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Role of midlatitude baroclinic condition in heavy rainfall events directly induced by tropical cyclones in South Korea

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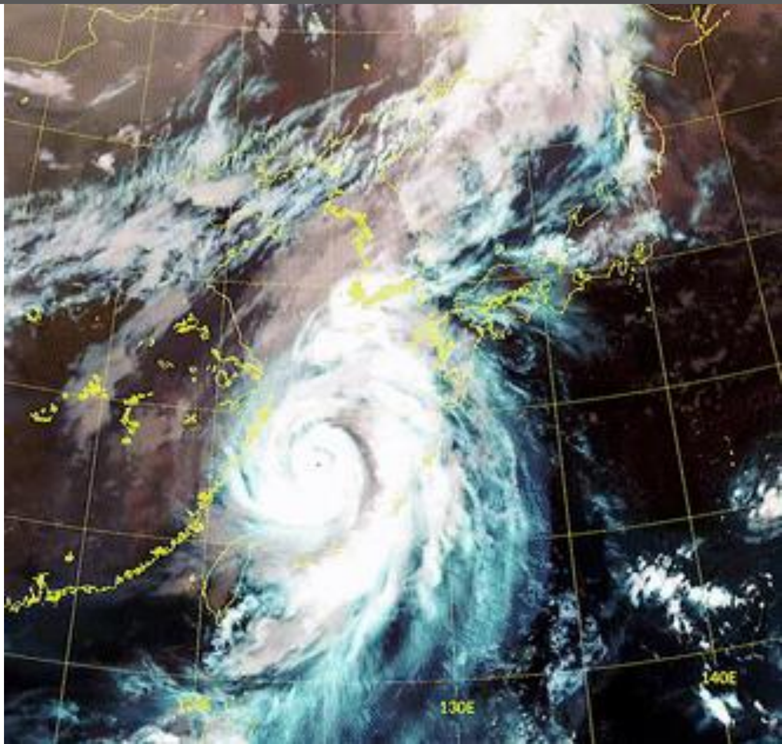


- The **Structural changes of TCs** and **modification of midlatitude flow** during ET have been extensively studied [see Evans et al. (2017) and Keller et al. (2019) for comprehensive reviews].
- However, it is still unclear **how TC–midlatitude flow interaction modulates TC rainfall**. A few studies have been conducted on the landfalling hurricanes in eastern North America (e.g., Atallah and Bosart 2003; Atallah et al. 2007; Milrad et al. 2009), but such analyses are **still lacking in East Asia**.
- Some studies have addressed midlatitude preconditioning in East Asia (Byun and Lee 2012; Baek et al. 2015), but their analyses were confined to the indirect effects of TCs (i.e., predecessor rainfall events).

How does **midlatitude baroclinic condition** modulates the heavy rainfall events ***directly*** induced by TCs in South Korea?

TC–midlatitude flow interaction

Structure changes of TCs

Modification of midlatitude flow

?

Modulation of HREs

HRE: heavy rainfall event

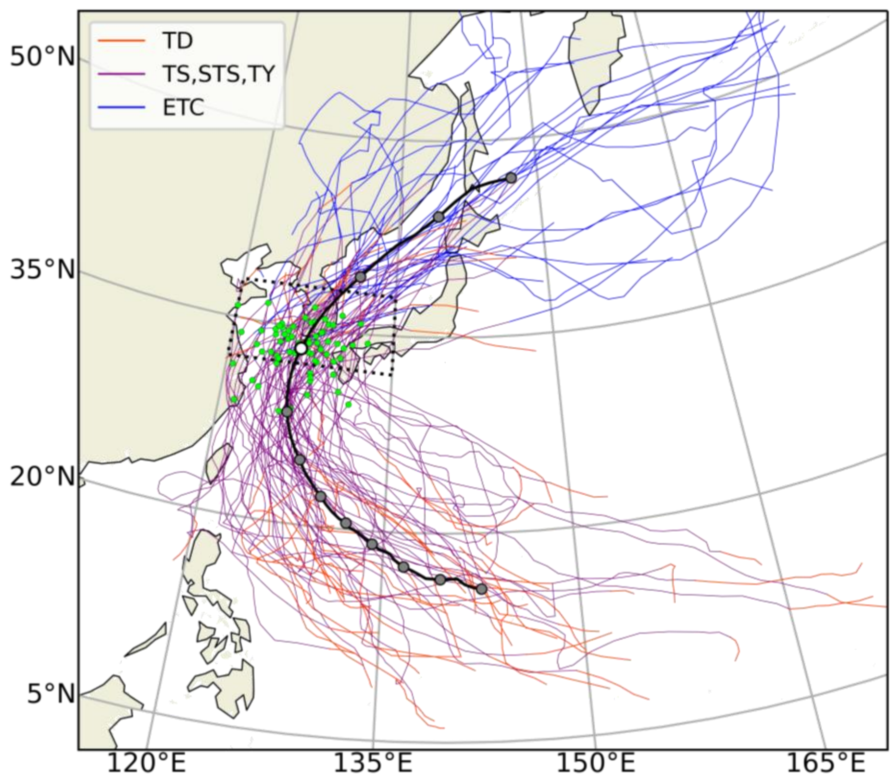
Data & methods

Dataset (JJAS, 1979–2020)

- ERA5 reanalysis data (6 hourly, 1.5°x1.5°, 37 levels)
- Hourly precipitation records from weather stations in South Korea
- RSMC Tokyo-Typhoon Center TC best track

HREs (directly induced by TCs)

- 110 mm (12 h)$^{-1}$ at any single station
- Concurrence with TC in 32°–38°N, 120°–135°E → **A total of 68 events**



About 80% of TCs complete ET during or after HREs, continuing their lifecycle as extratropical cyclones.

TC locations in the mature stage of HREs (0 h)

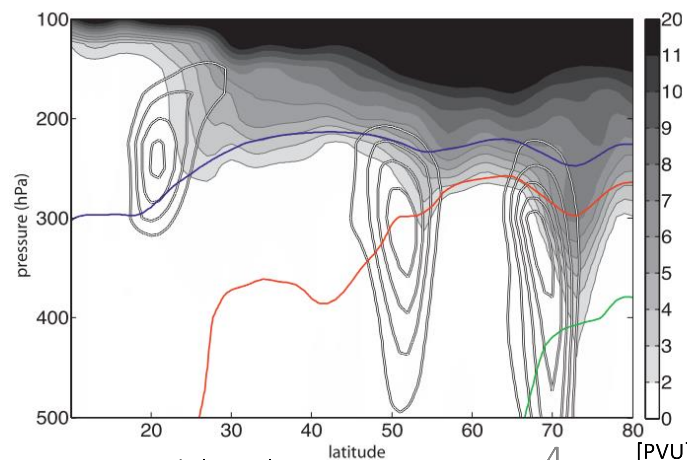
Mean TC track (from -8 days to +3 days)

Tropopause-based self-organizing map (SOM) clustering

SOM Parameters	Selected option
Input data	Dynamic Tropopause (2-PVU height) at 30°–53°N & 105°–145°E at 0 h
Array of nodes	1 × 2
Topology of node	Rectangular
Shape of map	Sheet
Initialization method	Linear initialization
Training method	Batch training
Neighborhood function	Epanechnikov function
Neighborhood radius	2 (initial), 1 (final)
Number of iterations	1,000 (rough training), 2,000 (fine tuning)

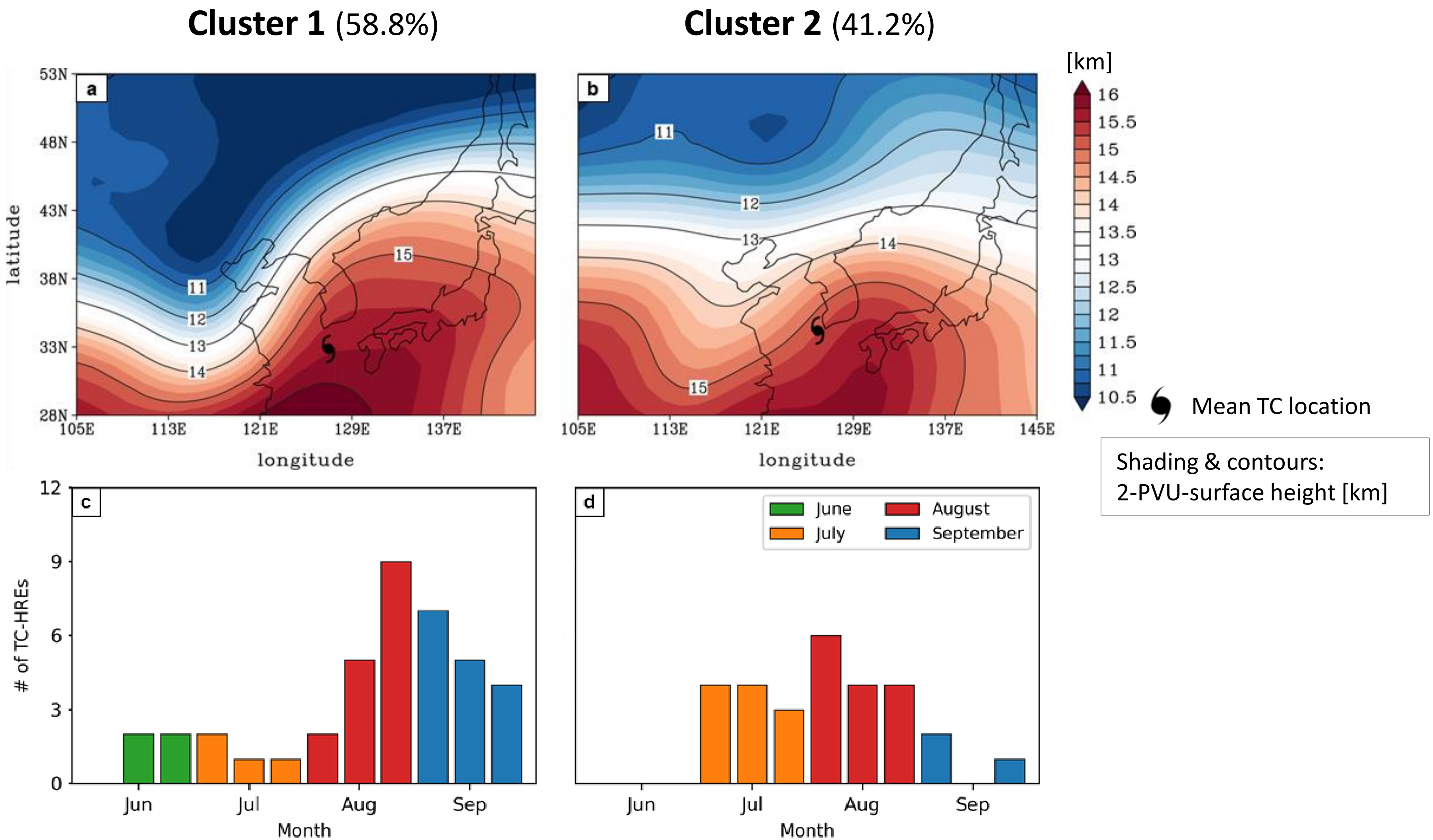
Why dynamic tropopause?

- The extent of TC–midlatitude flow interaction is known to be largely sensitive to midlatitude upper-level conditions.
- As an indicator of a waveguide for synoptic disturbances, it well captures not only the Rossby wave undulation but also the jet strength (deduced from its horizontal gradient) at the tropopause level, which represent the baroclinic environment.



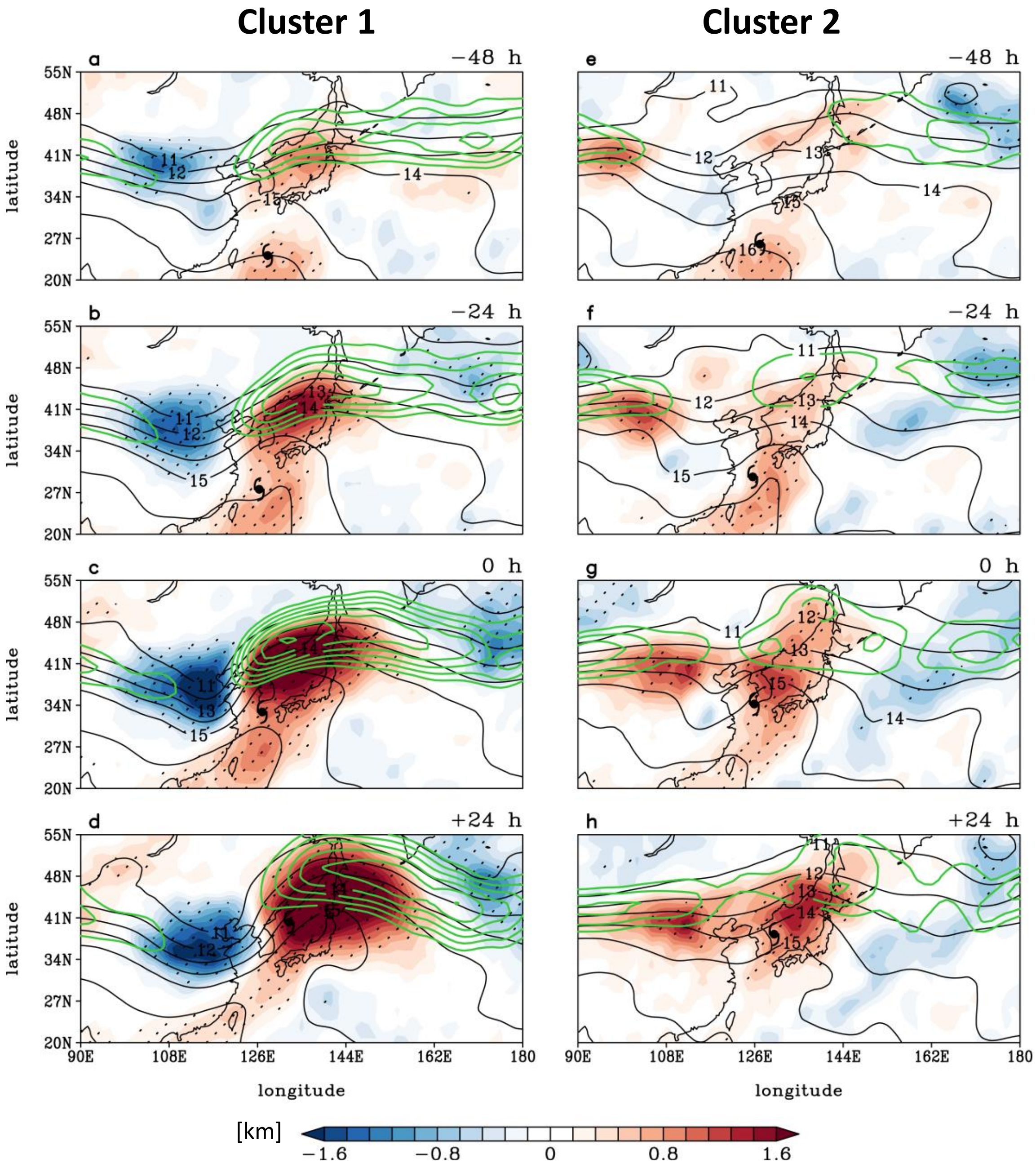
Martius et al. (2010)

Overview of two HRE clusters



- Cluster 1: HREs under **strongly baroclinic** condition (late-summer type)
- Cluster 2: HREs under **weakly baroclinic** condition (mid-summer type)

Synoptic conditions: Tropopause (2-PVU surface)

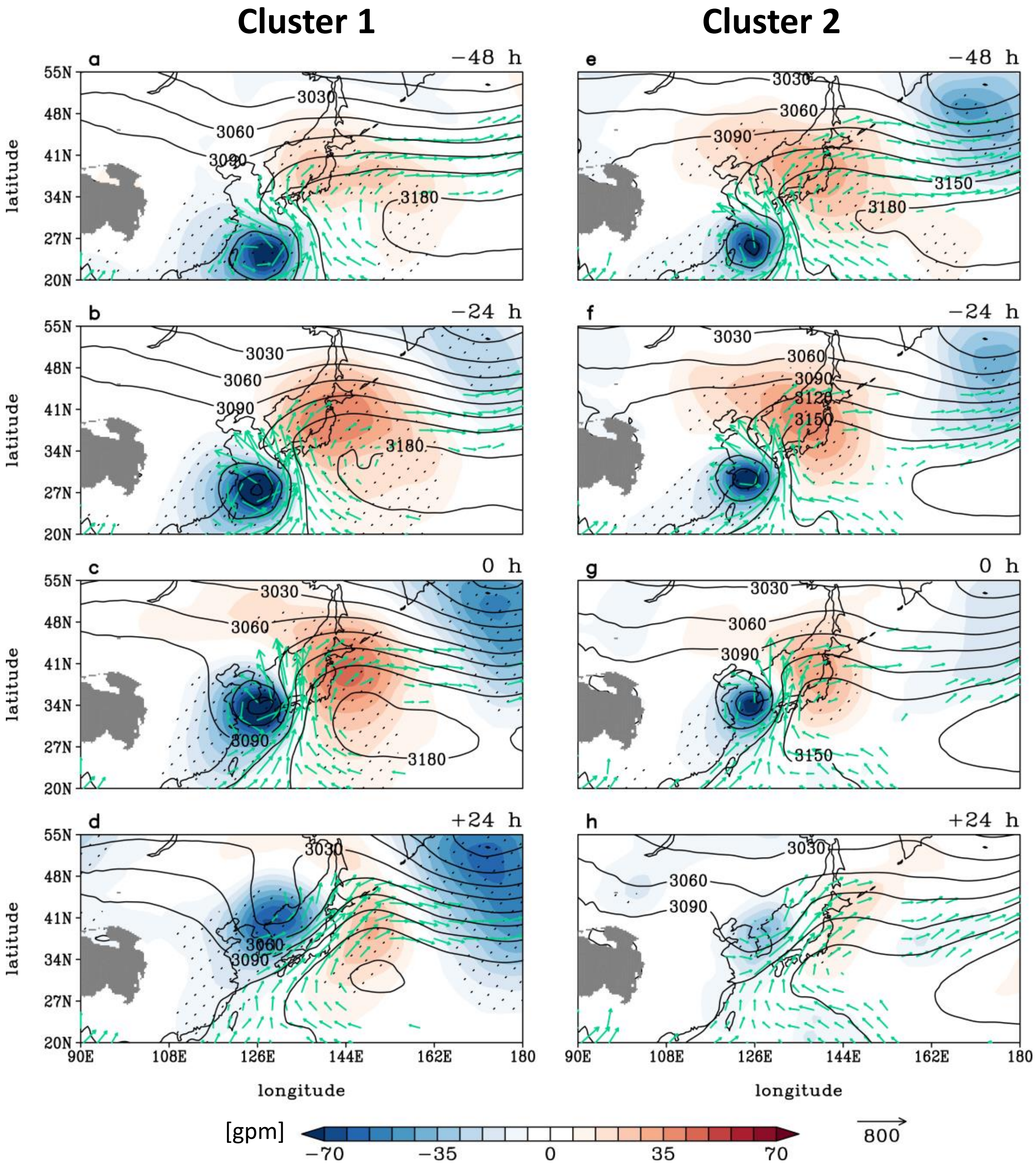


- C1 exhibits the amplifying trough-ridge couplet at tropopause, while C2 does not.

Mean TC location

Black contours: 2-PVU height [km]
Shading: 2-PVU height anomaly [km]
Green contours: : $|\mathbf{V}|$ at 2-PVU surface [m s^{-1}]

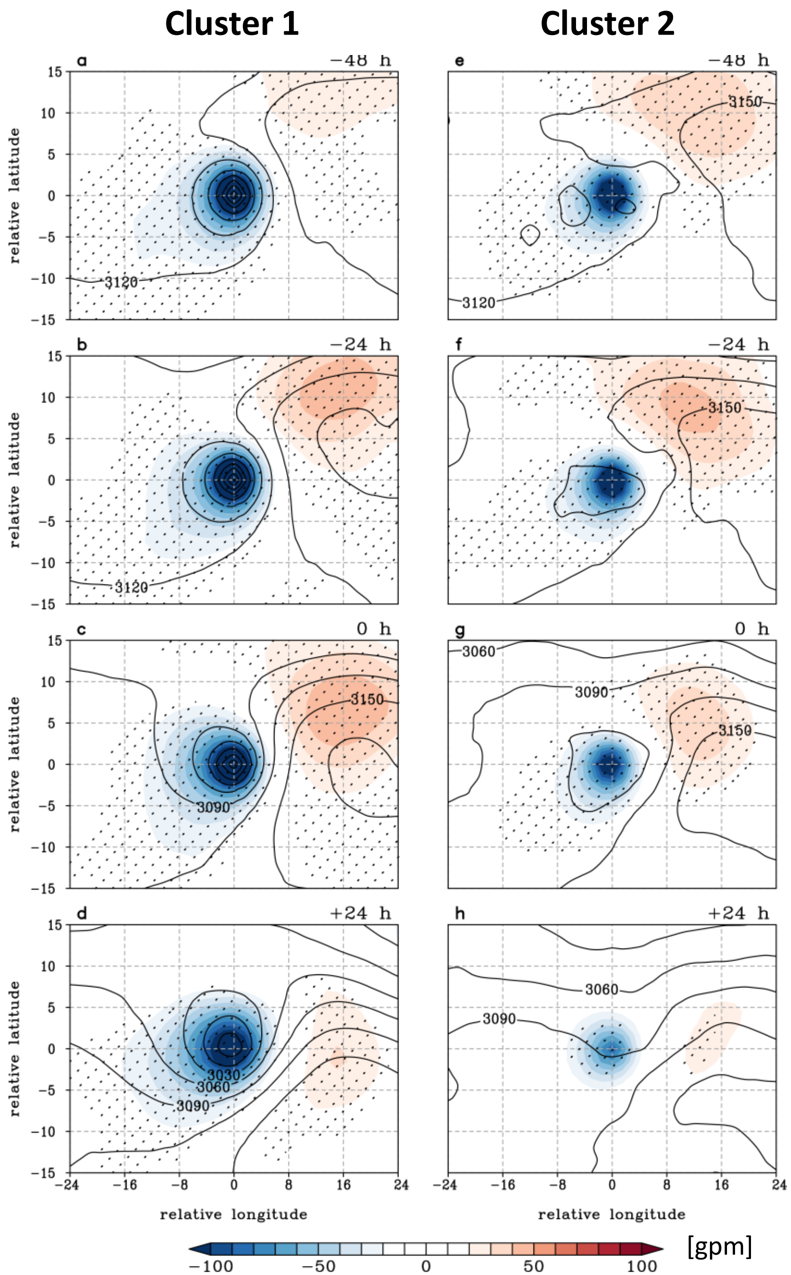
Synoptic conditions: Lower troposphere (700 hPa)



- C1 TCs sustain their size and intensity after HREs, while C2 TCs rapidly dissipate.

Contours: 700-hPa GPH [gpm]
Shading: 700-hPa GPH anomaly [gpm]
Vectors: **IVT** [> 300 kg m^{-1} s^{-1}]

Synoptic conditions: Lower troposphere (TC-centered)

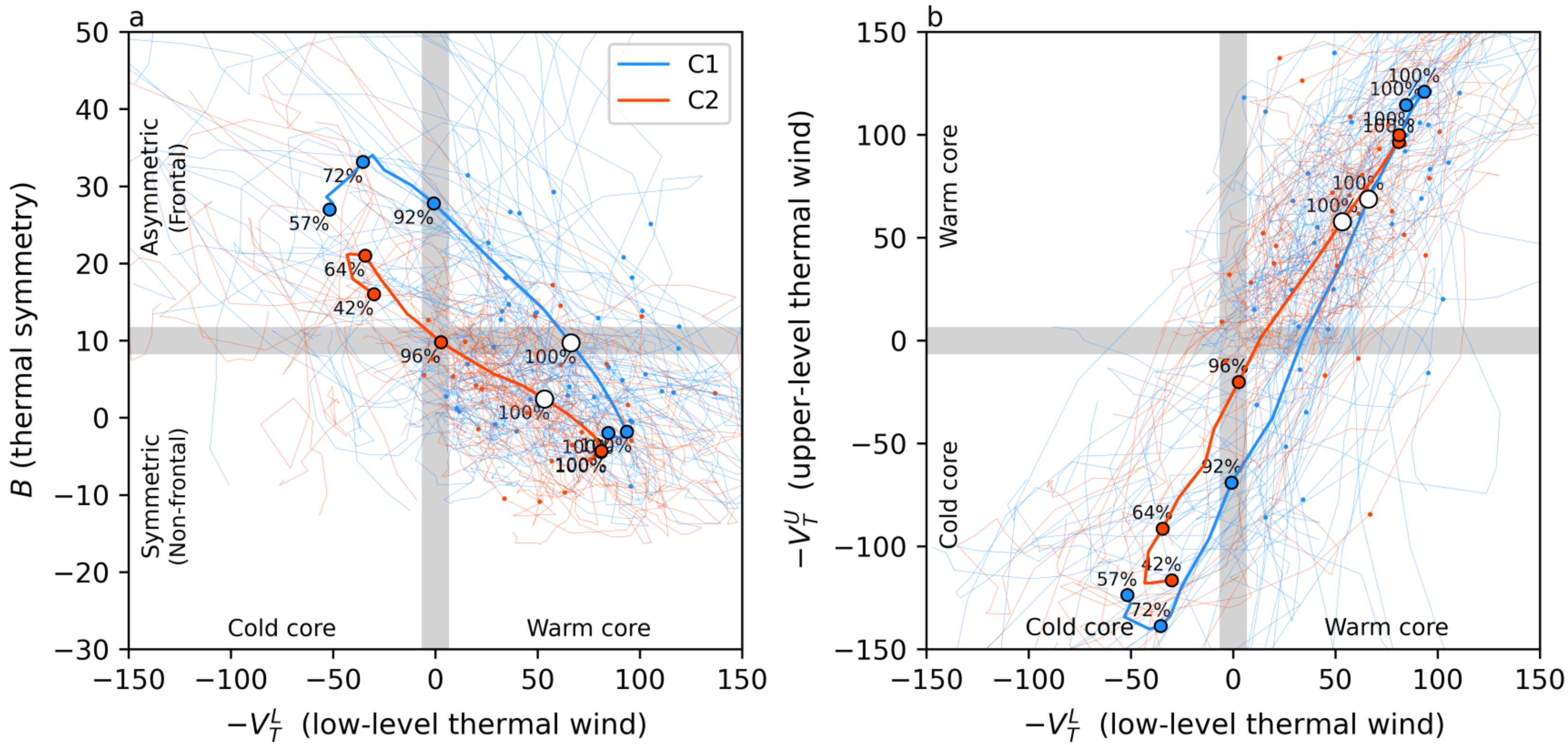


- The distinct TC evolution is not an artifact of composite analysis in which TC locations differ by events.

Contours: 700-hPa GPH [gpm]
Shading: 700-hPa GPH anomaly [gpm]

Cyclone phase space (CPS) diagram

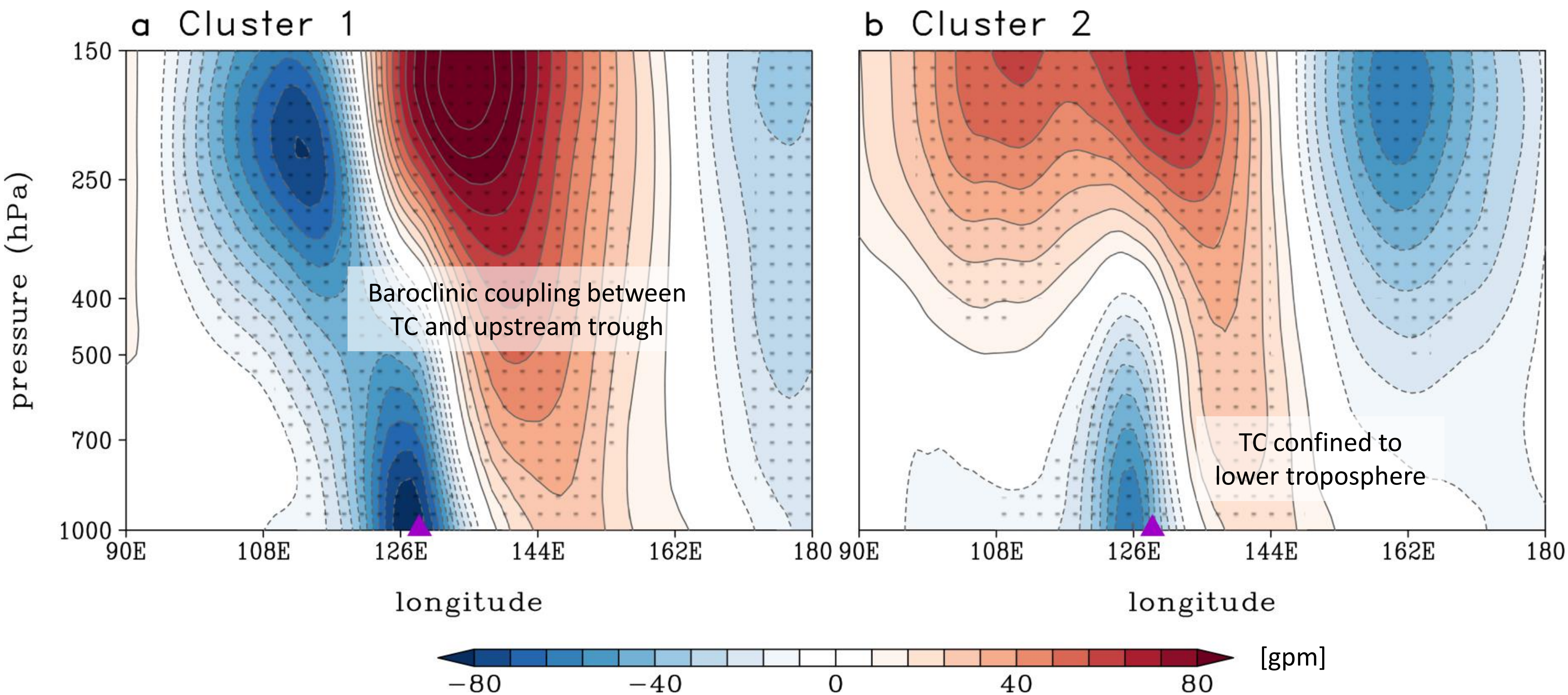
$-V_T^L$ vs. B $\qquad$ $-V_T^L$ vs. $-V_T^U$



- C1 TCs exhibit the rapid development of thermal asymmetry and replacement of upper-level warm core by cold core, compared to C2 TCs.
- More than 90% of C1 TCs complete ET and continue their lifecycle as extratropical cyclones, whereas only about 60% of C2 TCs do so.

Synoptic conditions: lon-pres cross section (33°–39°N)

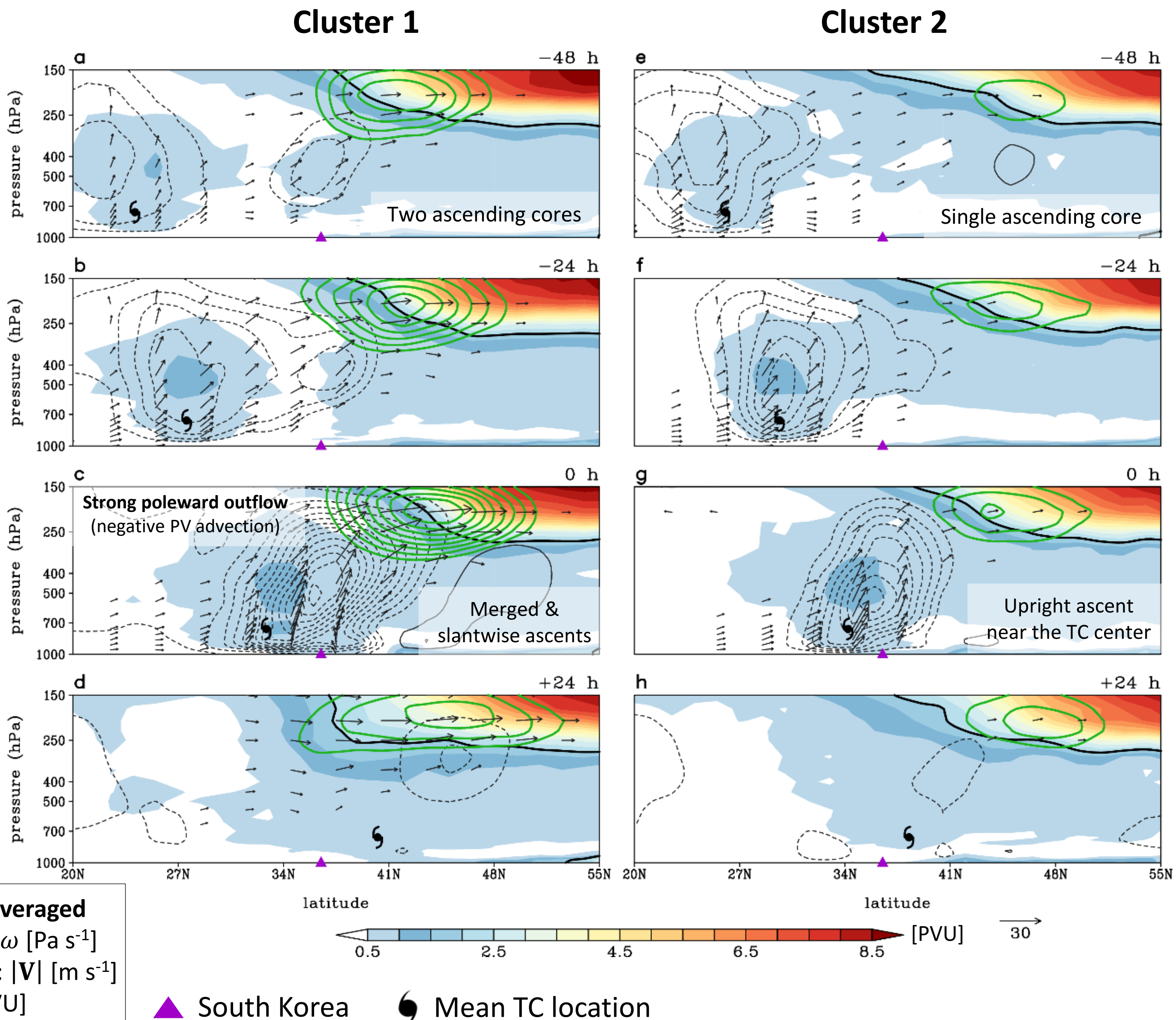
In the mature stage of HREs (0 h)



33°–39° N averaged
Shading: GPH anomaly [gpm]
Black contours: PV anomaly [PVU]

▲ South Korea

Synoptic conditions: lat-pres cross section (124°–131°E)



124°–131°E averaged
Black contours: ω [Pa s^{-1}]
Green contours: $|\mathbf{V}|$ [m s^{-1}]
Shading: PV [PVU]
Vectors: $v\omega$ [m s^{-1}]

Potential vorticity (PV) diagnosis of tropopause evolution

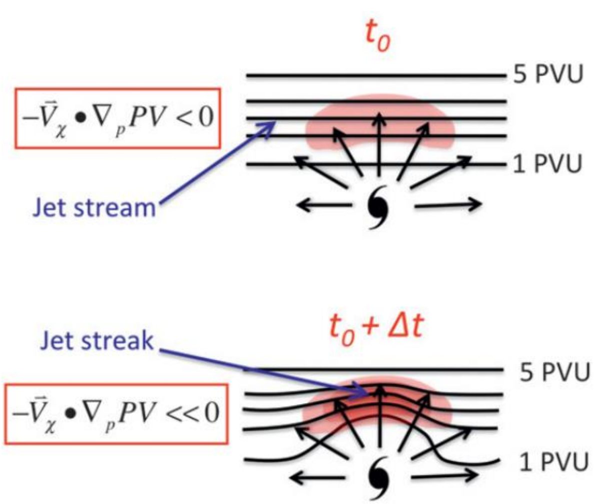
PV tendency equation

negligible negligible

$$\frac{\partial P}{\partial t} = -\mathbf{V}_{\psi} \cdot \nabla P - \mathbf{V}_{\chi} \cdot \nabla P - \cancel{\omega \frac{\partial P}{\partial p}} - g\left[(\zeta + f)\frac{\partial \dot{\theta}_{Dia}}{\partial p} + \cancel{\frac{\partial \dot{\theta}_{Dia}}{\partial y}\frac{\partial u}{\partial p}} - \frac{\partial \dot{\theta}_{Dia}}{\partial x}\frac{\partial v}{\partial p}\right]$$

Advection by rotational wind | Advection by divergent wind | Vertical advection | Diabatic production

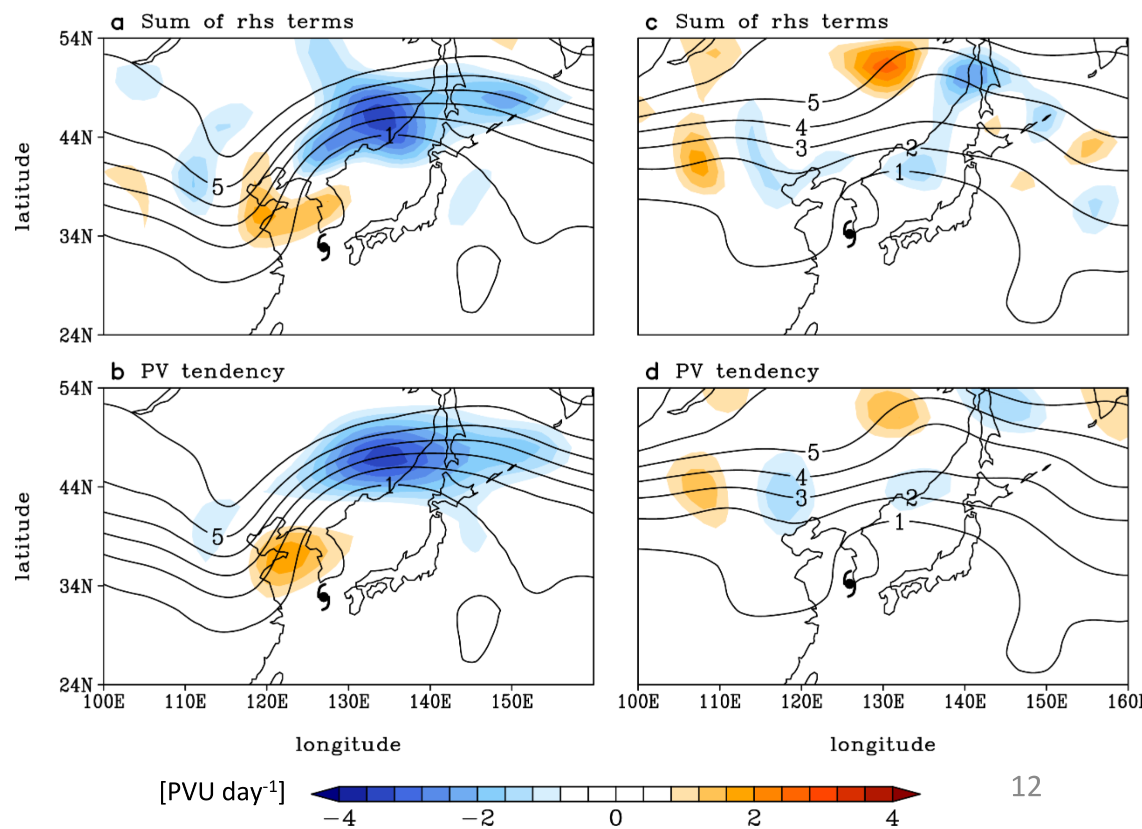
* 250–150-hPa layer average is applied



Archambault et al. (2013)

At mature stage of HREs (0 h)

Cluster 1 **Cluster 2**



Potential vorticity (PV) diagnosis of tropopause evolution

At mature stage of HREs (0 h)

$$\frac{\partial P}{\partial t}$$

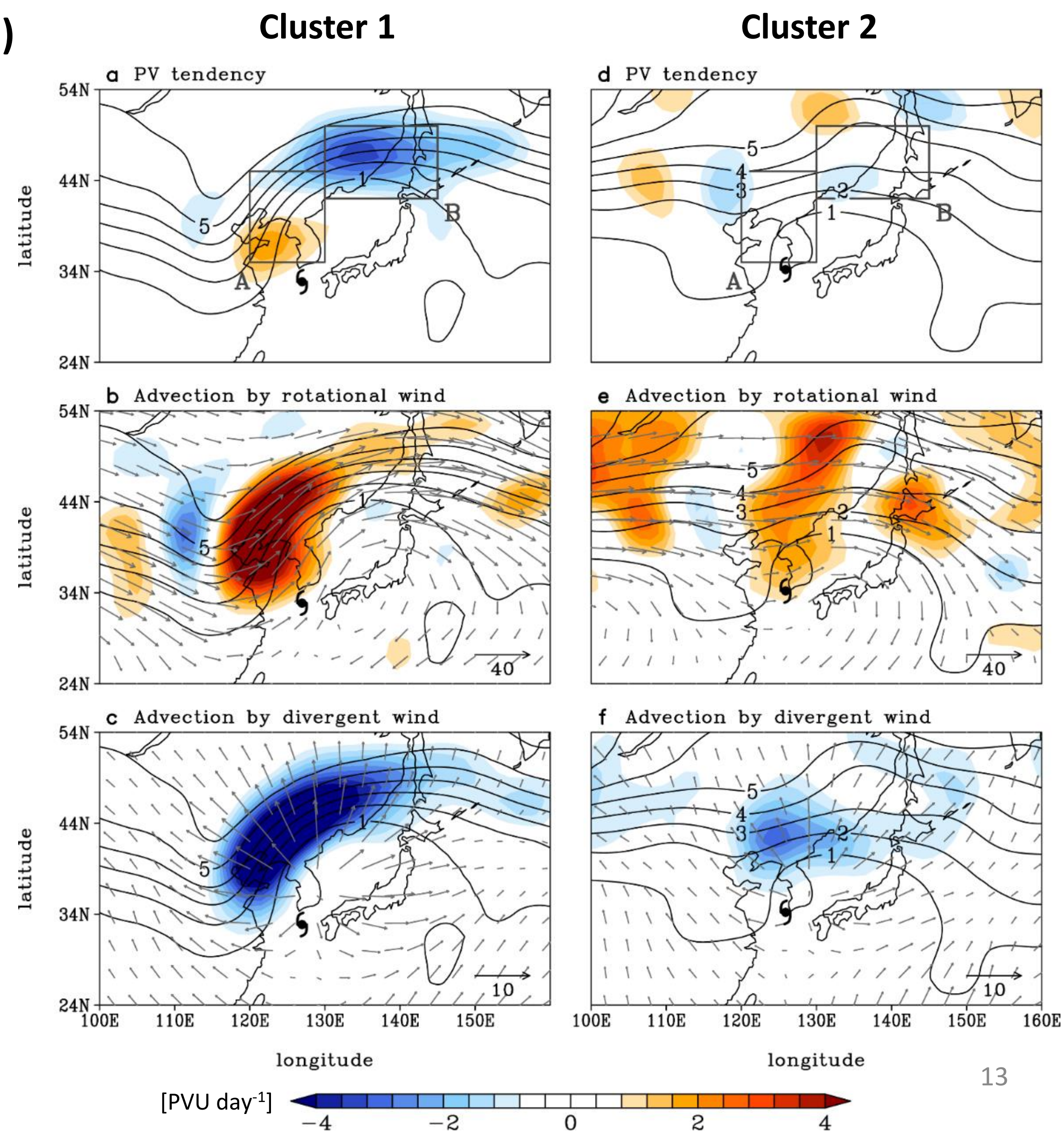
$$-\mathbf{V}_{\psi} \cdot \nabla P$$

(mostly, by midlatitude flow)

$$-\mathbf{V}_{\chi} \cdot \nabla P$$

(mostly, by TC outflow)

250–150-hPa average
Shading: PV budget term [PVU day^{-1}]
Black contours: PV [PVU]



Quasi-geostrophic (QG) diagnosis of vertical motion

Dynamic forcing (ω_{Dyn})

negligible in synoptic-scale motion

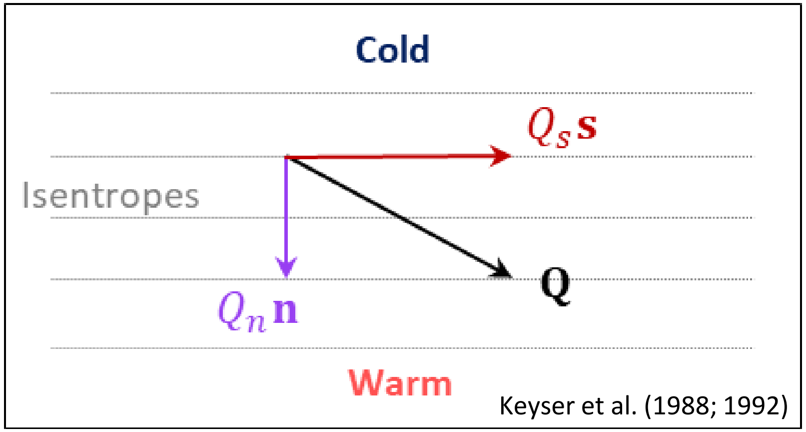
$$\left(\sigma_0\nabla^2 + f_0^2\frac{\partial^2}{\partial p^2}\right)\omega = \boxed{-2\nabla\cdot Q_n\mathbf{n} - 2\nabla\cdot Q_s\mathbf{s}} + \cancel{f_0\beta_0\frac{\partial v_g}{\partial p}} - \frac{\kappa}{p}\nabla^2 J$$

Transverse Q-vector forcing (ω_n)

Shearwise Q-vector forcing (ω_s)

Beta forcing (ω_{Beta})

Diabatic forcing (ω_{Dia})



$Q_s\mathbf{s}$: Shearwise Q vector

- Lagrangian change of $\nabla\theta$ direction following the geostrophic motion
- Trough/ridge, isolated vortex (e.g., TC)

$Q_n\mathbf{n}$: Transverse Q vector

- Lagrangian change of $\nabla\theta$ magnitude following the geostrophic motion
- Confluent/diffluent flows (e.g., jet entrance)

Quasi-geostrophic (QG) diagnosis of vertical motion

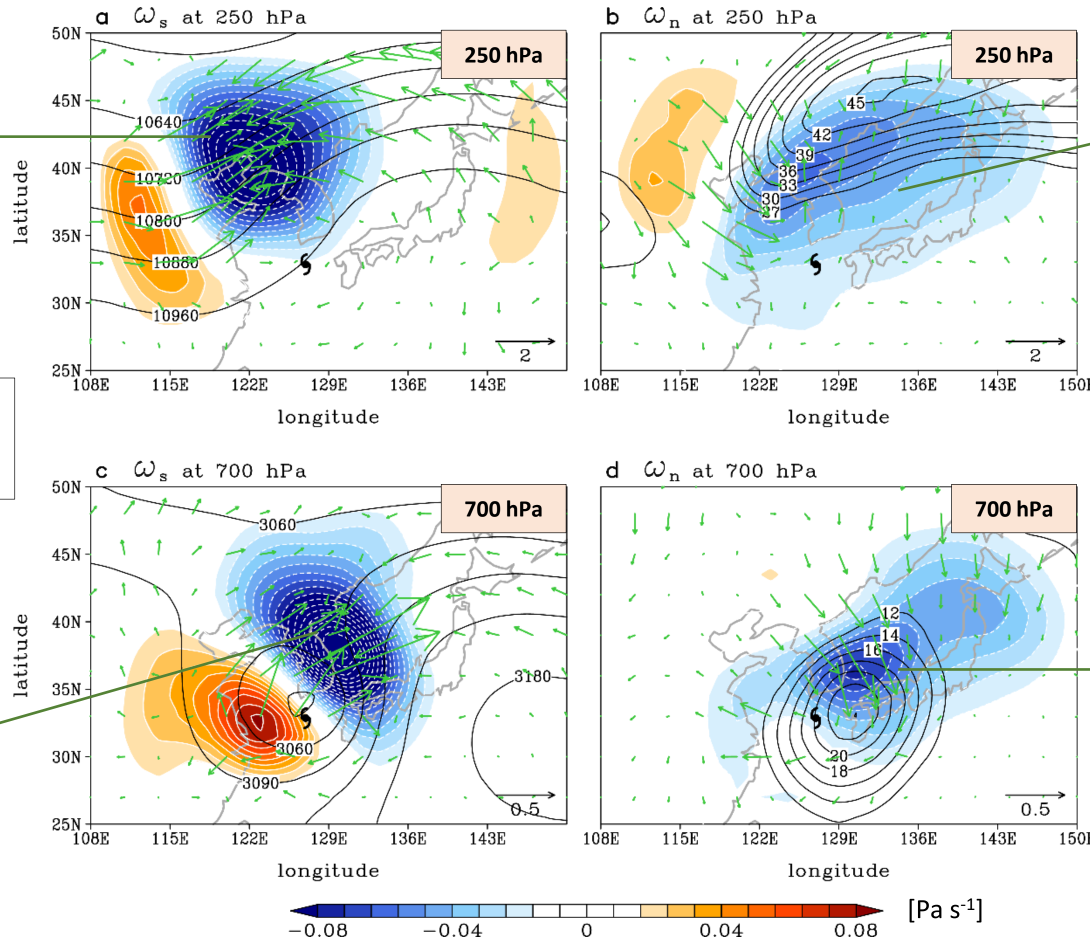
Cluster 1

At mature stage of HREs (0 h)

Ascending ω_s by upper-level trough and ridge

Elongated ascending ω_n by confluent motion around the jet entrance (secondary circulation)

Black contours: GPH [gpm]
Shading: ω_s [Pa s^{-1}]
Vectors: $Q_s\mathbf{s}$ [10^{-12} m^2 kg s^{-1}]



Black contours: $|\mathbf{V}|$ [m s^{-1}]
Shading: ω_n [Pa s^{-1}]
Vectors: $Q_n\mathbf{n}$ [10^{-12} m^2 kg s^{-1}]

Ascending ω_s by TC-induced rotating flow

Elongated ascending ω_n by southerly TC flow (warm front development)

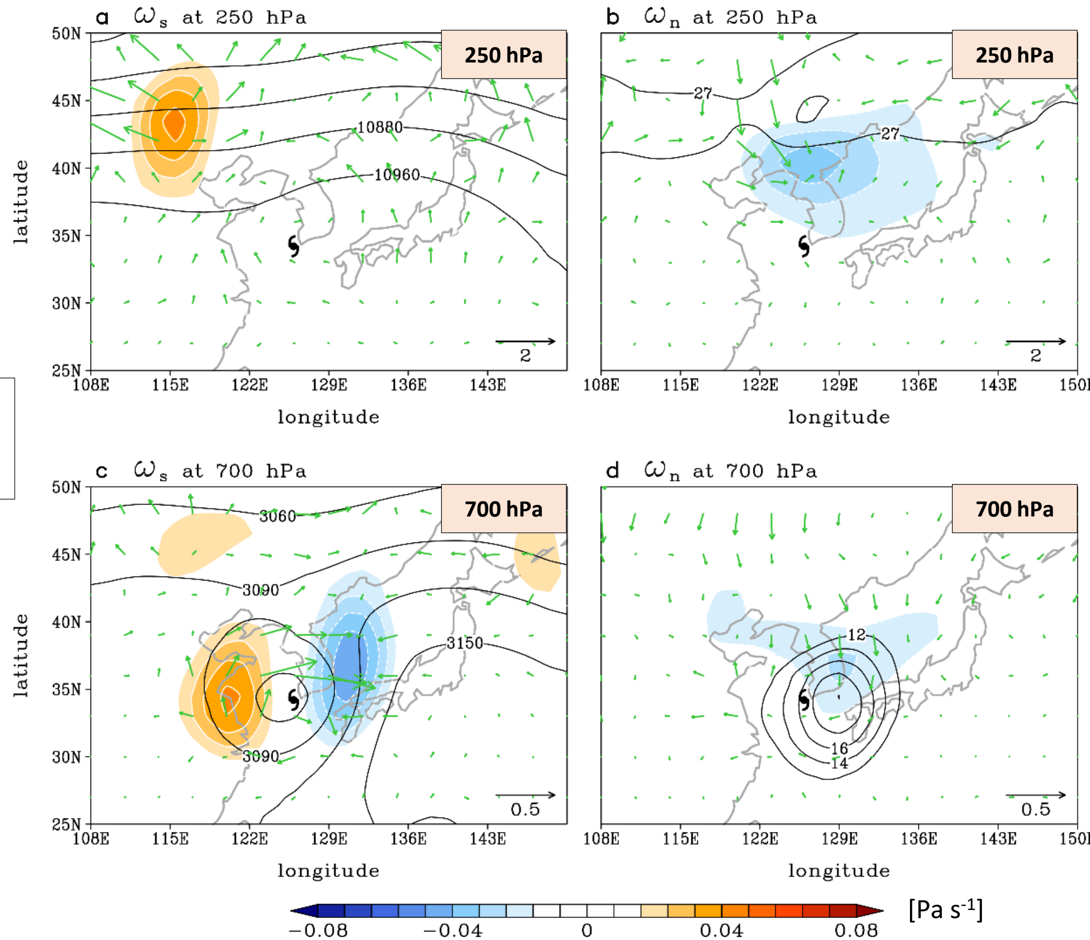
- Widely-enhanced ω_{Dyn} ($= \omega_n + \omega_s$) is associated with various dynamical processes manifesting synergistic TC–midlatitude flow interaction.

Quasi-geostrophic (QG) diagnosis of vertical motion

Cluster 2

At mature stage of HREs (0 h)

Black contours: GPH [gpm]
Shading: ω_s [Pa s^{-1}]
Vectors: $Q_s\mathbf{s}$ [10^{-12} m^2 kg s^{-1}]

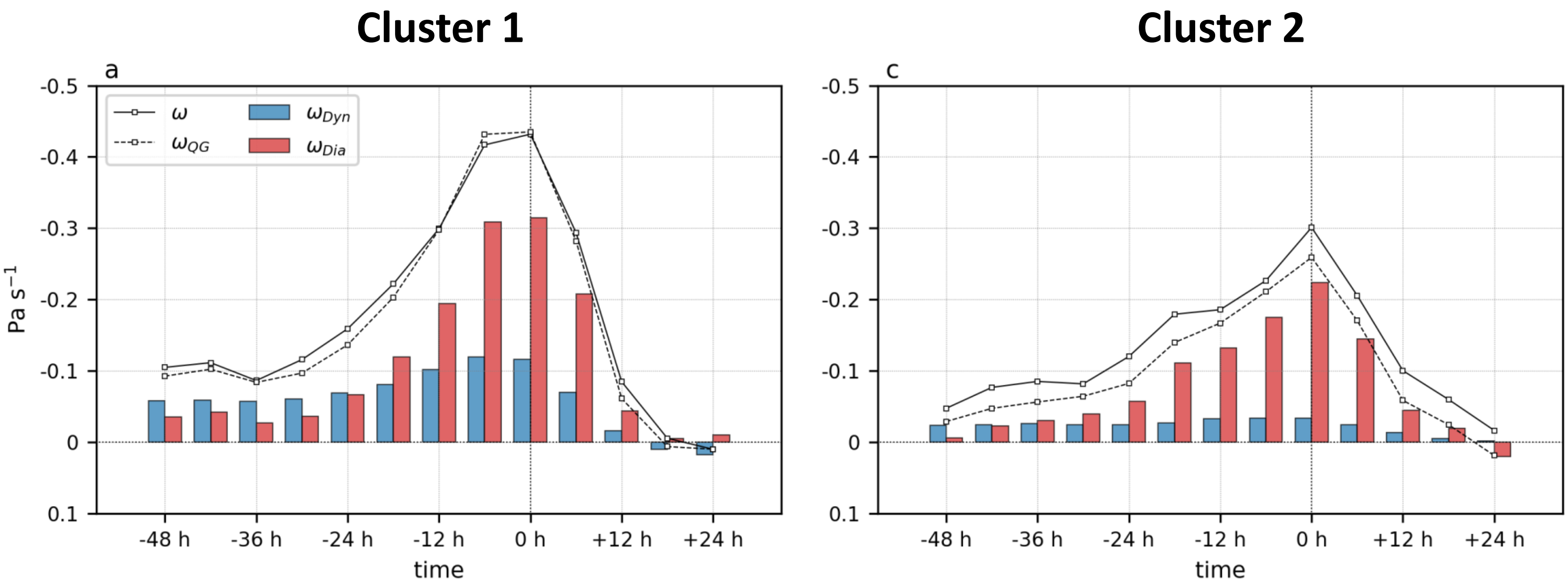


Black contours: |**V**| [m s^{-1}]
Shading: ω_n [Pa s^{-1}]
Vectors: $Q_n\mathbf{n}$ [10^{-12} m^2 kg s^{-1}]

- The dynamic ascent is feeble in both the upper and lower troposphere.

Quasi-geostrophic (QG) diagnosis of vertical motion

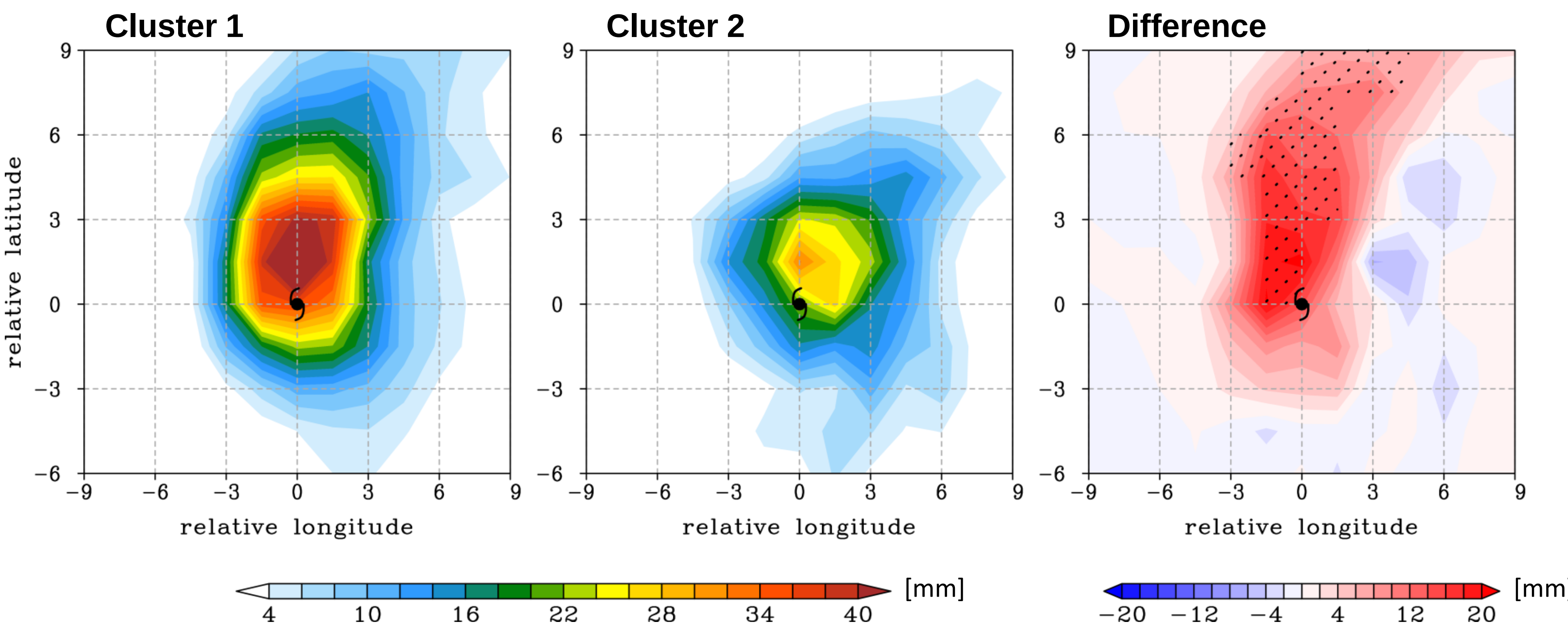
At 500 hPa



- C1 HREs is characterized by the nonlinear feedback of ω_{Dyn} and ω_{Dia} fostered by TC–midlatitude flow interaction.
- C2 HREs are dominated by ω_{Dia} with negligible ω_{Dia}, implying the dominant role of inherent diabatic TC convection.

Comparison of TC rainfall distribution (TC-centered composite)

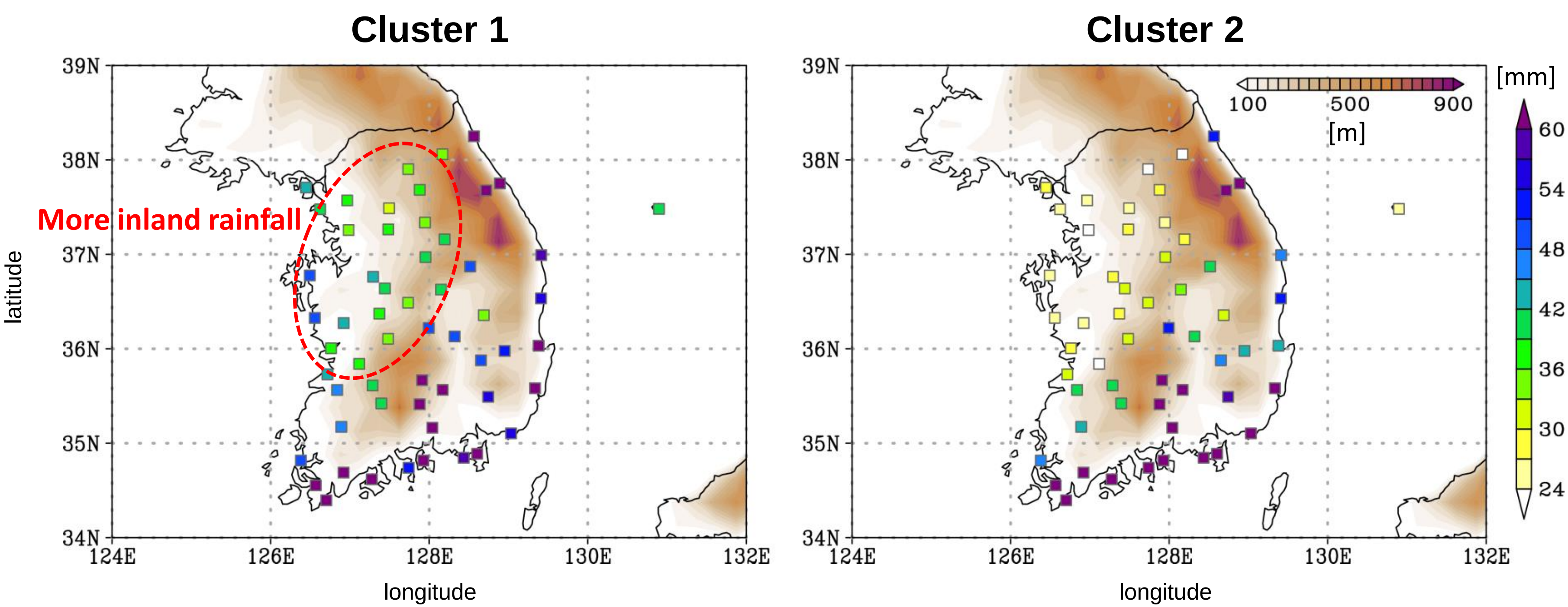
ERA5 12-h accumulated ERA5 total precipitation at 0 h



- TC rainfall is largely enhanced to the north of TC center in C1, whereas rainfall is relatively confined to TC center in C2.
- This is consistent with the **widely enhanced ω_{Dyn} in C1** and the **weak and spatially limited ω_{Dyn} in C2**.

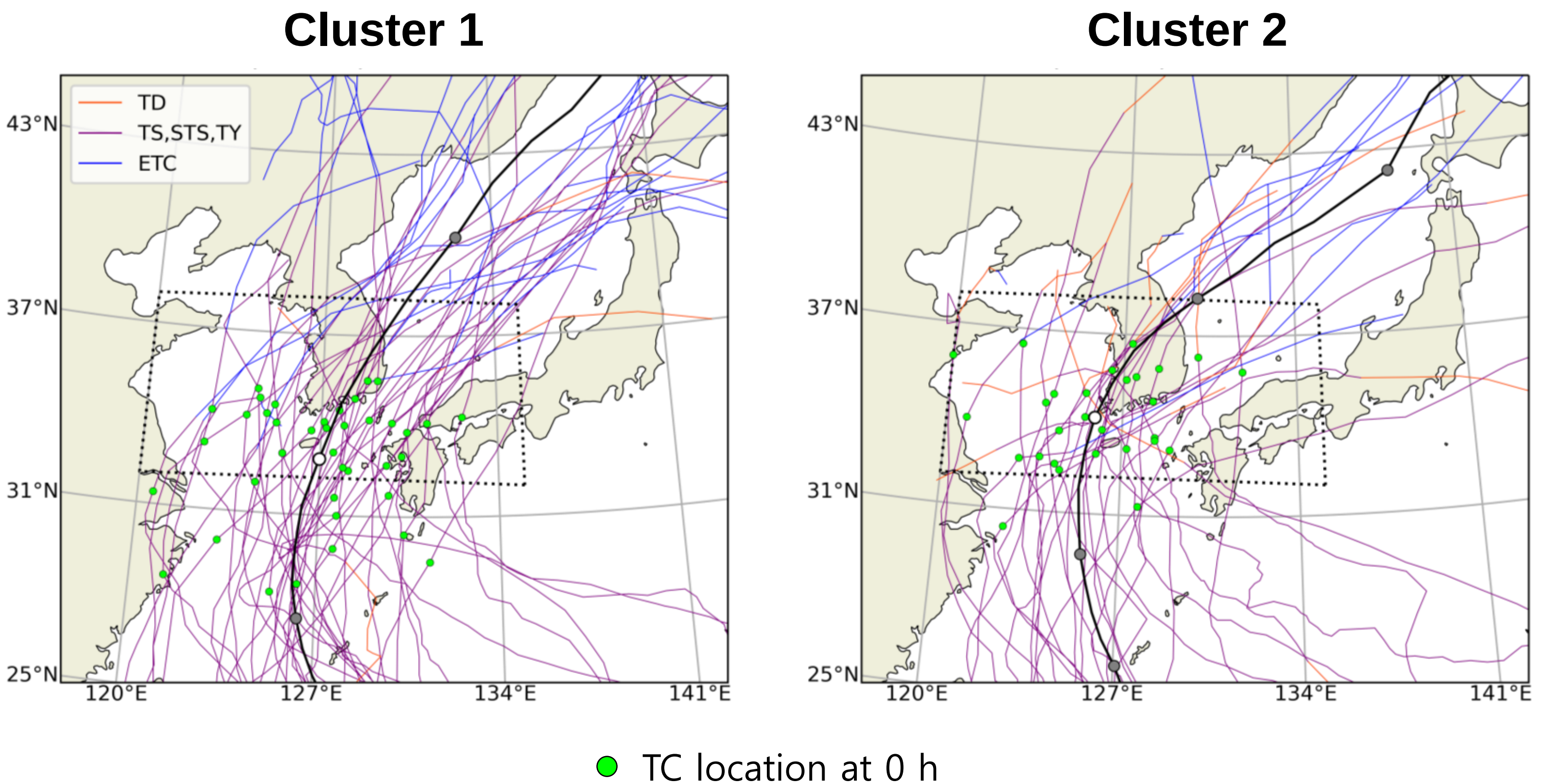
Comparison of TC rainfall distribution (South Korea)

Maximum 12-h accumulated rainfall across 57 stations



- C1 HREs bring more inland rainfall than C2 HREs (i.e., nationwide impact).
- This is consistent with the widely enhanced ω_{Dyn} in C1 and the weak and spatially limited ω_{Dyn} in C2.

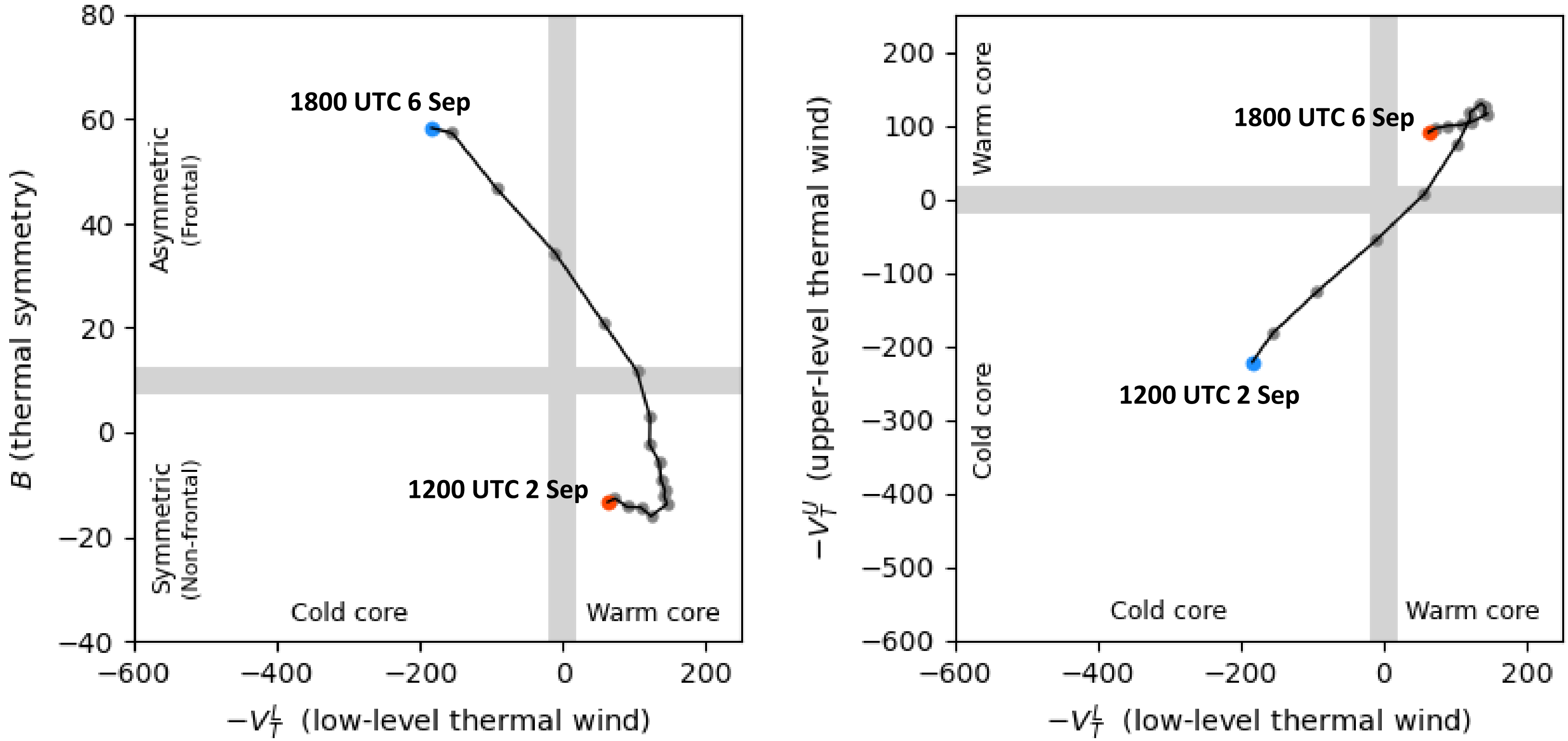
Comparison of TC tracks



- Unlike C2 HREs, C1 HREs are in the mature stage even before landfalling.
- This is consistent with the widely enhanced ω_{Dyn} in C1 and the weak and spatially limited ω_{Dyn} in C2.

Representative case: Hinnamnor (2022)

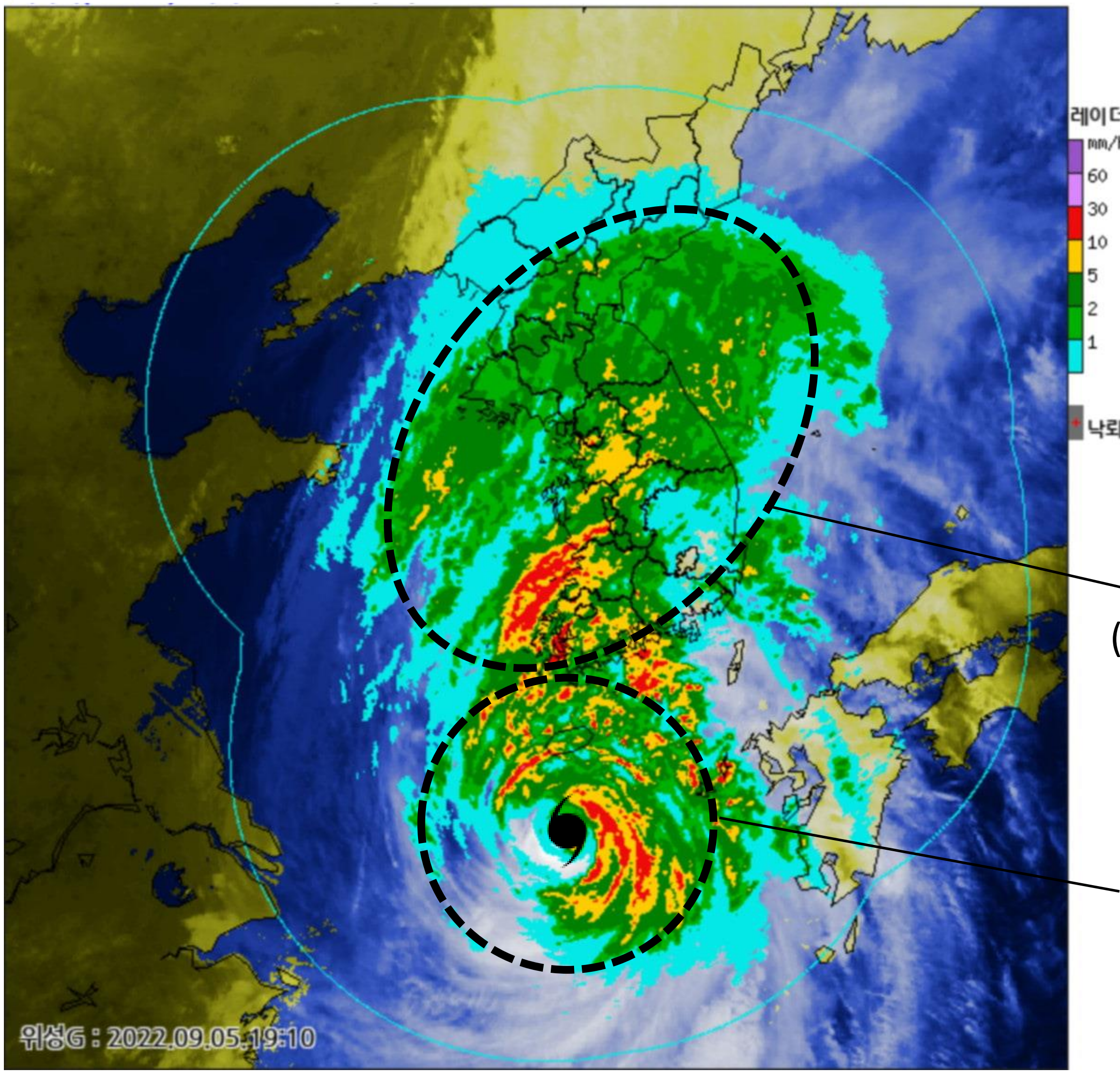
Cyclone phase space diagram



- Hinnamnor (2022) strongly interacted with midlatitude flow, following the typical evolution path of ET in the western North Pacific.

Representative case: Hinnamnor (2022)

1910 KST 5 September



TC-ahead rain shield
(TC–midlatitude flow interaction)

Spiral rainband
(inherent TC convection)

Summary

- C1: HREs under **strongly baroclinic** condition (58.8%)
  - Late-summer prevalence
  - Quasi-stationary trough-ridge couplet
  - Phase locking of TCs with upstream trough
  - Significant structural changes of TCs

"Synergistic"
TC-midlatitude flow interaction

Widely enhanced QG dynamic uplift ➡
- ✓ Widespread rainfall to the north of TC center
- ✓ HREs even prior to TC landfall

- C2: HREs under **weakly baroclinic** condition (41.2%)
  - Mid-summer prevalence
  - Unamplified tropopause pattern
  - Rapid TC dissipation
  - Maintenance of tropical features of TCs

"Weak"
TC-midlatitude flow interaction

Vertical motion confined to inherent TC convection ➡
- ✓ Narrow rainfall area near the TC center
- ✓ HREs during TC landfall

Summary

How does **midlatitude baroclinic condition** modulates the heavy rainfall events ***directly*** induced by TCs in South Korea?

TC–midlatitude flow interaction

Structure changes of TCs

Modification of midlatitude flow

?

Modulation of HREs

HRE: heavy rainfall event

- Midlatitude baroclinic condition plays a critical role in the strength of TC–midlatitude flow interaction and thereby determines the spatial extent of tropical cyclone rainfall.
- Thus, midlatitude environment should be carefully considered as a factor of heavy rainfall events directly induced by tropical cyclones.
- These results may be also applied to neighboring countries (e.g., China, Japan).