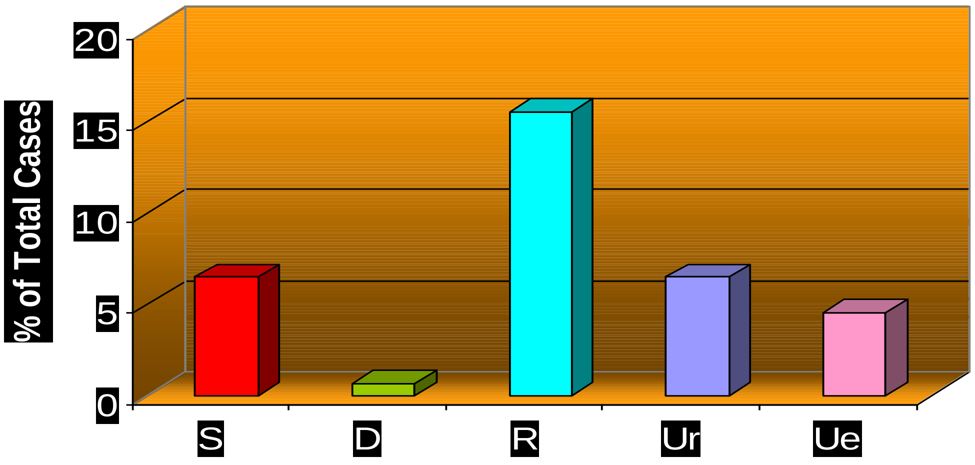
Classification of cases (total: 310; 31 TCs)

Classification	**Criteria**
TC moving towards the steering vector	Deviation between the steering vector and the TC motion vector < 10º
TC moving towards the DH vector	Deviation between the DH and the TC motion vector < 15º
TC moving towards the resultant of the steering and DH vectors	The TC motion vector is in between the steering and DH vectors

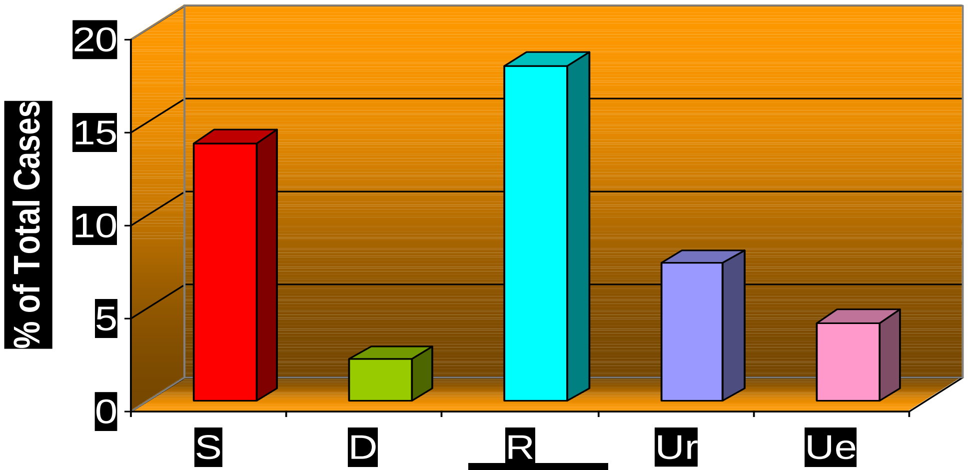
Contribution of various terms

S - Steering control; D - DH control;
R - Resultant control
Ur – Unresolvable; Ue – Unexplainable

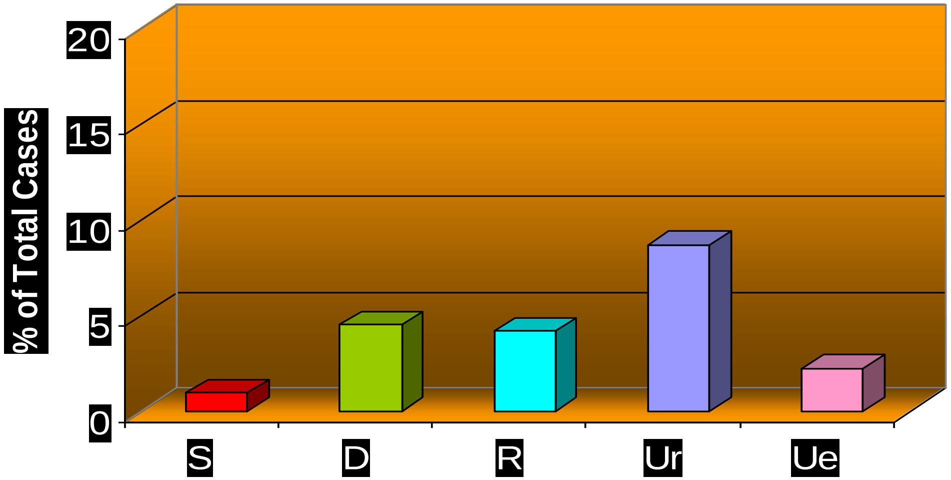
Strong Steering (>10 kt)



Normal Steering (5-10 kt)



Weak Steering (<5 kt)



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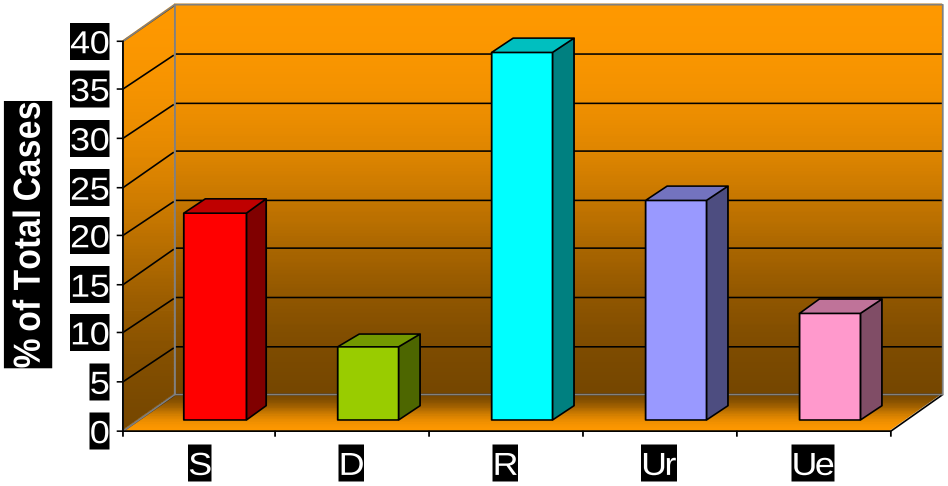
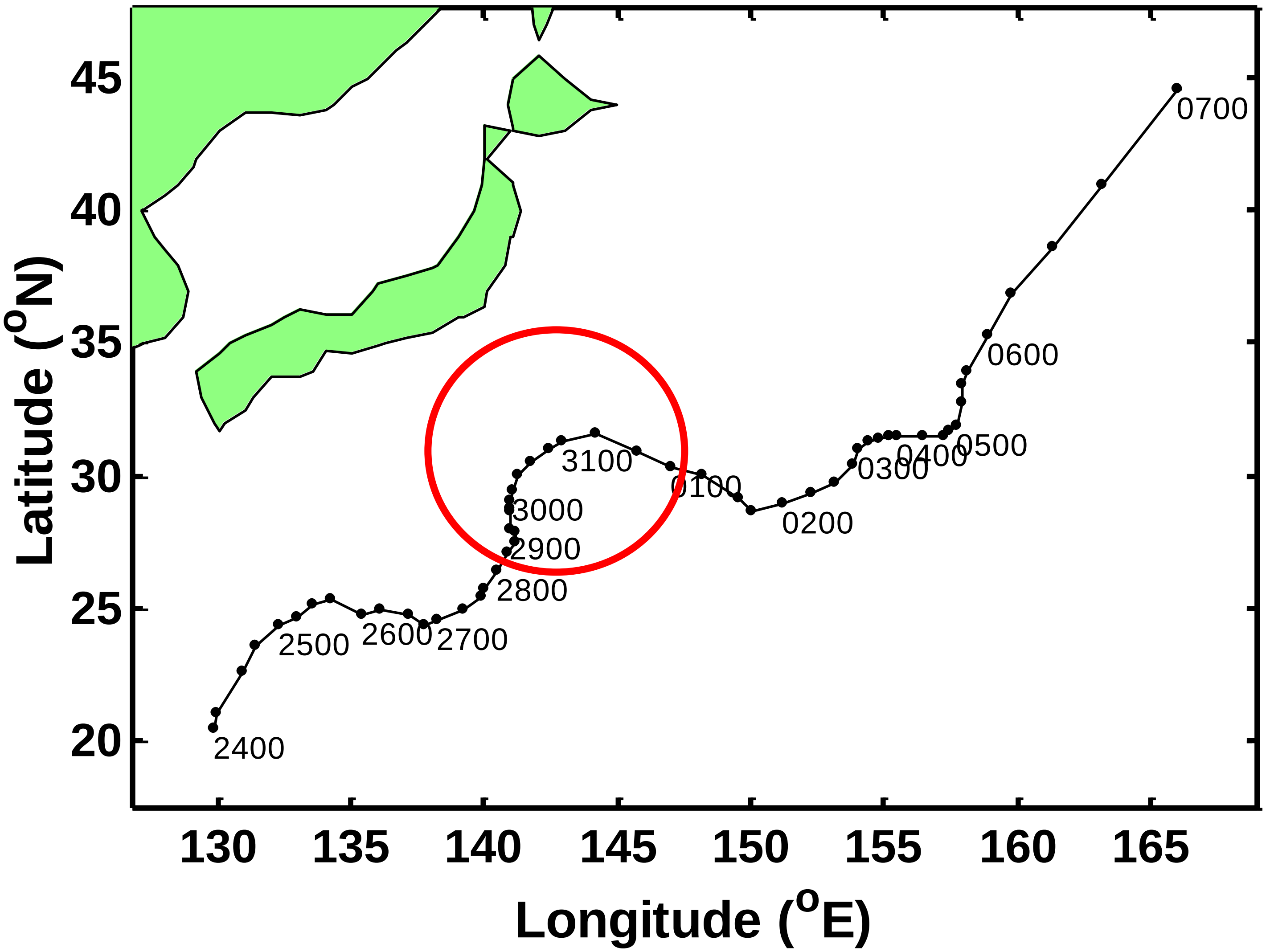
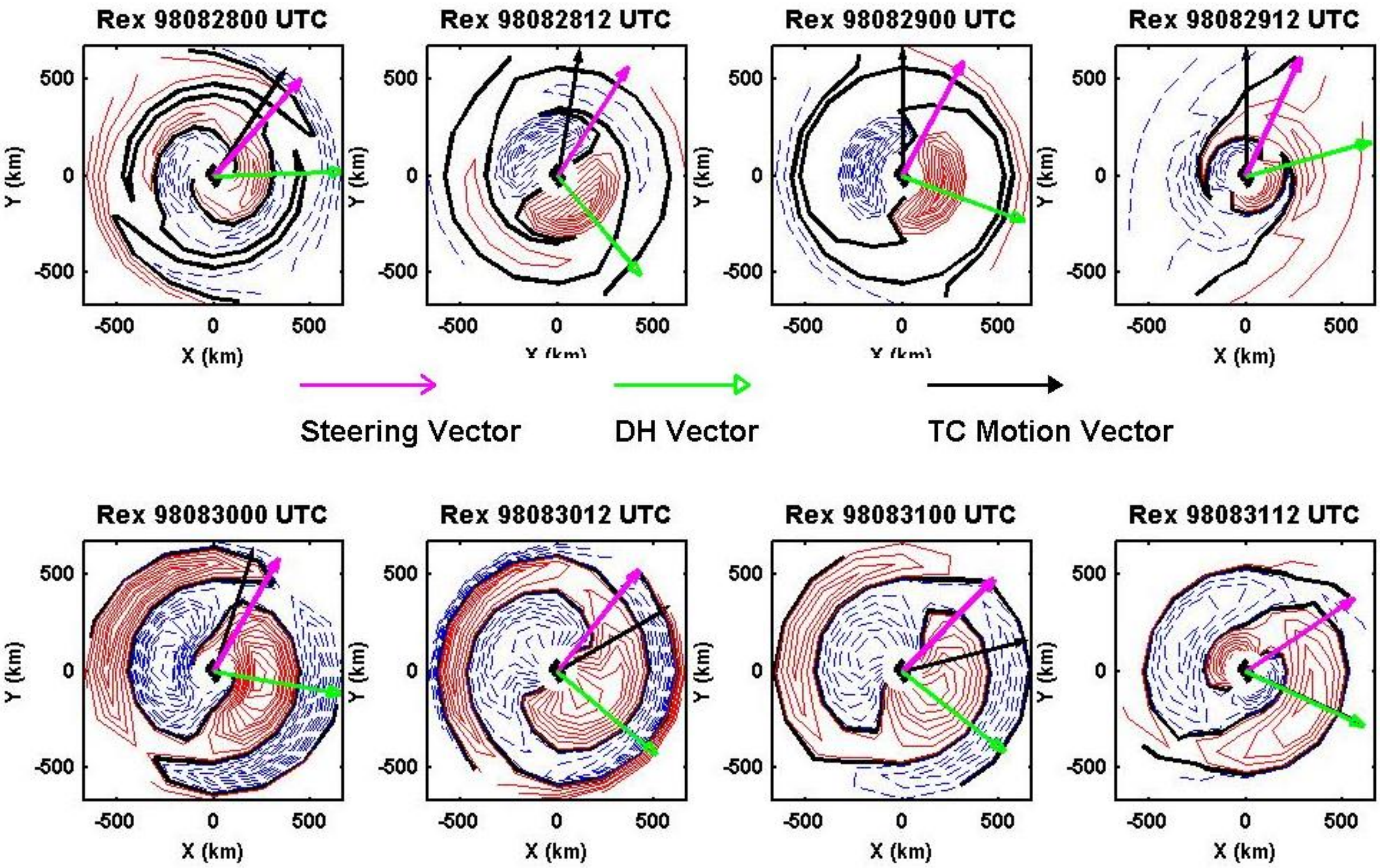


Chan et al. (2002)

Typhoon Rex (1998)

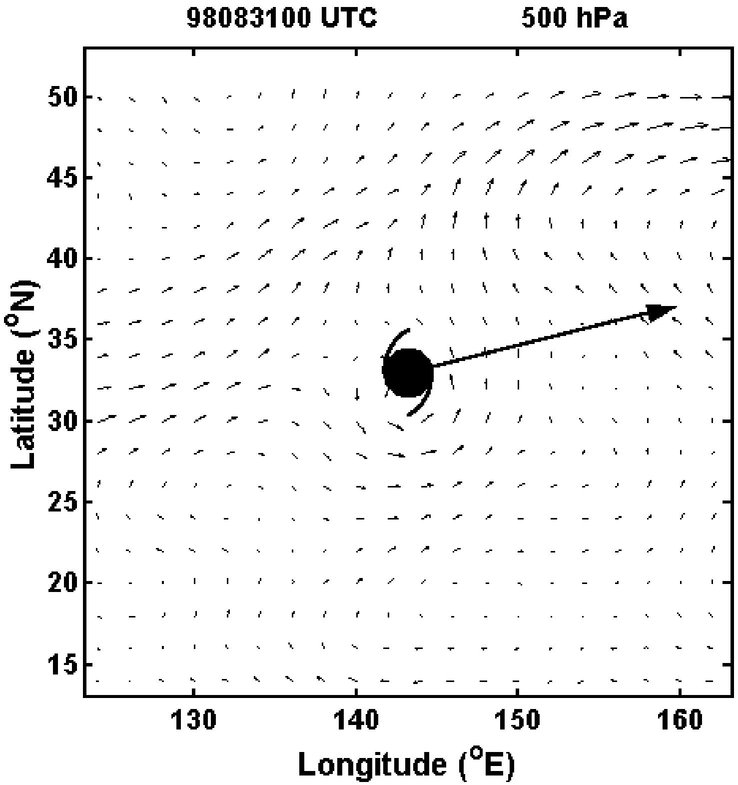


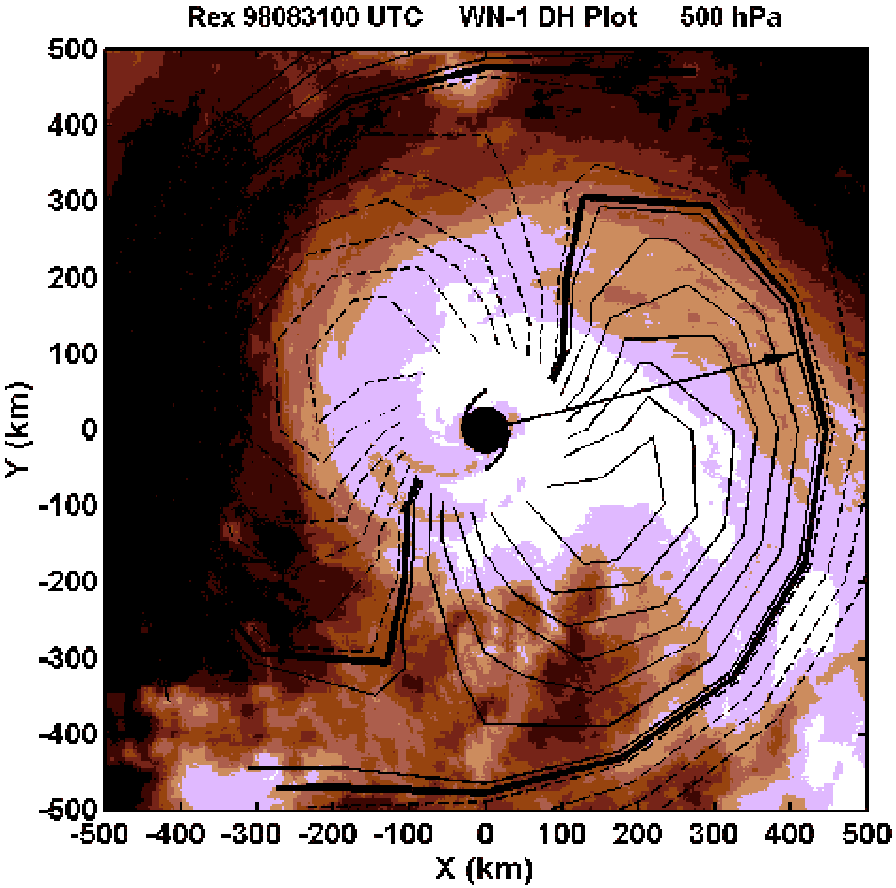
Typhoon Rex (1998) – WN-1 DH distribution



Typhoon Rex (1998)

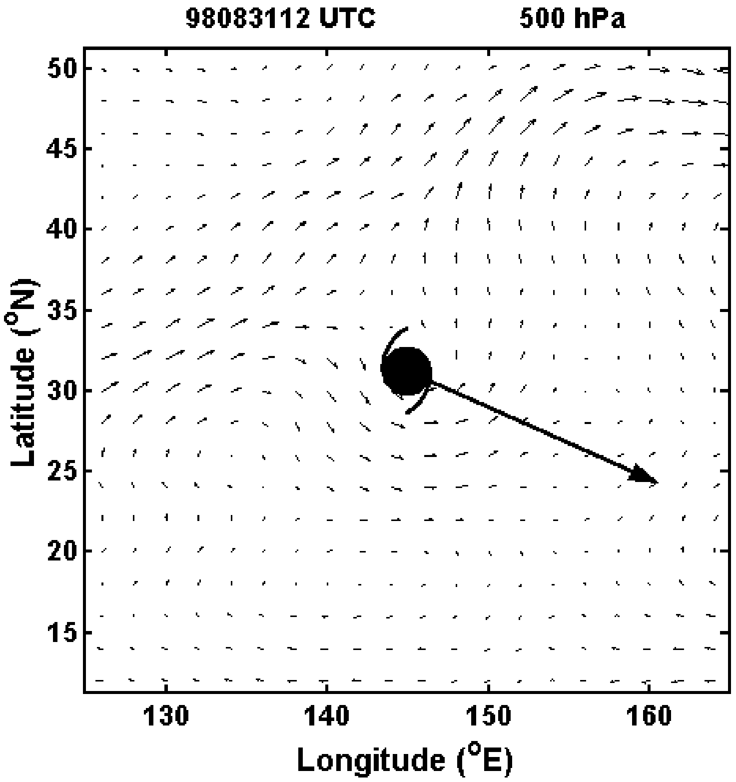
Chan et al. (2002)

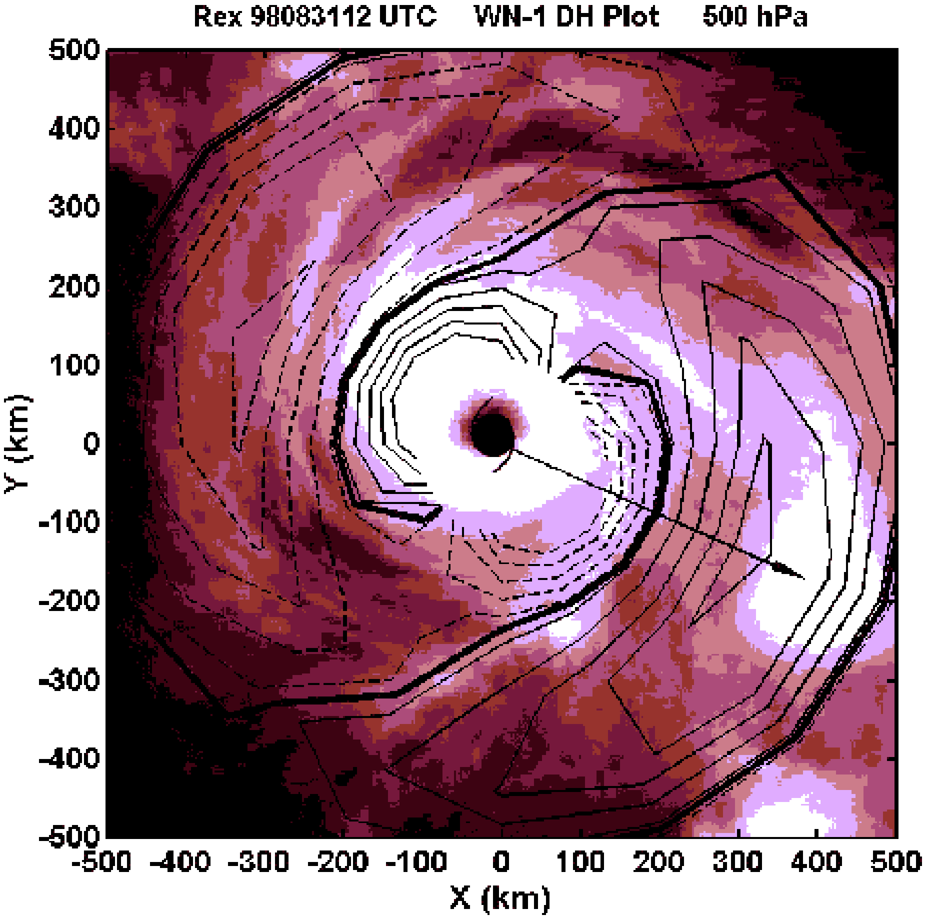




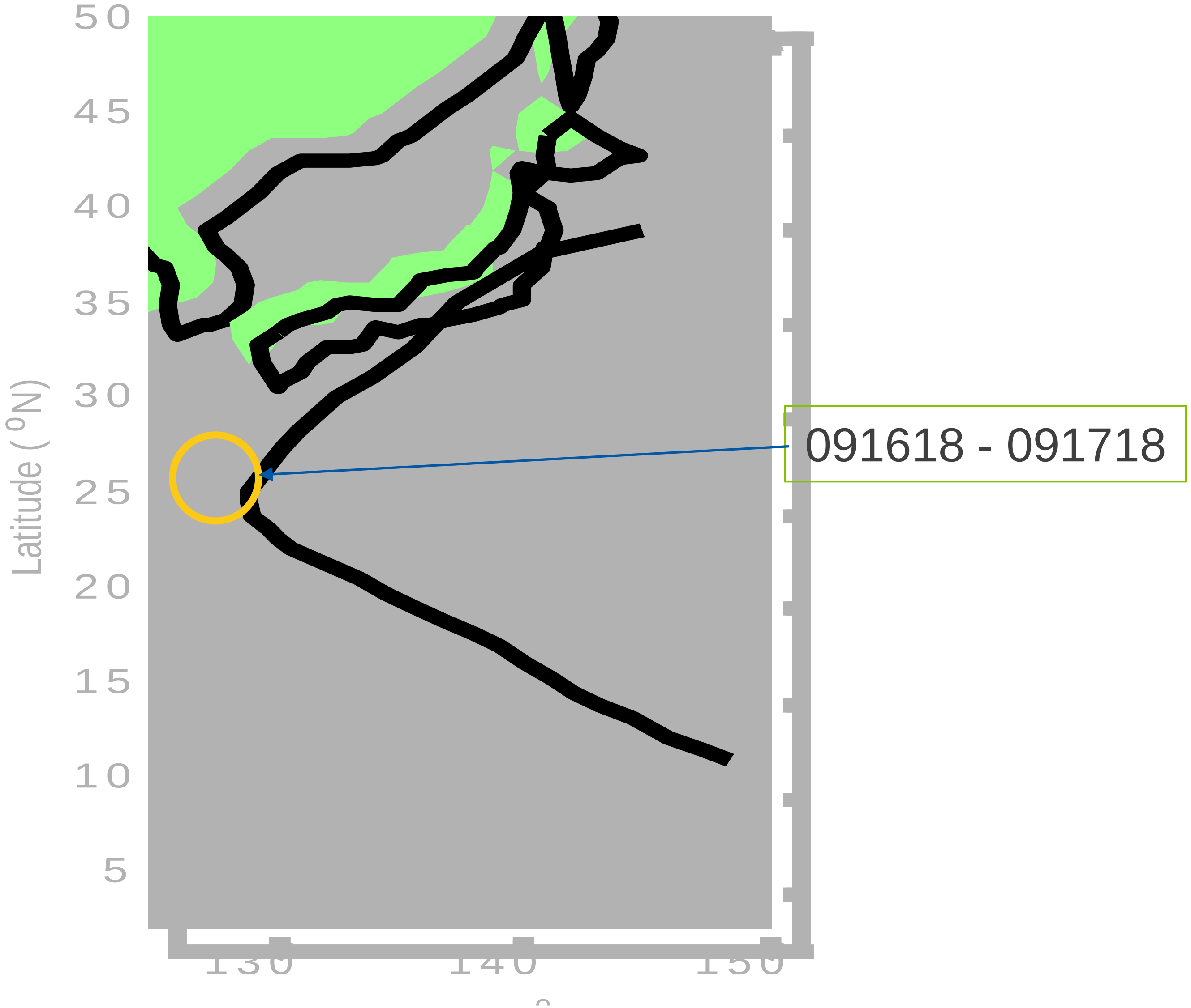
Typhoon Rex (1998)

Chan et al. (2002)



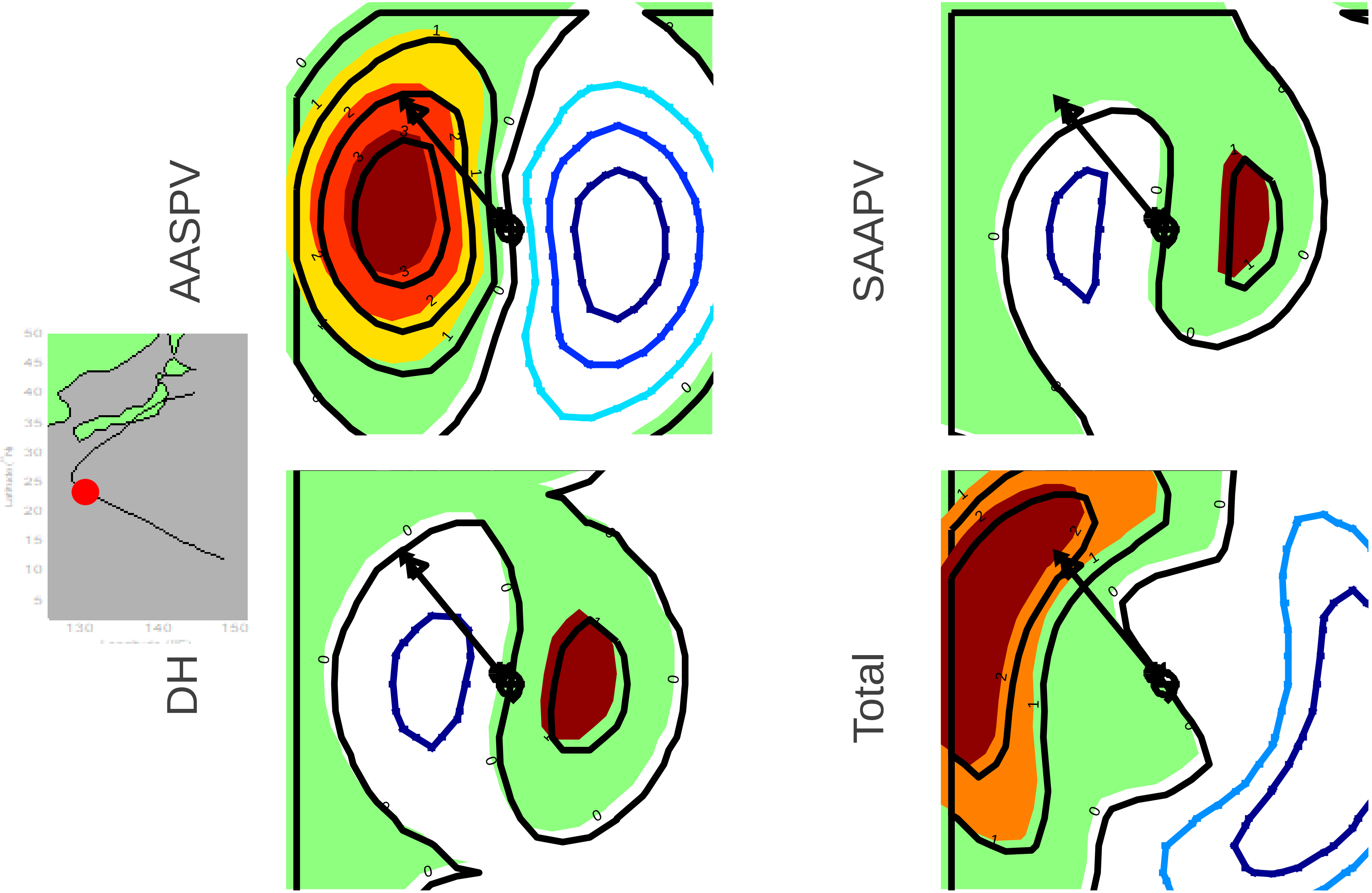


Typhoon Flo (1990)



Chan et al. (2002)

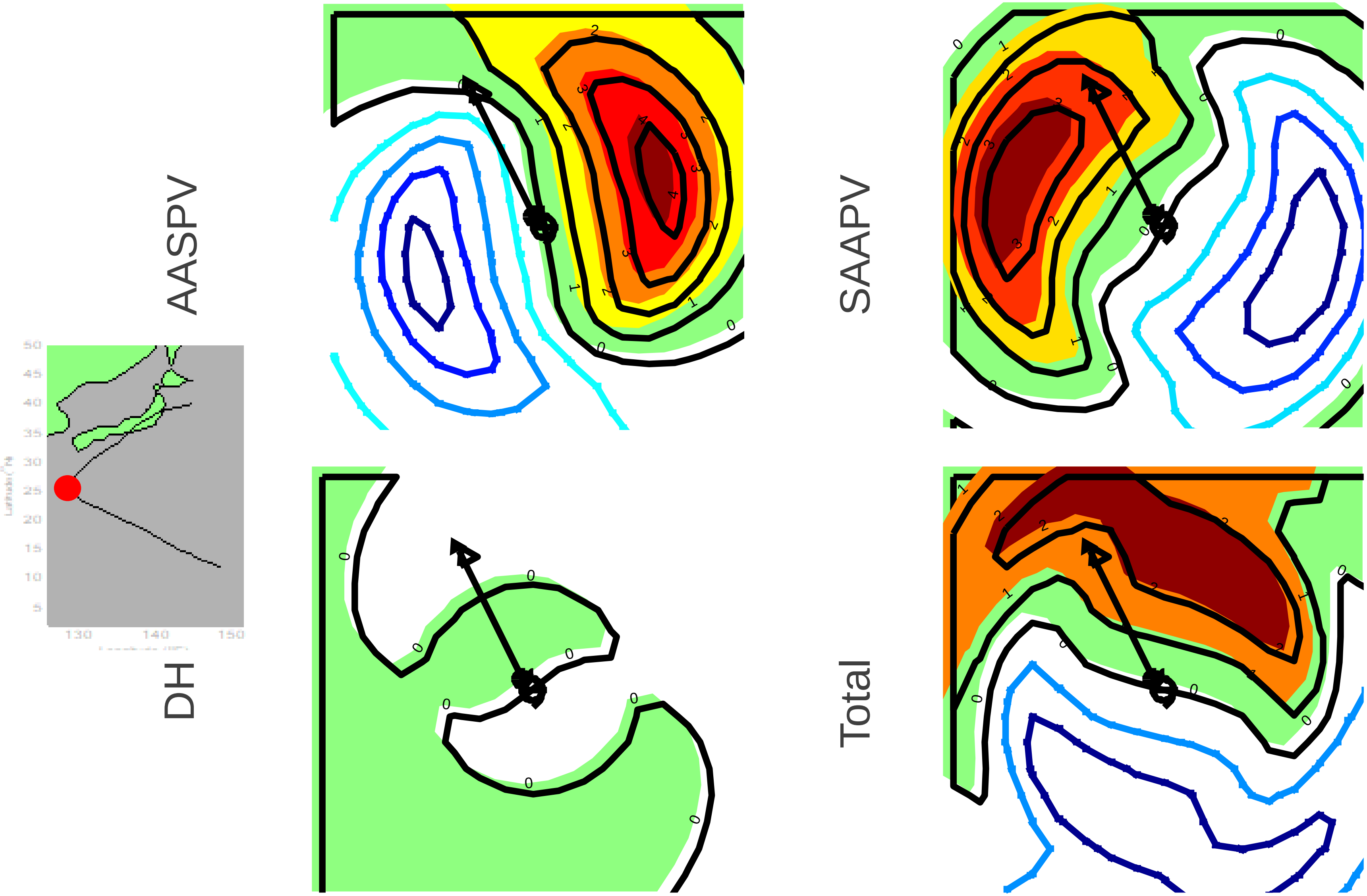
Distribution of various WN-1 terms in the PV tendency equation
Typhoon Flo (091618)



Chan et al. (2002)

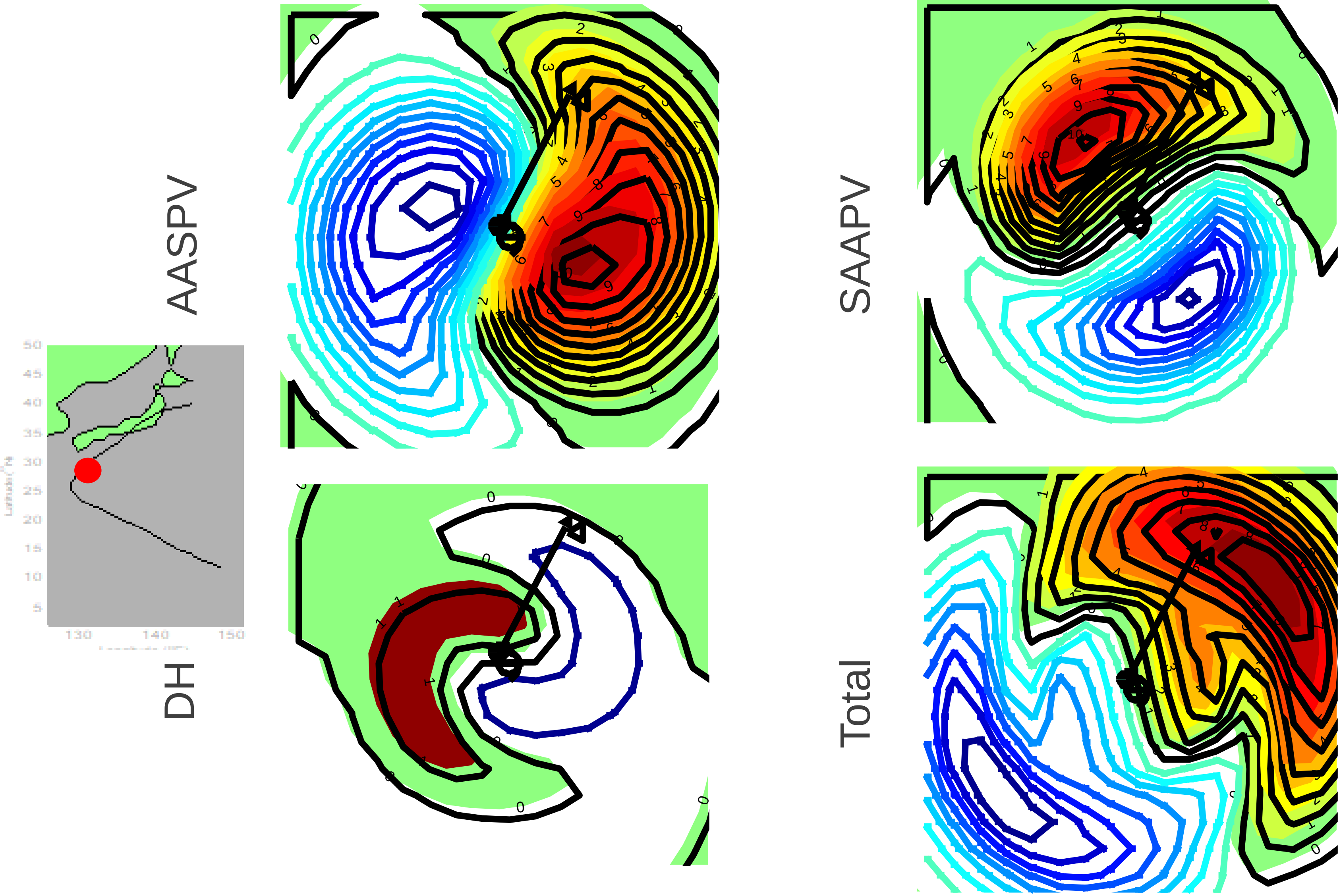
Distribution of various WN-1 terms in the PV tendency equation

Typhoon Flo (091700)



Chan et al. (2002)

Distribution of various WN-1 terms in the PV tendency equation Typhoon Flo (091718)



Baroclinic concept of tropical cyclone motion

A tropical cyclone will move towards an area of maximum potential vorticity tendency contributed by horizontal and vertical advection of potential vorticity, AS WELL AS diabatic heating associated with the convection of the tropical cyclone.