Roving Seminar
2023/06/29
Online

Recent progress in the understanding of tropical cyclone motion

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Tropical cyclones (in the last 150 years)

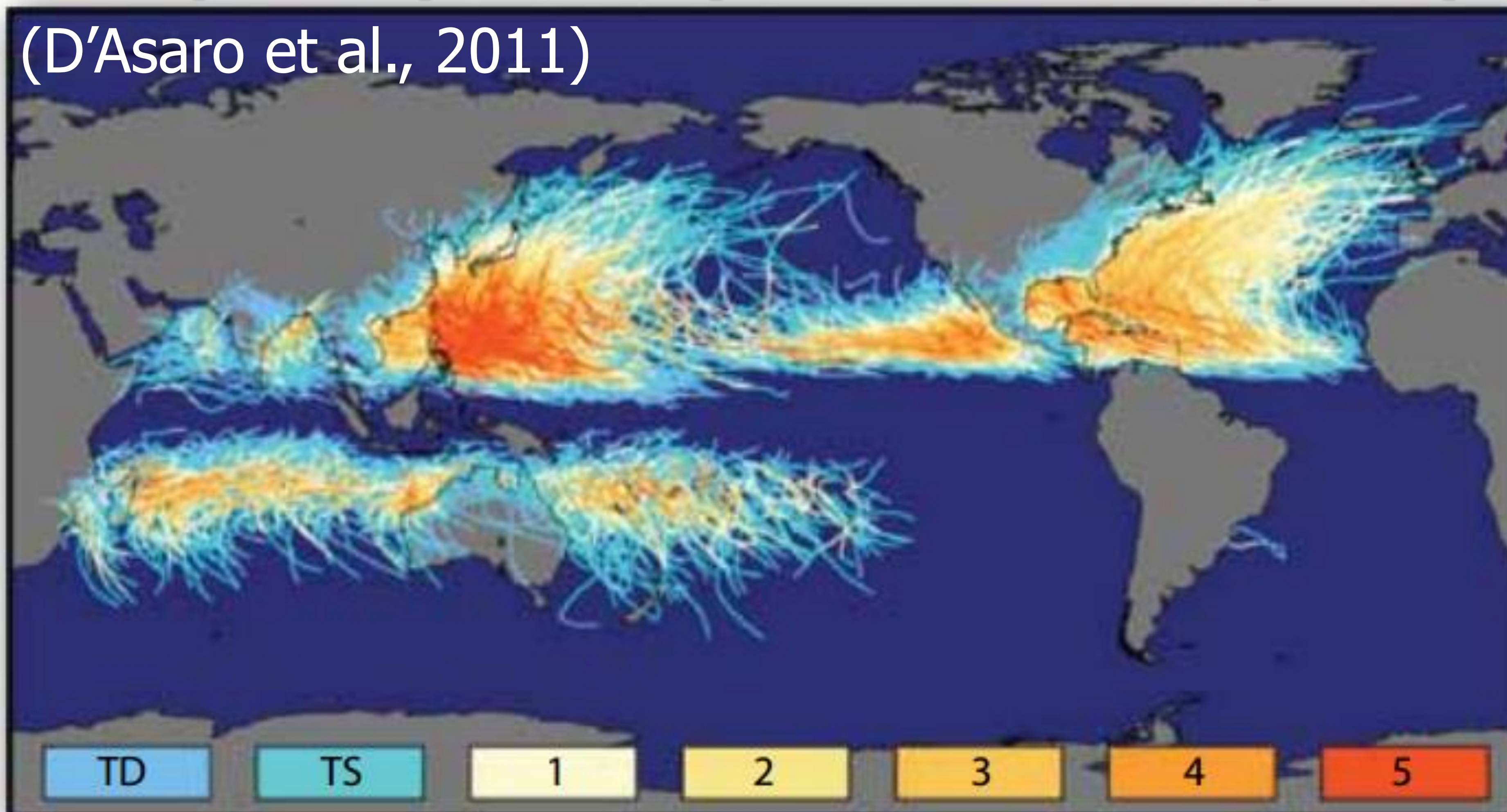
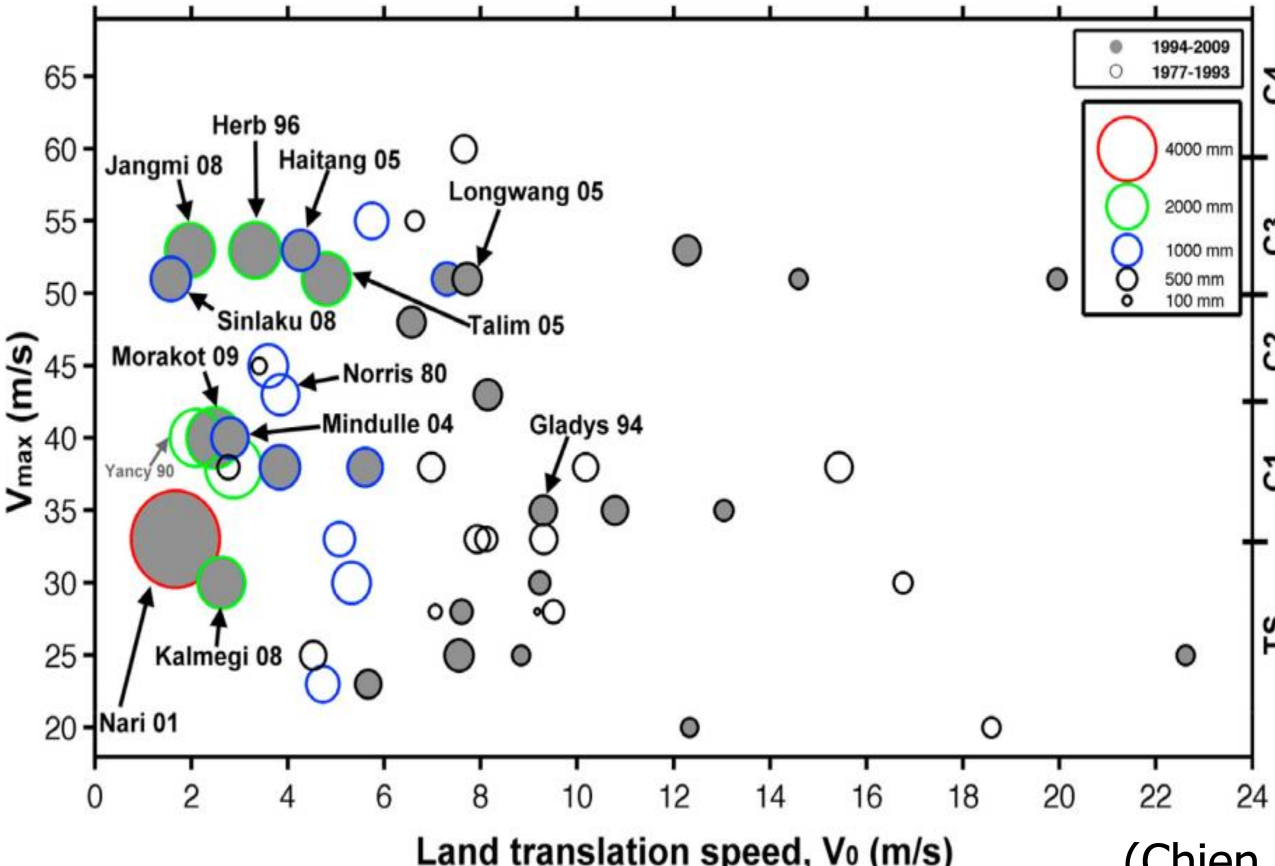


Figure 1. Worldwide tropical cyclone tracks through 2006 from the National Hurricane Center and the Joint Typhoon Warning Center, spanning nearly 150 years. Each track is colored by storm intensity using the Saffir-Simpson storm categories (Tropical Depression, Tropical Storm, and Tropical Cyclone categories 1 [wind 33–42 m s^{-1}] to 5 [wind > 70 m s^{-1}]). The tracks show that the regions of most frequent and intense storms are in the western North Pacific. *Image courtesy of NASA Earth Observatory*

Why are track forecasts important?

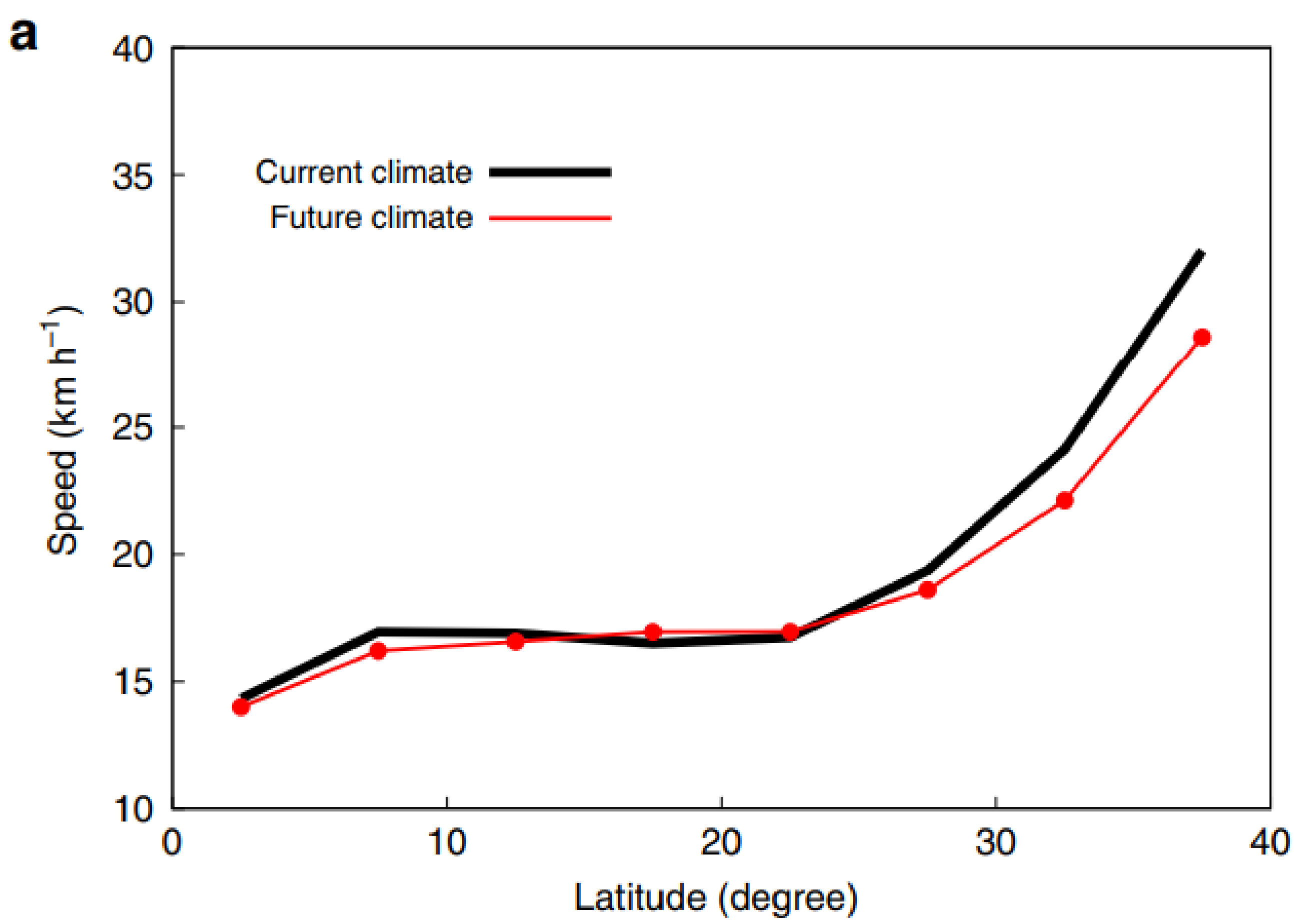
- The forecasts of intensity, rainfall, and storm surge become less meaningful if the track forecast is incorrect.
- Slowly moving TCs cause torrential rainfall.



(Chien and Kuo, 2011)

Slowdown trend under global warming

- Slowdown trend is expected in midlatitudes under the global warming condition.

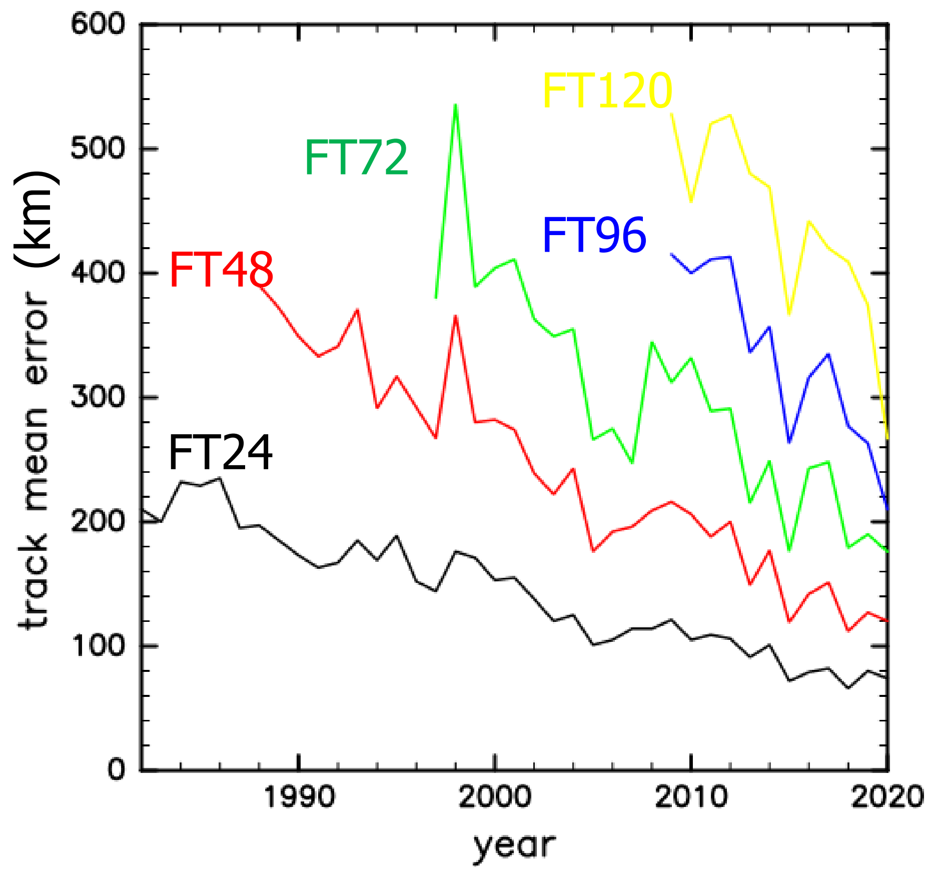


(Yamaguchi et al. 2015)

TC forecast errors by RSMC Tokyo

- Track: Decreasing over the last several decades.
- Nevertheless, 72-h track forecast errors are still 200 km on average.

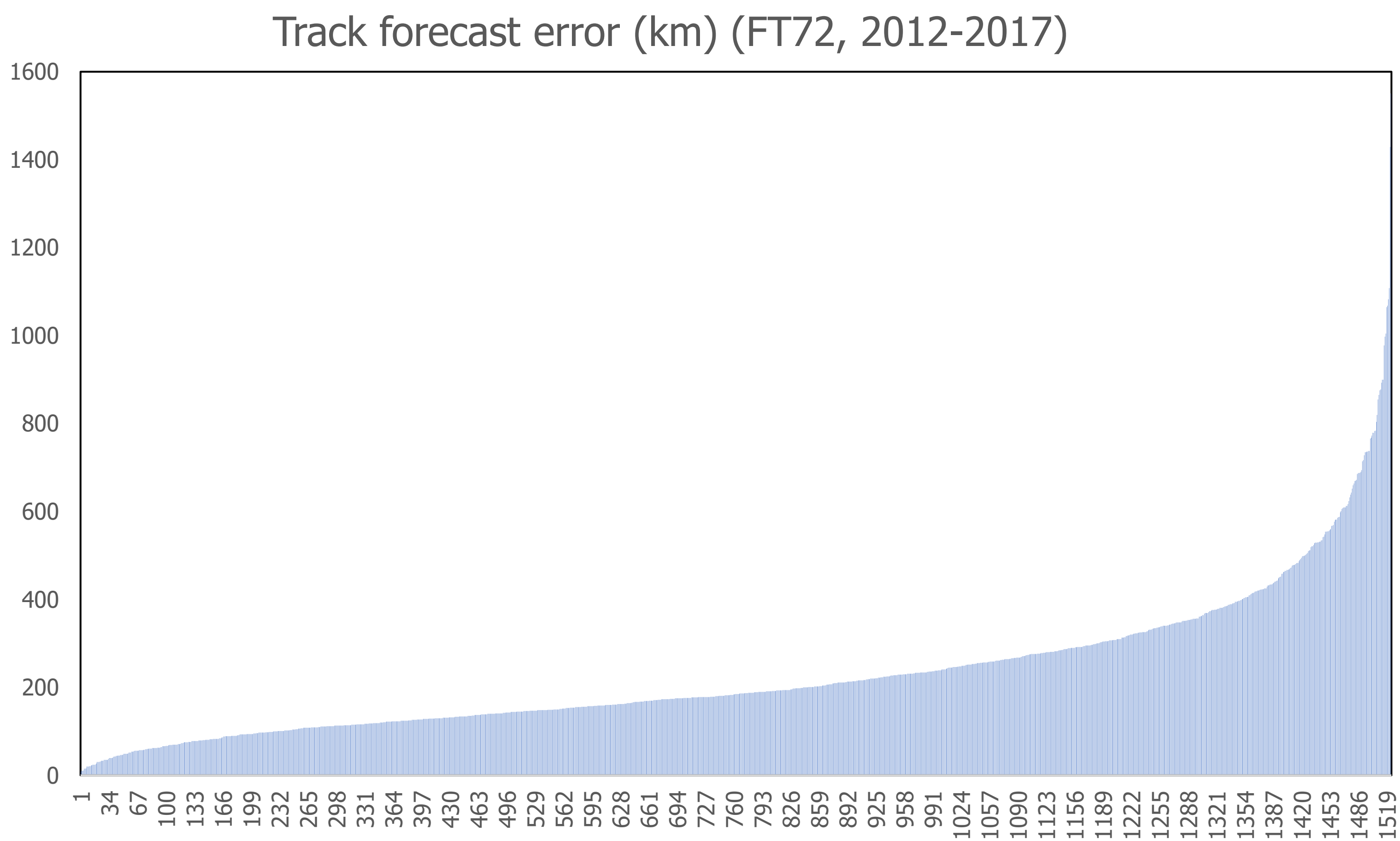
Track forecast errors (1982-2020)



(Ito 2016; updated)

Forecast busts

- In approximately 1% of all cases, 3-day forecast errors exceed 1000 km.
- It is important to understand the reason why.



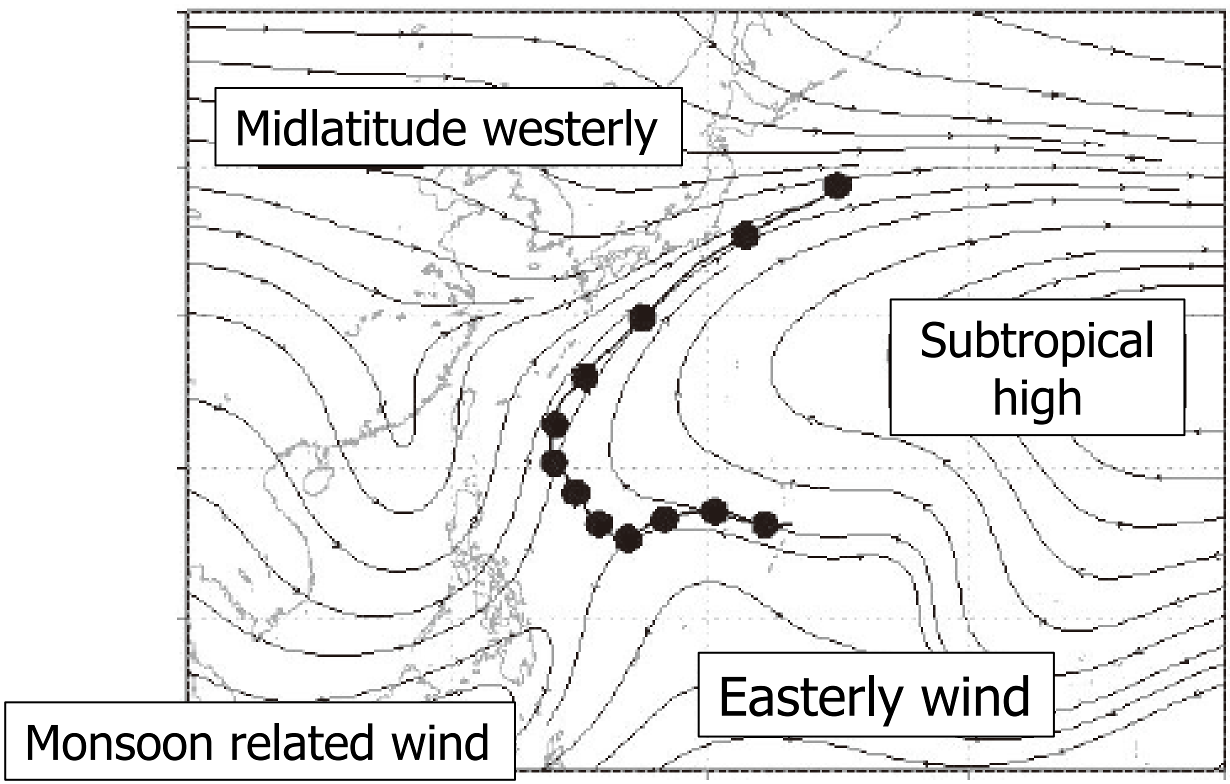
Outline

- TC track is largely controlled by the synoptic scale flow but affected by β-gyre effect, asymmetric diabatic heating, and other factors.
- In this lecture, we briefly explain these factors.

Flow v.s. TC track

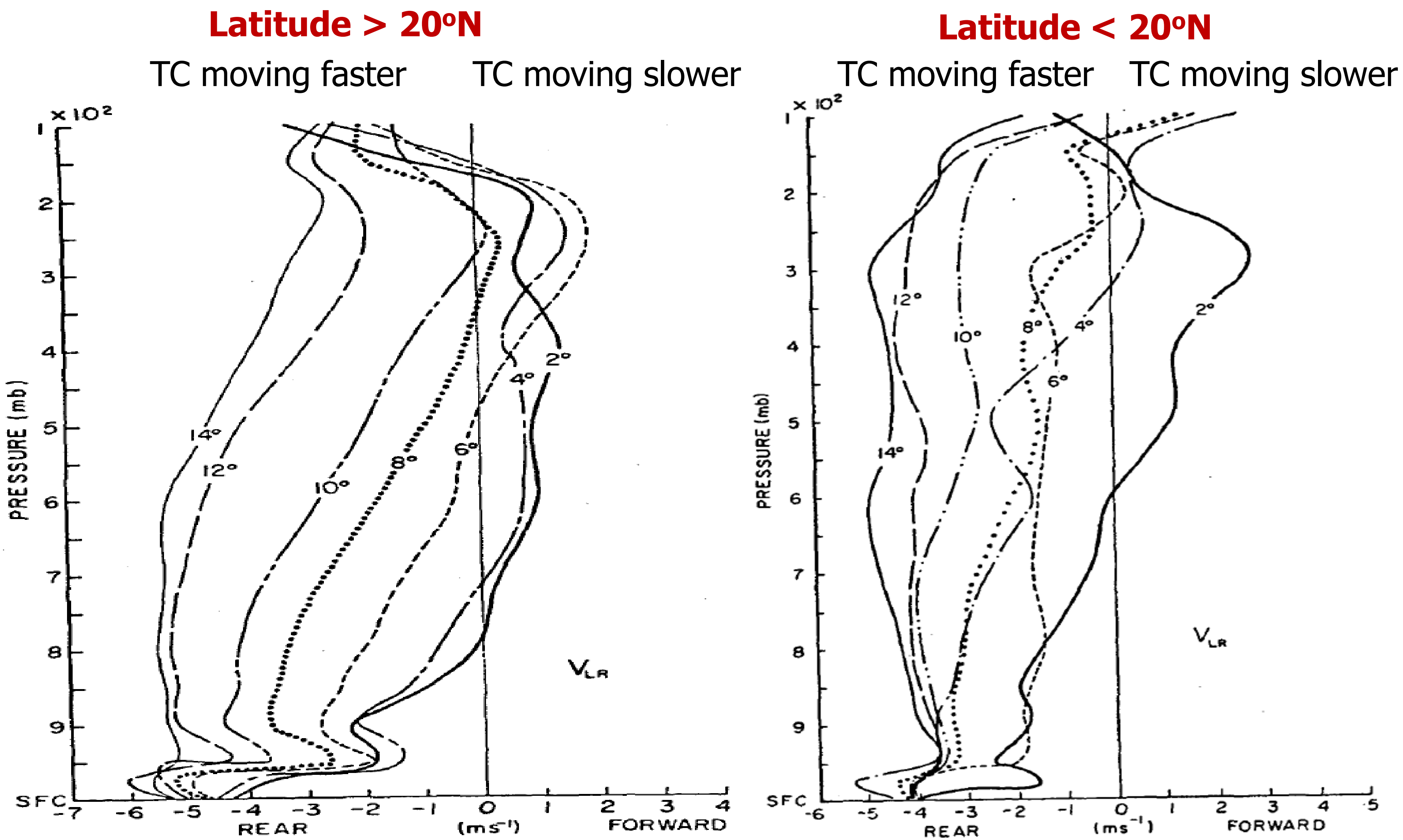
Synoptic scale flow

- As a first-order approximation, TC motion is like the motion of a toy boat following river flow.
- A flow controlling TC motion has a synoptic scale such as midlatitude westerly, subtropical high, easterly wind, and monsoon.



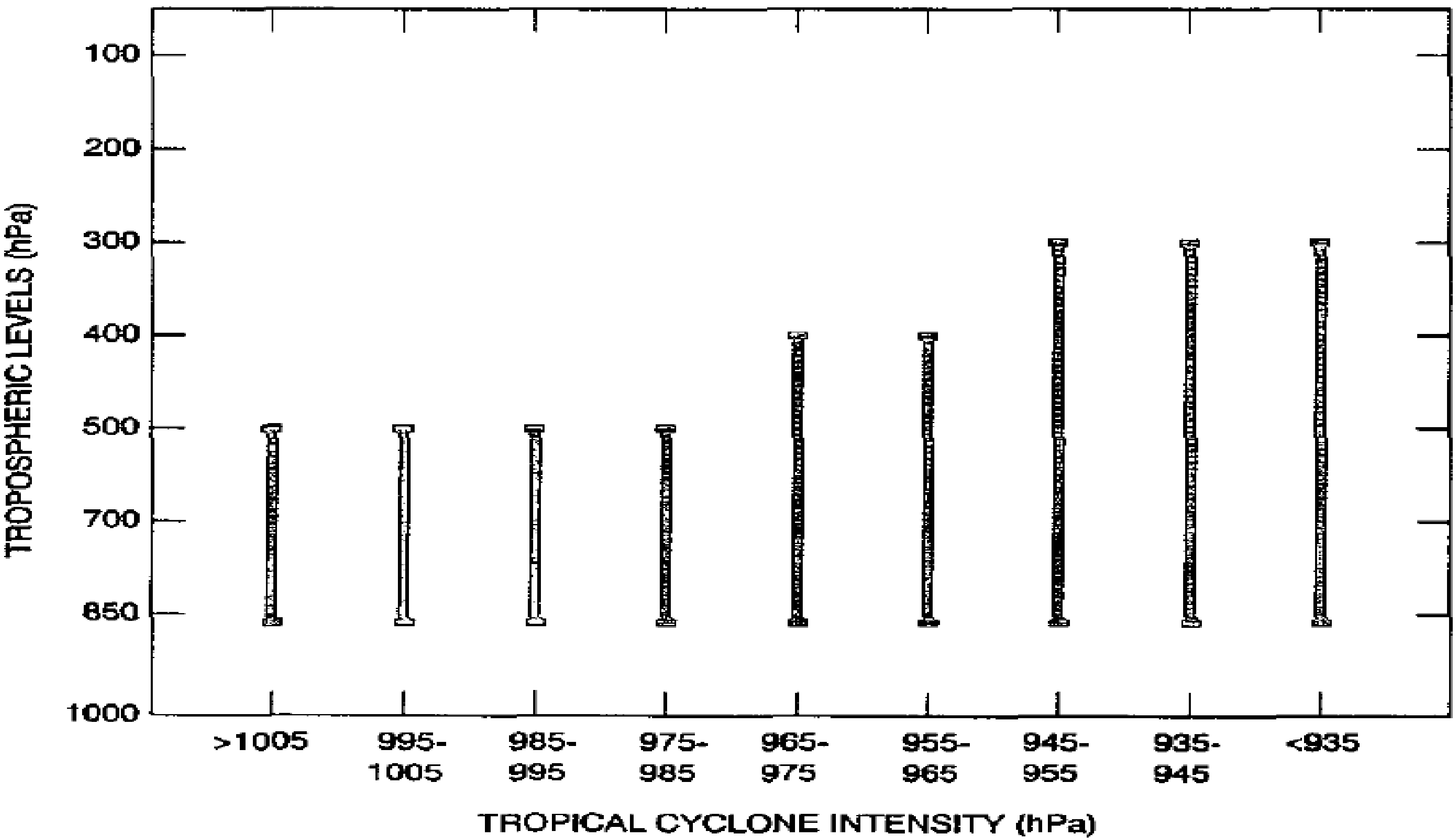
Fudeyasu et al. (2013)

Comparing TC motion to winds within a certain radius



(George and Gray, 1976)

Optimum steering flow layer

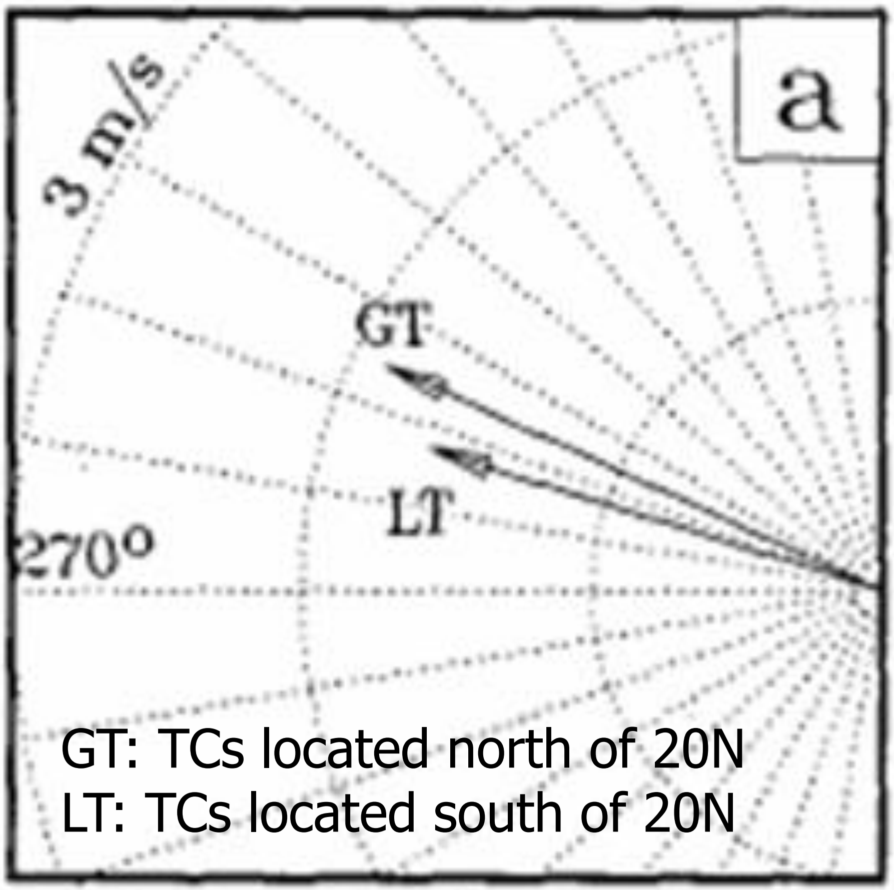


(Velden and Leslie, 1991)

Difference b/w track and steering flow

- TC motion is slightly deviated from the steering flow (~2 m/s).
- The direction of deviation is west-northward.

TC motion minus steering flow



(Chan 2010; Carr and Elseberry, 1990)

Short summary: Flow v.s. TC track

- As a first-order approximation, TC motion is like the motion of a toy boat following river flow.
- Synoptic scale phenomena such as midlatitude westerly, subtropical high, easterly wind, and monsoon largely control the TC motion.
- Optimal steering flow
  - 5-7° radial mean or radial-band mean
  - 500-850 hPa mean
    (if a TC is strong, 300-850 hPa mean)
- TC track is deviated from steering flow by 2 m/s.
- Note: The steering flow is not fully composed of large-scale wind. Steering flow may include the contributions of TC and small-scale features.

β-gyre concept

Nondivergent vorticity equation

- Consider the following in pressure coordinates,

$$\frac{Du}{Dt} - fv = -\frac{\partial \Phi}{\partial x} + F_x \qquad (1)$$

$$\frac{Dv}{Dt} + fu = -\frac{\partial \Phi}{\partial y} + F_y \qquad (2)$$

- Taking $\partial(2)/\partial x - \partial(1)/\partial y$ yields

$$\underbrace{\frac{\partial \zeta}{\partial t}}_{\text{tendency}} = \underbrace{-u\frac{\partial \zeta}{\partial x} - v\frac{\partial \zeta}{\partial y} - w\frac{\partial \zeta}{\partial z}}_{\text{advection-term}} \underbrace{- \frac{\partial f}{\partial y} v}_{\text{Coriolis-term}}$$

$$\underbrace{-\left(f + \zeta\right)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)}_{\substack{\text{divergence term} \\ \text{(stretching term)}}} \underbrace{- \frac{\partial w}{\partial x}\frac{\partial u}{\partial z} + \frac{\partial w}{\partial y}\frac{\partial v}{\partial z}}_{\text{tilting term}} + \underbrace{\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}}_{\text{friction term}}$$

Nondivergent vorticity equation (contd.)

- If we can neglect the divergence term, tilting term, and friction term, the equation is simplified. (Later on, I will introduce examples in which the divergence term is not negligible)

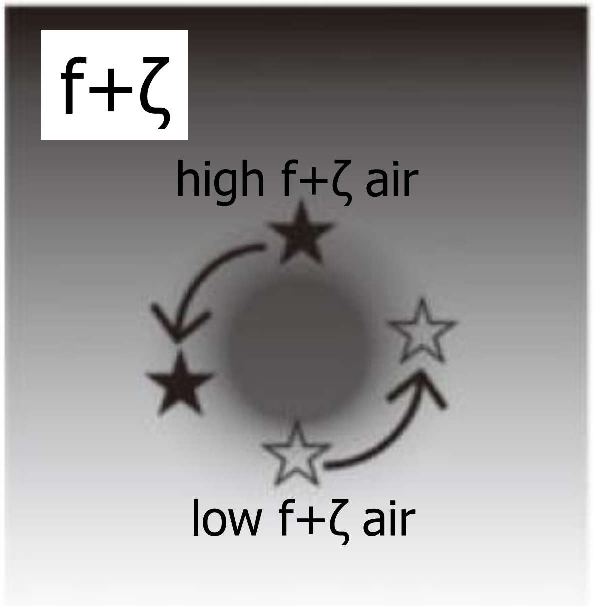
$$\frac{D\zeta}{Dt}+\frac{\partial f}{\partial y}v=0$$

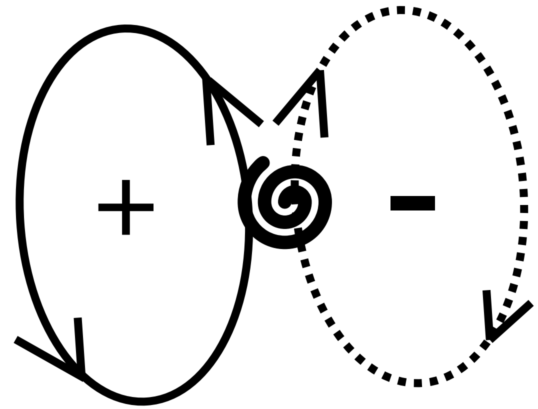
- Since the Corioris parameter f depends only on a latitude, $\partial f\ /\partial t+u\partial f\ /\partial x=0$. Therefore,

$$\frac{D\zeta}{Dt}+\frac{\partial f}{\partial t}+u\frac{\partial f}{\partial x}+v\frac{\partial f}{\partial y}=\frac{D\zeta}{Dt}+\frac{Df}{Dt}=0$$

- It simply states $\zeta + f$ is a conserved quantity.

β-gyre effect

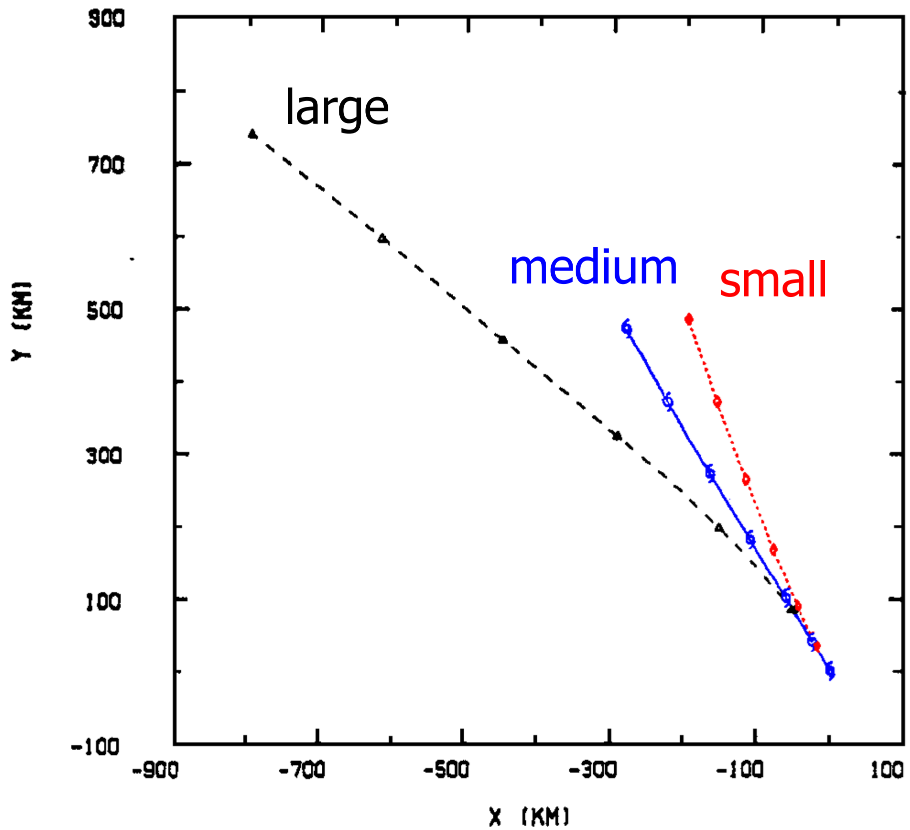




- High f to the north and high ζ near the TC center.
- TC wind transports high $f+\zeta$ air to the west and low $f+\zeta$ air to the east
- It results in TC motion through two pathways
  - ➢Increase of vorticity in the west (westward motion)
  - ➢Advection due to the wind (northward motion)

Sensitivity of β-gyre on size and intensity

- The impact of a β-gyre becomes larger for a large TC (Fiorino and Elsberry, 1989).
- Northward component becomes stronger for a strong TC (Chan and Elsberry, 1987).



(Fiorino and Elsberry, 1989)

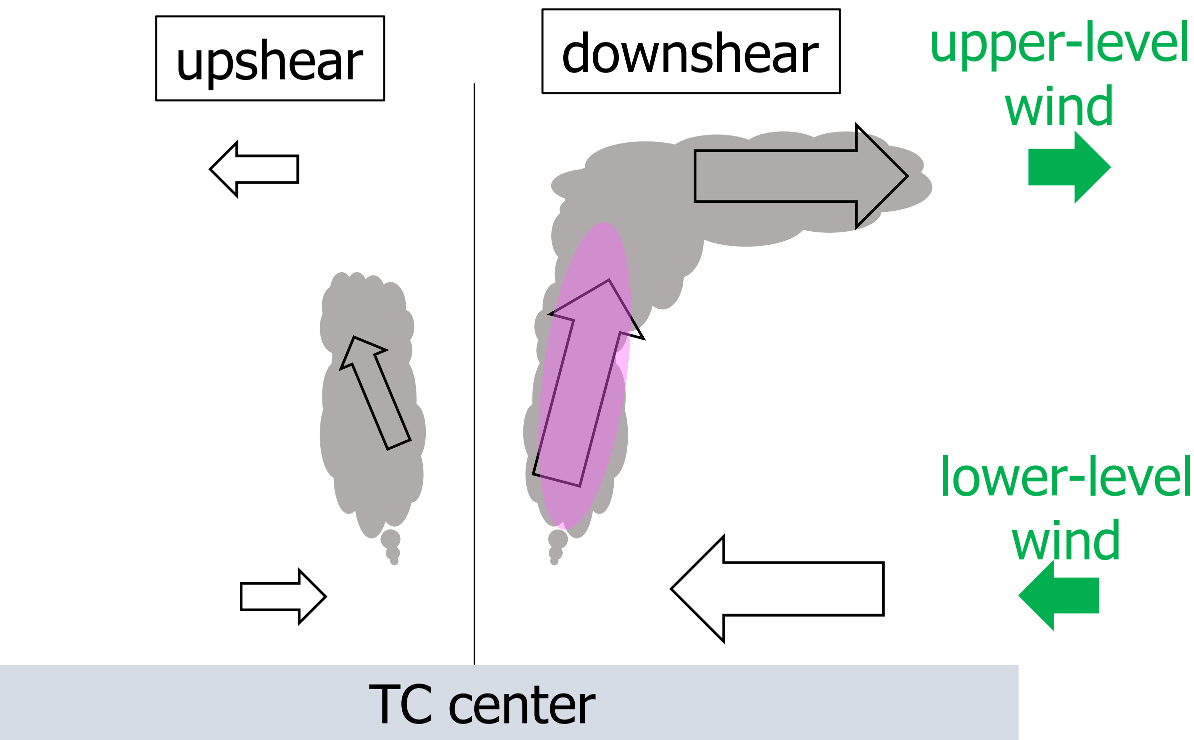
Short summary: β-gyre concept

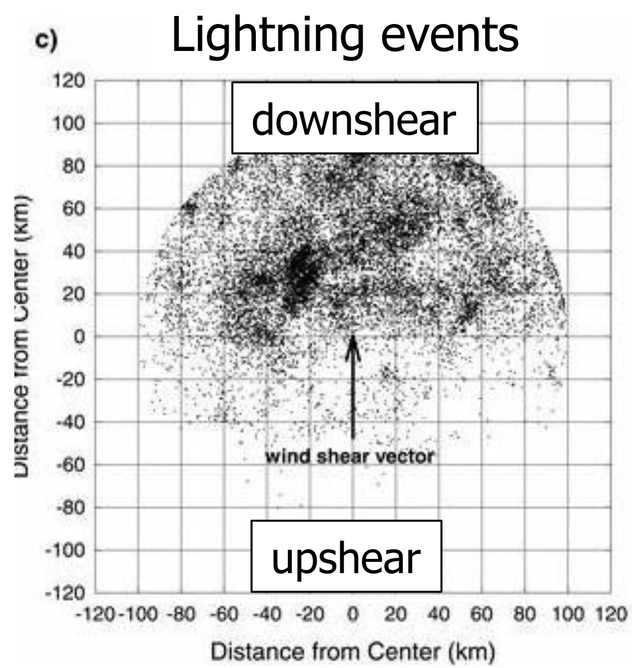
- In addition to large-scale flow, a TC can move northwestward by itself through the conservation of absolute vorticity $\zeta + f$.
- The mechanism is that a high $\zeta + f$ air is transported to the west due to the cyclonic wind.
- The impact is large for a large TC.
- It may explain the difference of 2 m/s between the TC motion and steering flow (at least partly).
- Note: It is almost impossible to estimate the impact of β-gyre for a TC in the real world.

Asymmetric diabatic heating

Asymmetric convection due to VWS

- Under a vertical wind shear (VWS; environmental upper-level wind minus low-level wind), convections are active from the downshear to downshear-left.
- In a downshear side, the low-level convergence and upper-level divergence is strong





(Corbosiero and Molinari, 2002)

Asymmetric diabatic heating impacting on TC track

- Wu and Wang (2000) showed that asymmetric diabatic heating can modify the TC track.
- The vorticity is generated beneath the strong heating (downshear to downshear-left in VWS).
- In a vorticity equation, the divergence term is not negligible under the VWS.

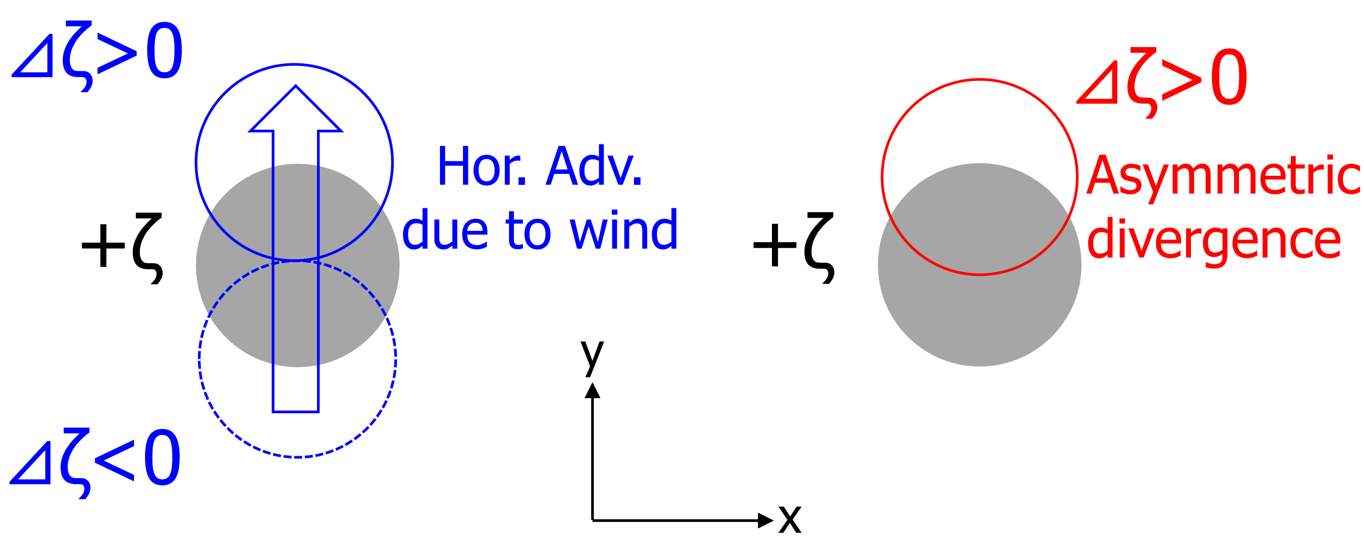
$$\underbrace{\frac{\partial \zeta}{\partial t}}_{\text{tendency}} = \underbrace{-u\frac{\partial \zeta}{\partial x} - v\frac{\partial \zeta}{\partial y} - w\frac{\partial \zeta}{\partial z}}_{\text{advection-term}} \underbrace{- \frac{\partial f}{\partial y} v}_{\text{Coriolis-term}}$$

$$\underbrace{-\left(f + \zeta\right)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)}_{\substack{\text{divergence term}\\\text{(stretching term)}}} \underbrace{- \frac{\partial w}{\partial x}\frac{\partial u}{\partial z} + \frac{\partial w}{\partial y}\frac{\partial v}{\partial z}}_{\text{tilting term}} + \underbrace{\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}}_{\text{friction term}}$$

Vorticity equation and TC motion

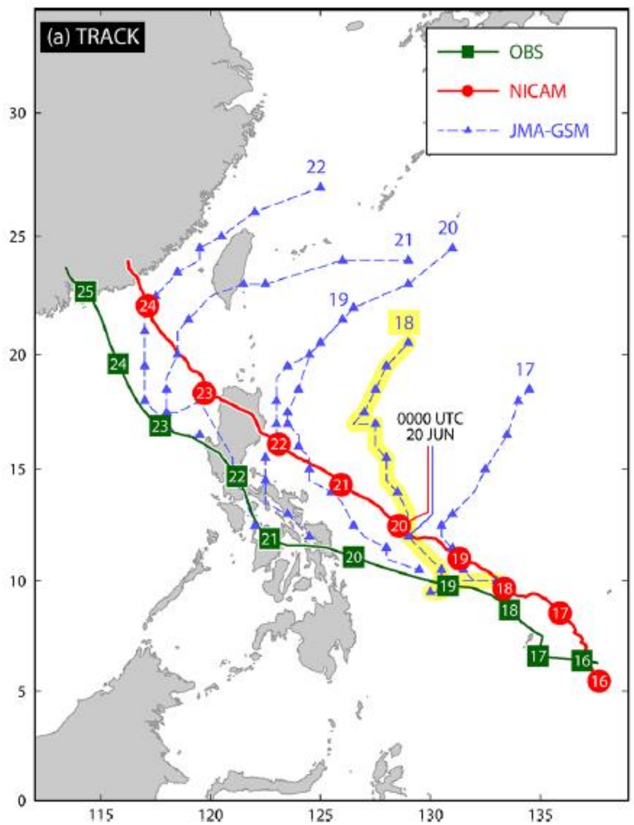
- A TC can be regarded as a region with large vorticity.
- Therefore, the TC motion corresponds to the wavenumber-1 component of vorticity tendency.

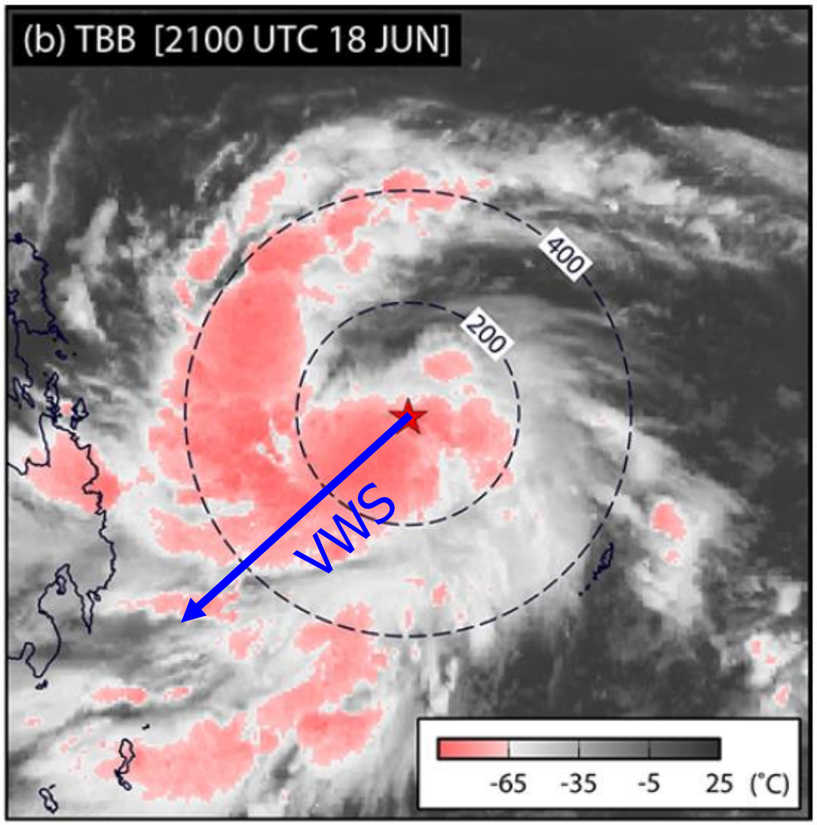
$$\frac{\partial \zeta}{\partial t} = \underbrace{\boxed{-u\frac{\partial \zeta}{\partial x} - v\frac{\partial \zeta}{\partial y}}}_{\text{Hor. Adv.}} \underbrace{\boxed{-w\frac{\partial \zeta}{\partial z}}}_{\text{Vert. Adv.}} \underbrace{\boxed{-\frac{\partial f}{\partial y}v}}_{\text{Coriolis}} \underbrace{\boxed{-\left(f+\zeta\right)\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)}}_{\text{Divergence}}$$



Example: Track of TC Fengshen (2006)

- A northward bias is sometimes seen in model forecasts.
- In case of TC Fengshen (2006), the nonhydrostatic NICAM model successfully reproduced the TC track.
- Active convection was in the downshear.

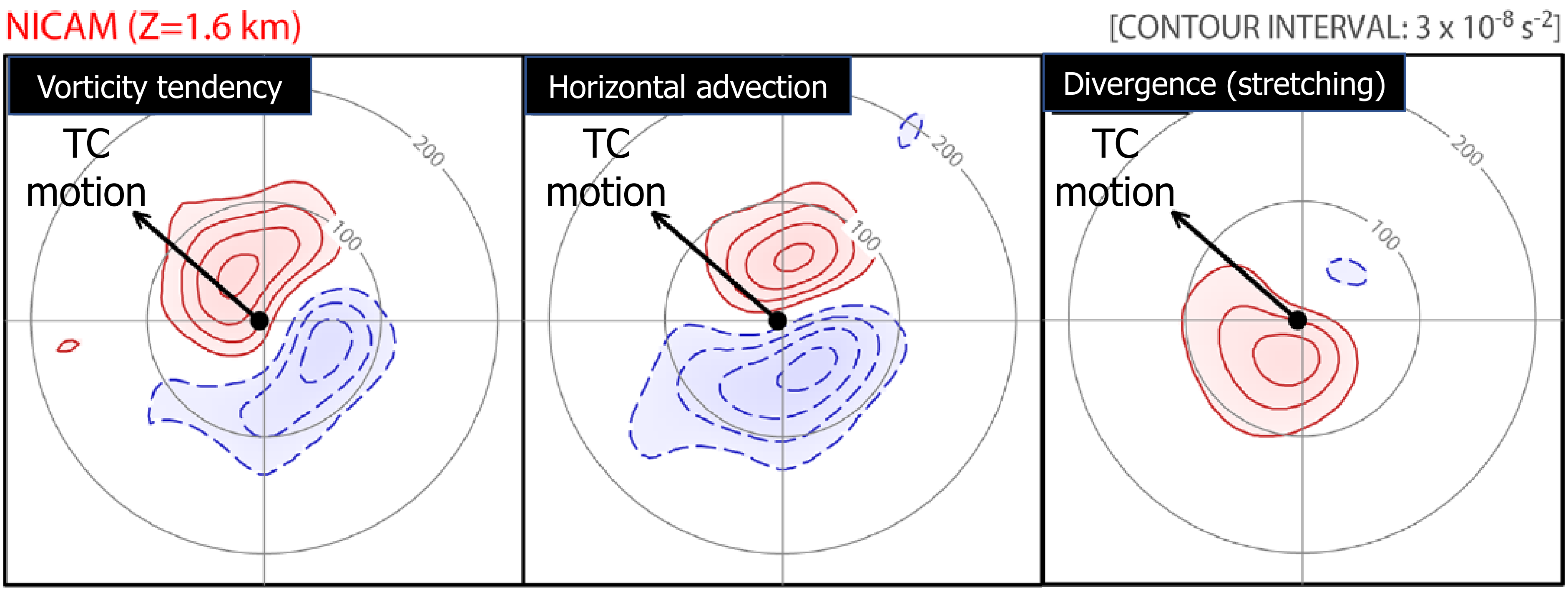




(Yamada et al. 2016)

Diagnosis with a vorticity equation

- Dominant terms in a vorticity equation are horizontal advection term and divergence (stretching) term.
- Vorticity increases in the northwest correspoinding to the northwestward motion.
- The horizontal advection makes a TC move northward, while the divergence term makes it move southwesward.



(Yamada et al. 2016)

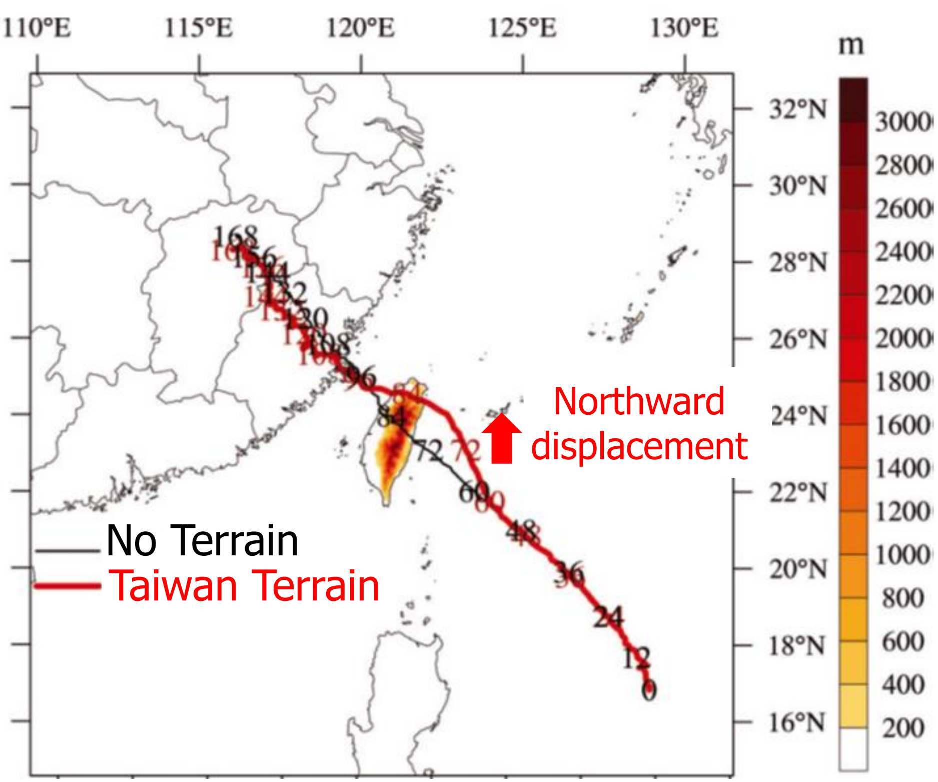
Short summary: Asymmetric diabatic heating

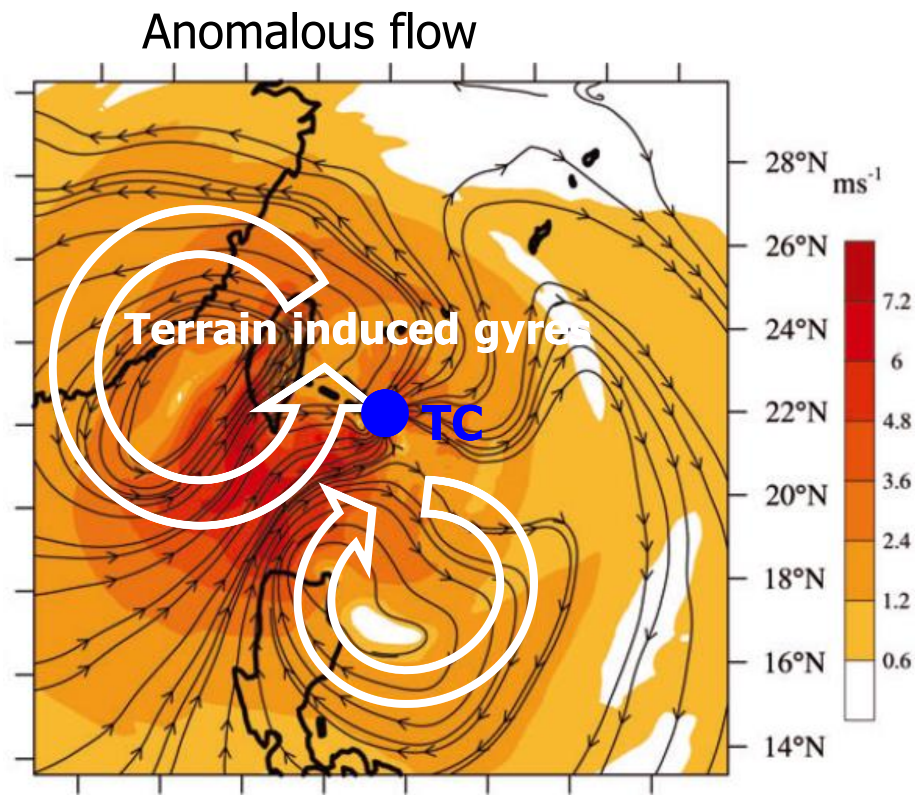
- Vertical wind shear (VWS; upper-level wind minus low-level wind) gives the active convection from the downshear to downshear-left.
- The TC motion is modulated toward the maximum direction of active convection. From a vorticity equation viewpoint, it is explained by a divergence (stretching) term that is not negligible comparing with horizontal advection.
- In some cases, NWP models show the northward bias in TC track forecasts. It might be explained by the insufficient representation of asymmetric diabatic heating associated with the VWS.

Other factors

Idealized simulation for terrain effect

- No background flow except for β-gyre effect.
- For a give setup, westward wind is blocked by Taiwan terrain. It induced gyres leading to the northward deflection.

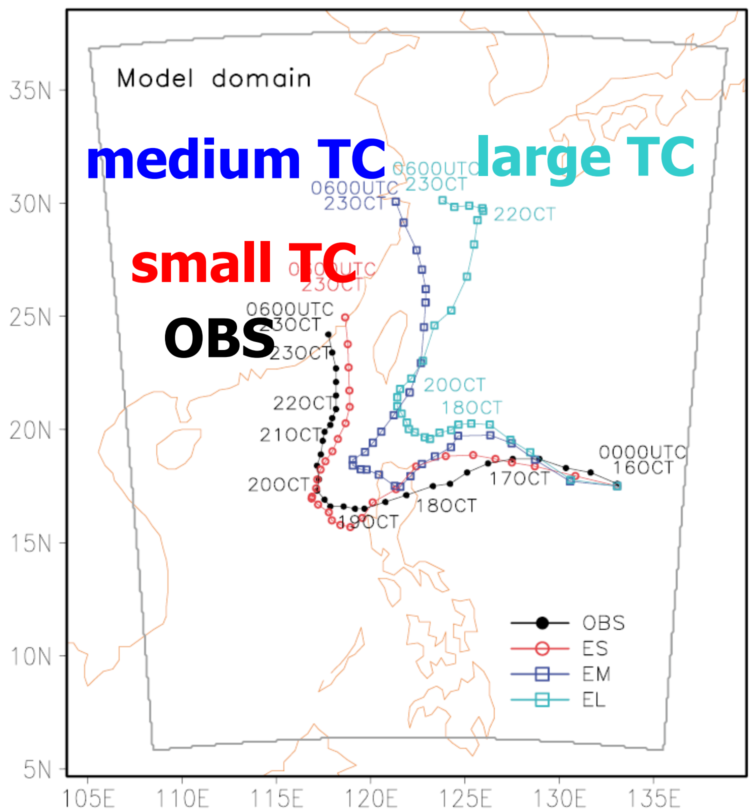


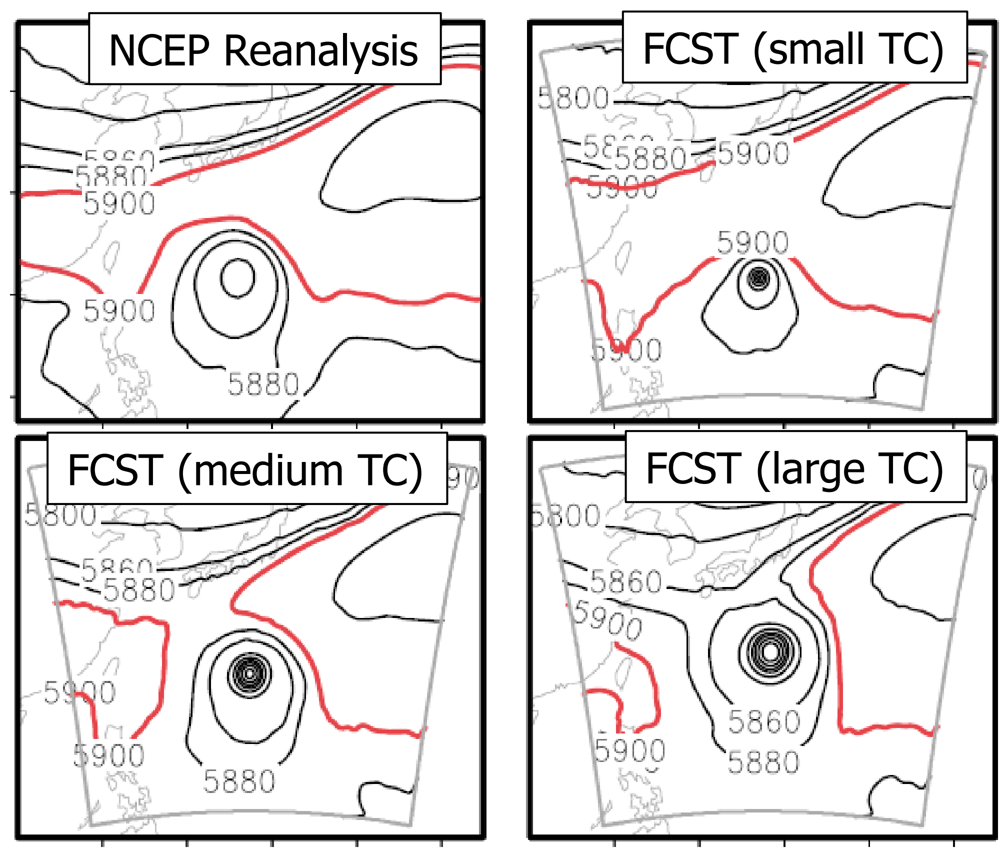


(Tang and Chan, 2014)

A large TC can retreat subtropical high

- With the increase of initial storm size, subtropical high tends to withdraw.
- Large TCs located on the southwestern edge of the subtropical high turn northwards earlier.

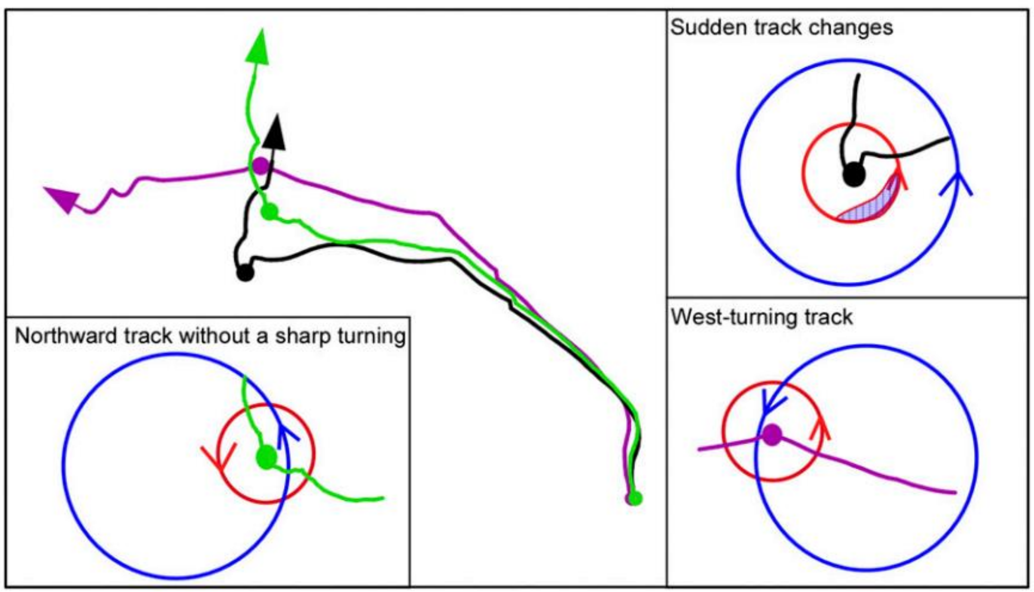




(Sun et al., 2015, JGR)

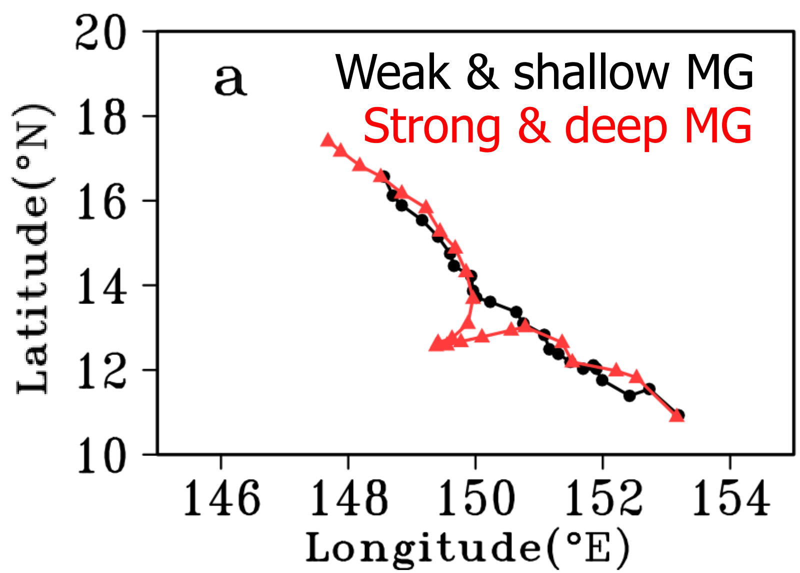
Interaction with monsoon gyre (MG)

- Three types: northward (with or without a sharp turn) or westward path.
- Northward path with a sharp turn tends to be simulated when a MG is strong and deep, a TC is weak, and a TC is relatively closer to MG center.



(Liang and Wu, 2015)

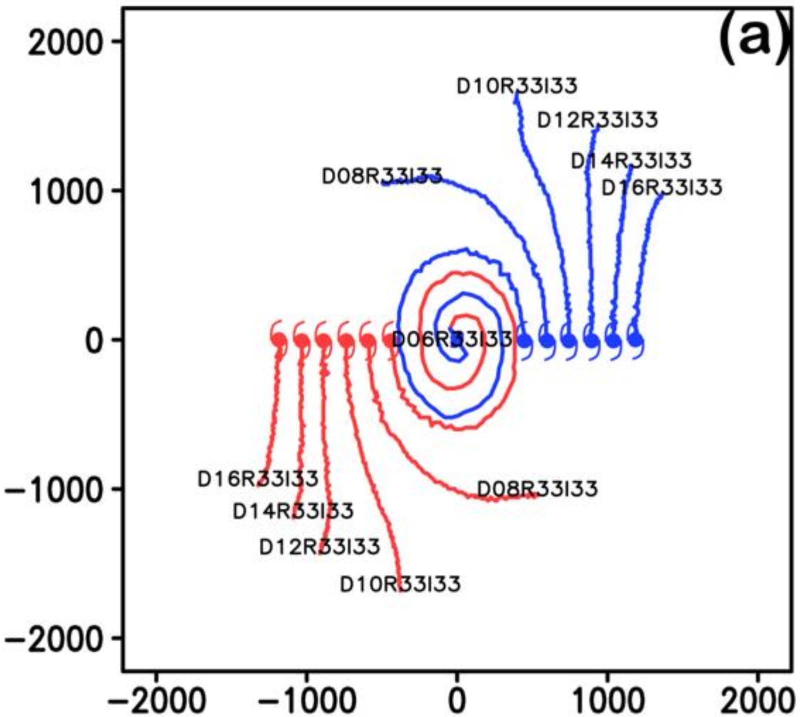
Idealized simulation with WRF

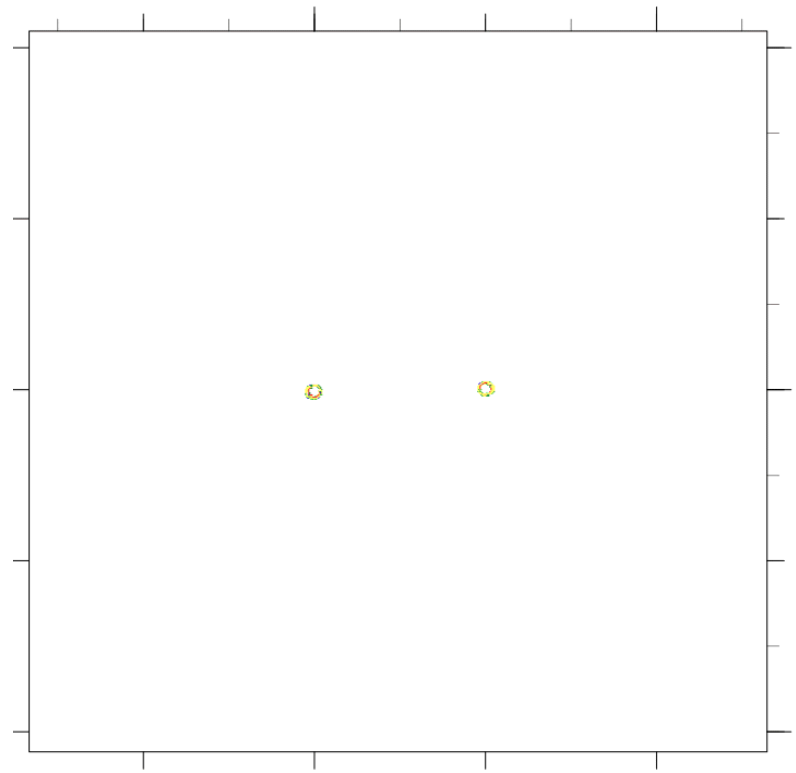


(Ge et al., 2018)

Fujiwhara effect

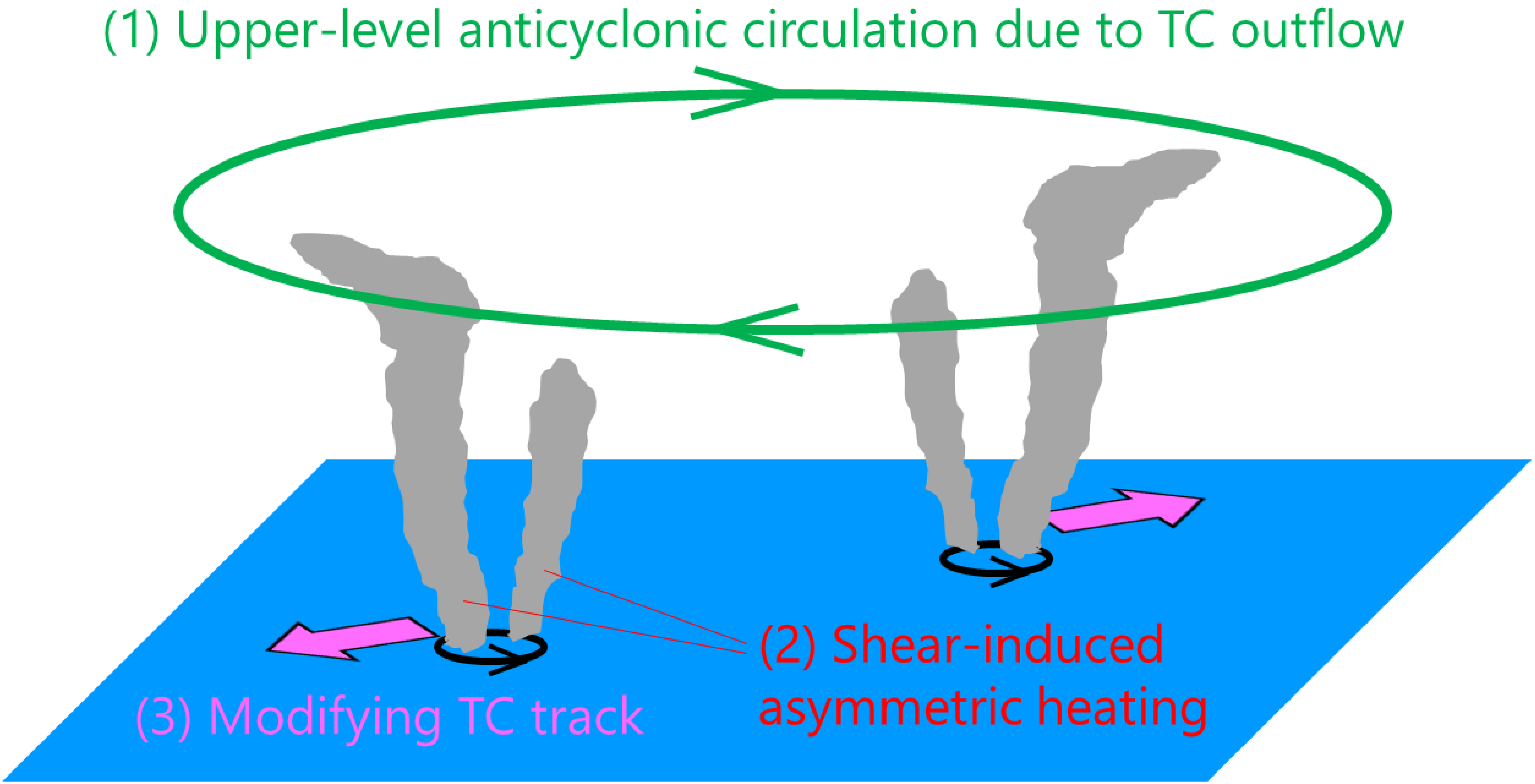
- Binary TCs cyclonically rotate each other if they are separated by less than 1500 km.
- Recent studies show that the motion of binary TCs separated by 1000-2000 km are substantially modulated by asymmetric diabatic heating.





(Lee et al., 2023; Ito et al., 2023)

Three-dimensional Fujiwhara effect



(Lee et al., 2023; Ito et al., 2023)

Concluding remarks

- TC motion has been traditionally believed to follow the large-scale flow, which is acceptable as a first order approximation.
- However, the actual TC track is modulated by β-gyre, asymmetric diabatic heating, topography, and other factors. A large TC even modifies a synoptic scale flow.
- Therefore, it is important to understand not only the large scale feature but also other factors and TC characteristics in terms of track forecasts.