



Dynamics of the Asian Summer Monsoon Anticyclone: Insights from Potential Vorticity Tendency Diagnostics

Ninghui Li¹, Jonathon S. Wright¹, Philip Rupp², Alison Ming³, Shenglong Zhang¹, and Jie Gao⁴

¹Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Tsinghua University, Beijing 100084, China

²Meteorological Institute Munich, Ludwig-Maximilian University Munich, Munich, 80333, Germany

³Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, CB3 0WA, UK

⁴Laoshan Laboratory, Qingdao, 266237, China

Correspondence: Jie Gao (jgaots2017@163.com) and Jonathon Wright (jswright@tsinghua.edu.cn)

Abstract. The Asian Summer Monsoon Anticyclone (ASMA) is a dominant circulation in the upper troposphere and lower stratosphere (UTLS) during boreal summer and exhibits pronounced temporal and spatial variability. While its time-mean structure and climatological characteristics are well documented, the mechanisms governing its temporal evolution, particularly its eastward and westward propagation, episodic eddy-shedding events, and the emergence of multimodal behavior are remaining incompletely understood. Using multiple reanalysis datasets (JRA-3Q, ERA5, MERRA-2) from 2000–2020, this study analyzes the dynamic structures of the ASMA, the analysis shows that the ASMA exhibits a trimodal structure with centers over the Iranian Plateau, Tibetan Plateau, and western Pacific, identified via a multi-center vortex tracking algorithm applied to the 370 K isentropic surface to distinguish persistent and transient anticyclones. Further results show that mean zonal and meridional advection are the primary drivers of potential vorticity (PV) tendency, while total diabatic heating that plays a crucial modulating role in ASMA evolution. A key contribution of this work lies in the formulation and application of an ASMA-specific PV tendency diagnostic, which builds upon established PV budget and enables a more rigorous quantification of the respective roles of dynamical and thermodynamical processes in the anticyclone’s intensification and zonal propagation across its three modes. This diagnostic decomposes total PV tendency into dynamic components (e.g., horizontal and vertical advection) and thermodynamic components (e.g., latent heating and background radiation), enabling the separation of the combined effects of anticyclone propagation and intensification by capturing a characteristic tripole pattern of PV tendency. Compared to conventional methods, this new diagnostic provides a more rigorous and precise quantification of the physical processes governing the ASMA’s zonal movements and overall development, thereby advancing our scientific understanding of the ASMA’s variability and underlying mechanisms in the UTLS region.

1 Introduction

The Asian summer monsoon anticyclone (ASMA) is a prominent atmospheric circulation feature during boreal summer, manifesting as an extensive anticyclonic vortex in the upper troposphere and lower stratosphere (UTLS). Bounded by the subtropical westerly jet to the north and the tropical easterly jet to the south, the ASMA resides at the interface between the tropics and sub-



tropics and extends vertically from approximately 300 to 70 hPa (Hsu et al., 1999; Randel and Park, 2006; Nützel et al., 2016; Manney et al., 2021). The ASMA is fundamentally driven by diabatic heating associated with the Asian summer monsoon. Strong land–sea thermal contrasts induce low-level convergence over the Asian continent and adjacent oceans, promoting deep ascent and convection over elevated terrain such as the Iranian and Tibetan plateaus (Gill, 1980; Hoskins and Rodwell, 1995; Honomichl and Pan, 2020; Siu and Bowman, 2020). The associated convective diabatic heating amplifies upper-tropospheric divergence, which in turn leads to the formation and maintenance of a large-scale anticyclonic circulation in the UTLS. The UTLS region influenced by the ASMA is also characterized by the presence of the Asian tropopause aerosol layer, which can interact with the anticyclonic circulation and modulate its structure and variability (Vernier et al., 2015; Honomichl and Pan, 2020). Despite this well-established conceptual framework, the ASMA exhibits pronounced intraseasonal and interannual variability linked to variations in surface heating and subtropical jet dynamics, and the mechanisms governing this variability remain an active area of research (Garny and Randel, 2013; Ren et al., 2019; Manney et al., 2021; Rupp and Haynes, 2021).

A variety of diagnostic approaches have been used to characterize the extent, location, modality and other structural aspects of the ASMA, reflecting both the dynamical complexity of the system and the availability of long-term reanalysis datasets. Observational analyses have shown that the ASMA exhibits pronounced temporal variability, including large-amplitude east–west oscillations and systematic center propagation on intraseasonal timescales. Rather than remaining a single, coherent vortex, the anticyclonic circulation frequently reorganizes, with circulation centers alternately intensifying over the Iranian Plateau (IP), Tibetan Plateau (TP), and the western Pacific. These zonal movements are often accompanied by structural instabilities, including vortex splitting, merging, and episodic eddy-shedding events (Zhang et al., 2002; Popovic and Plumb, 2001; Yan et al., 2018; Siu and Bowman, 2020). Previous studies have employed a range of diagnostics. The horizontal extent, location, and modality of the ASMA have commonly been identified using geopotential height and zonal wind fields at 100 and 200 hPa (Zhang et al., 2002; Qian et al., 2002; Wei et al., 2014; Nützel et al., 2016; Wang et al., 2022), as well as PV on isentropic surfaces between 360 and 380 K (Garny and Randel, 2013; Ploeger et al., 2015; Amemiya and Sato, 2018; Rupp and Haynes, 2020; Manney et al., 2021). Streamfunction-based diagnostics, including the Montgomery streamfunction (MSF) on isentropic surfaces, have also been widely used to track the evolution of the ASMA and its eddy-shedding behavior that the westward and eastward anticyclones breaking off form the main anticyclone (Popovic and Plumb, 2001; Yan et al., 2018; Siu and Bowman, 2020). In addition, numerical model simulations and idealized experiments have provided valuable insight into the roles of both natural variability and anthropogenic forcing in shaping the anticyclonic circulation (Amemiya, 2018; Amemiya and Sato, 2018; Rupp and Haynes, 2020; Pan et al., 2022; Zhang et al., 2024). A summary of commonly used diagnostics and definitions of ASMA location is provided in Table 1. Despite these extensive efforts, substantial challenges remain. Diagnosed ASMA characteristics can differ across reanalysis products, and ongoing updates to data assimilation systems may further amplify such discrepancies (Nützel et al., 2016; Manney et al., 2021). The frequent coexistence of multiple anticyclonic centers and their zonal migration imply that approaches emphasizing a single dominant vortex or time-mean structure are often insufficient (Zhang et al., 2002; Siu and Bowman, 2020). Observational evidence indicates that the ASMA frequently consists of two or more concurrent circulation centers, and in some cases more than three, highlighting the need for diagnostic that explicitly account for its multi-center and multimodal structure.



The development and intensification of the ASMA are commonly examined using diagnostics that describe the evolution of its low-PV core. A frequently used measure is the time variation of the area enclosed by low-PV contours, as diabatic heating and upper-level divergence associated with deep convection act to expand low-PV regions in the UTLS (Garny and Randel, 2013). Complementary diagnostics, such as geopotential height anomalies relative to the zonal mean and variations in streamfunction, have also been shown to capture key aspects of ASMA evolution (Xue et al., 2020; Zhang et al., 2021). Despite their methods, these diagnostics have limitations when applied to the ASMA. Low-PV is already present over the Asian monsoon region at the onset of boreal summer, and the seasonal evolution of the background PV field is characterized by a gradual increase in mean PV. This background evolution complicates attempts to disentangle intrinsic ASMA intensification from changes inherited from preexisting conditions. Moreover, although PV-area based diagnostics are conceptually motivated by analogous studies of the stratospheric polar vortex, the underlying physical processes differ substantially. In the polar vortex, diabatic heating and transport barriers play a dominant role, whereas the ASMA is strongly influenced by deep convection, divergent outflow, and interactions with the subtropical jet, limiting the direct transferability of polar vortex diagnostics to the monsoon anticyclone. These challenges highlight the need for diagnostic that can explicitly separate ASMA intensification from zonal propagation and background PV evolution, while remaining applicable to its multi-center and time varying structure. Addressing this need requires diagnostics that quantify not only the magnitude of low-PV anomalies but also the processes governing their temporal tendencies.

In this study, we track ASMA movements and occurrence based on the method by Siu and Bowman (2020), with particular focus on intercomparisons across recent reanalysis products to quantify the anticyclone's persistent and transient behaviors. Additionally, we use PV tendency diagnostic to quantify ASMA intensification, which provides deeper insights into the physical mechanisms governing its westward/eastward propagation and overall development. Section 2 details the datasets, followed by descriptions of the isentropic vortex tracking methodology and PV tendency equation calculations in Section 3. Key findings are presented in Section 4, and Section 5 and 6 include conclusions and discussions of the results.

2 Data

Climate research relies heavily on observational data for validating frameworks, predicting changes, and testing multi-scale process understanding, but these intricate processes often require reanalysis products due to observational limitations (Davis et al., 2017; Rupp, 2018). In this study, we analyze variations of the ASMA in three of the most recent 'full input' reanalysis products (Manney et al., 2021): the European Centre for Medium-Range Weather Forecasts (ECMWF) Fifth Reanalysis of the Atmosphere (ERA5; Hersbach et al., 2020); the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2; Gelaro et al., 2017), and the Japanese Reanalysis for Three Quarters of a Century (JRA-3Q; Kosaka et al., 2024). Our study covers the warm seasons of the Northern Hemisphere (May to September) of 2000-2020. All reanalysis products are interpolated to a common $1.25^\circ \times 1.25^\circ$ latitude-longitude grid and subselected in time to produce 6-hour fields. The key details of the reanalysis products are listed in Table 2. The ERA5 dataset does not provide a direct product for latent heating. Therefore, this study adopts the combination of top net shortwave radiation (mttswr), top net longwave radiation (mttlwr),



Table 1. Overview of studies for determining the locations of the ASMA. Geopotential height, zonal wind, and relative vorticity are denoted by ϕ , u , and ζ , respectively.

Reference	Dataset	Study Period	Variables Analyzed	Identification Method
Zhang et al. (2002)	NCEP-1	July-August 1980–1994	ϕ , u at 100 hPa	Maximum ϕ along ridgeline
Qian et al. (2002)	NCEP-1	July-August 1958–1997	ϕ , u at 100 hPa	Maximum ϕ along ridgeline
Zhou et al. (2006)	NCEP-1	June-August 1950–1999	ϕ at 100 hPa	Maximum ϕ
Zarrin et al. (2010)	NCEP-1	June-August 1971–2000	ϕ , ζ at 100 hPa	Maximum ϕ along ridgeline; Maximum negative ζ
Yan et al. (2011)	NCEP-1	June-August 2005–2009	ϕ , u at 100 hPa	Maximum ϕ along ridgeline
Wei et al. (2014)	ERA-40 CFSR ERA-I	June-August 1958–2002	ϕ , u at 200 hPa	Maximum ϕ along ridgeline
Nützel et al. (2016)	JRA-25 JRA-55 NCEP-1 NCEP-2	June-December 1979–2014	ϕ , u at 100 hPa	Maximum ϕ along ridgeline
Honomichl and Pan (2020)	ERA-I	July-August 1979–2017	ϕ at 100 hPa, 150 hPa	Maximum ϕ along ridgeline
Garny and Randel (2013)	MERRA	May-September 2005–2009	PV at 360/380 K	PV threshold-based identification
Ploeger et al. (2015)	ERA-I	June-August 1979–2014	PV at 380 K	PV gradient analysis
Fairlie et al. (2014)	GEOS-5.2	June 2011	PV at 380 K	PV threshold-based identification
Amemiya and Sato (2018)	ERA-I	June-August 1979–2016	PV at 360/370/380 K	PV threshold-based identification
Popovic and Plumb (2001)	NCEP-1	July 1987–1990	MSF, PV at 370 K	Maximum MSF; PV threshold-based identification
Siu and Bowman (2020)	ERA-I	May-September 1979–2018	MSF, u , ζ at 370 K	Peaks of MSF; Zero zonal wind, $\pm\zeta$
Santee et al. (2017) Manney et al. (2021)	MERRA-2 ERA-I JRA-55	July-August 1979–2018	MSF at 350/370/390/410 K	MSF threshold values: 350 K ($344800 \text{ m}^2\text{s}^{-2}$); 370 K ($356500 \text{ m}^2\text{s}^{-2}$); 390 K ($367100 \text{ m}^2\text{s}^{-2}$); 410 K ($377300 \text{ m}^2\text{s}^{-2}$)



Table 2. Details of three reanalysis products.

Name	Source	Horizontal Resolution	Pressure Levels (No.)	Frequency	Reference
ERA5	ECMWF	$0.75^\circ \times 0.75^\circ$	1000 to 50 hPa (37)	6h	(Hersbach et al., 2020)
MERRA-2	NASA GMAO	$0.625^\circ \times 0.5^\circ$	1000 to 0.1 hPa (42)	6h	(Gelaro et al., 2017)
JRA-3Q	JMA	$1.25^\circ \times 1.25^\circ$	1000 to 0.1 hPa (45)	6h	(Kosaka et al., 2024)

and precipitation-related top latent heat flux (mttpm) to indirectly characterize latent heating. Among them, mttswr and mttlwr jointly depict the radiation budget balance at the top of the atmosphere, providing a thermal background field for latent heat release. mttpm directly corresponds to the latent heat released by water vapor phase change during precipitation, which is the core contributor to latent heating. The combination of these three variables can effectively make up for the lack of direct latent heating products in ERA5 and accurately reflect the spatiotemporal variation characteristics of latent heating.

3 Methodology

3.1 Vortex Tracking

The multi-center anticyclone tracking method in this study is proposed by Siu and Bowman (2020) which is based on the single center vortices method of Zhang et al. (2002). Three variables from reanalysis data are used to locate the centers of ASMA, including zonal wind, u , MSF, ψ , and relative vorticity, ζ . The first step is to determine the zonal zero-wind lines for the designated domain (spatial range of 15° – 45° N and 0° – 180° E for ASMA) at a specified analysis time (usually 6 hours) as the zero-wind contours is nearly zonal inside the AMA (Siu and Bowman, 2020). A Marching Squares Algorithm is employed to identify the isopleths of the zonal wind field $u = 0$. This algorithm systematically divides the wind field into numerous marching squares and utilizes a divide-and-conquer strategy to determine the intersection points at which the wind transitions from easterly to westerly directions (Lorensen, 2020). The Fig. 1 illustrates a potential anticyclone center, denoted by the blue open circle, which corresponds to the location of maximum in Montgomery, ψ . The bold black line indicates the contour line where $u = 0$, which intersects the center of the anticyclone. The regular grid points represent the data points derived from the reanalysis data. It is evident that the $u = 0$ contour line does not align perfectly with the grid points of the reanalysis data. Consequently, certain points in $u = 0$ isopleth require interpolation utilizing the two nearest data points; for instance, the data represented by the blue open circle necessitates interpolation from the adjacent upper and lower points, indicated by the red and blue dots, respectively.

After finding one or more sets of zero-zonal wind ($u = 0$) contours within the specific domain, the next step is to locate the vortex centers, if they exist, along these zero-zonal wind contours. The MSF along the zero-zonal wind isopleths does not pass through the grid points of the reanalysis data perfectly, and also need to be interpolated by the two nearest points. And the interpolated Montgomery, $\tilde{\psi}$ is the function of grid coordinates, (x_i, y_i) which can be expressed as

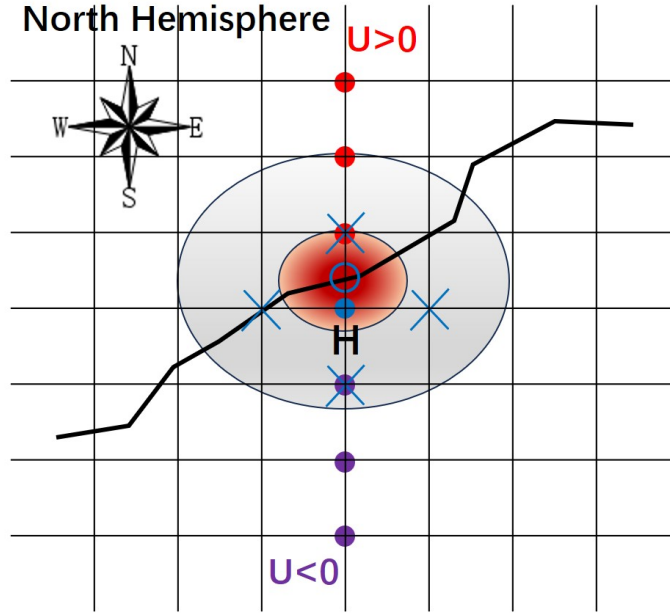


Figure 1. The scheme for identifying the vortex center and filtering out the spurious centers. The candidate vortex is represented by blue circle which locates at the maximum MSF, the reanalysis grid point closes to the candidate centre is indicated by a blue filled dot. The four reanalysis grid points closest to this closest point (the blue dot) are indicated by blue crosses. The black solid line is the contour of $u = 0$, the gray ellipse is the large area of anticyclone, the shading coral ellipse is the core of anticyclone. In northern hemisphere, the relative vorticity $\zeta < 0$ and the three grid points located poleward/equatorward of the nearest grid point must exhibit westerly/easterly winds, as denoted by red/purple dots, respectively. This scheme is re-organized based on Figure 5 of Siu and Bowman (2020)

$$\tilde{\psi}[f(x_i, y_i)] = \tilde{\psi}(s_i) \quad (1)$$

where s_i is the distance along the contour, e.g. from point (x_{i-1}, y_{i-1}) to (x_i, y_i) , calculated as the aggregate of the great-circle arc lengths corresponding to the contour segments, f represents the map function that maps (x_i, y_i) to s_i . For each set of contours, a local maximum of $\tilde{\psi}(s_i)$ is identified within the specified range of $s_i - \delta s \leq s_i \leq s_i + \delta s$, where δs is half-angle search window that $\delta s = R\delta a$, and δa is the central angle of the great-circle arc which is chosen to be 7.5° through Siu and Bowman (2020), R is the Earth radius. The minimum allowable distance between two adjacent peaks of $\tilde{\psi}$ (vortex centers) along a contour is denoted as δs , and the quantity of distinct vortices identified may fluctuate over time.

Furthermore, it is crucial to filter out vortices that may arise from small-scale features or from noise inherent in the gridded data, which these vortices are so called “spurious center”. The relative vorticity, ζ at the central grid point (indicated by the blue dot) and its four nearest grid points (represented by blue crosses) within the reanalysis grid is characterized as anticyclonic should be less than 0 ($\zeta < 0$) in Northern Hemisphere. Also, the three grid points located poleward and equatorward of the



central grid point must be westerly zonal wind ($u > 0$, red dots) and easterly zonal wind ($u < 0$, purple dots), respectively. The minimum length (great-circle arc distance) of each set of contours should be greater than $2R\delta a$ (Siu and Bowman, 2020). The last step is to differentiate the persistence and dynamics of sub-vortices over time by conducting a series of vortex analyses at various temporal intervals. The vortices are classified as “persistent”, if the location of a vortex center remains stable within a threshold of 10° of great-circle distance and exhibits continuity for a minimum of 18 hours, the remaining vortices are characterized as “transient” (Siu and Bowman, 2020). All the processes of vortex tracking are carried out on the 370 K isentropic surface.

3.2 PV tendency diagnostic

To quantify the multi-center structure, zonal propagation, and intensification of the ASMA on isentropic surfaces, this study employs a combined diagnostic based on the MSF, PV, and PV tendency. Each quantity plays a distinct and complementary role in the anticyclonic circulation in the UTLS. The MSF provides a dynamically consistent field for identifying anticyclonic centers on isentropic surfaces. Unlike geopotential height on pressure levels, the MSF directly incorporates both thermal and dynamical contributions. The MSF is used to identify and track multiple ASMA centers along the zero zonal-wind contour, following the approach of Siu and Bowman (2020), thereby enabling a characterization of persistent and transient anticyclonic modes. According to the definition of MSF from Lackmann (2011):

$$\psi = C_p T + gz, \quad (2)$$

where C_p is the specific heat at constant pressure of dry air, T is the temperature of the air on the isentropic surface, g is the gravitational acceleration, and z is geopotential height of the isentropic surface. While the MSF is used to locate and track ASMA centers, potential vorticity is employed to quantify the strength, spatial extent, and dynamical coherence of the anticyclonic circulation. PV is particularly advantageous in the UTLS because it is conserved under adiabatic and frictionless conditions and therefore provides a physically meaningful measure of vortex evolution (Hoskins et al., 1985). In this study, PV diagnostics are applied on the 370 K isentropic surface, which approximately corresponds to the climatological ASMA core. The local rate of change that is the isentropic density of pressure p with potential temperature θ can be expressed as:

$$\sigma = -g \frac{\partial p}{\partial \theta}. \quad (3)$$

Also, the ψ has a relationship with p and has a formula by Exner function (Amemiya and Sato, 2018; Kang and Son, 2021):

$$\frac{\partial \psi}{\partial \theta} = C_p \left(\frac{p}{p_0} \right)^{\frac{R_d}{C_p}} \quad (4)$$

where p_0 is a standard reference surface pressure, usually taken as 1000 hPa, R_d is the specific heat at constant pressure of dry air. Based on the momentum and continuity equations on the isentropic surface (Andrew et al., 1986). Then we use PV to



155 diagnose the location, area, and strength of the anticyclone at 370 K isentropic level, the simplified Ertel's PV under a small slope and a hydrostatic approximation is defined as

$$q = \frac{(\zeta + f)}{\sigma} \quad (5)$$

where ζ is relative vorticity, f the planetary vorticity (Joseph, 1981). The PV framework is a powerful tool to explain the development and dissipation of ASMA, particularly useful on the quantity conserved adiabatic-frictionless flow (Hoskins
160 et al., 1985). The Ertel's PV in pressure coordinate is defined as

$$q = -g(\zeta + f) \frac{\partial \theta}{\partial p} + g \left(\frac{\partial v}{\partial p} \frac{\partial \theta}{\partial x} - \frac{\partial u}{\partial p} \frac{\partial \theta}{\partial y} \right) \quad (6)$$

u and v are zonal and meridional wind, $\zeta = \partial v / \partial x - \partial u / \partial y$ (Tamarin and Kaspi, 2016; Kang and Son, 2021). Although instantaneous PV fields effectively describe the structure of the ASMA, they do not directly distinguish between changes arising from vortex intensification and zonal propagation or background PV evolution. To address this limitation, we analyze
165 the PV tendency, which explicitly quantifies the processes responsible for temporal changes in PV. By decomposing the PV tendency into dynamical and thermodynamical contributions, this approach allows the separation of anticyclonic strengthening from eastward or westward propagation to understanding ASMA multimodality. The term q is a nonlinear function of winds and potential temperature. The PV tendency is approximated to the sum of dynamic and thermodynamic terms if the frictions is negligible, we have

$$170 \quad \frac{\partial q}{\partial t} = -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - w \frac{\partial q}{\partial p} + Q \quad (7)$$

where t is time, w is vertical velocity at each level, Q is total diabatic heating including the temperature tendency due to moist process (latent heating) Q_{LH} , solar or longwave radiative heating, and friction etc. The friction term is negligible for the large-scale flow. Also, the PV tendency can be decomposed into a background flow component that represents the climatological mean and a perturbation component that accounts for anomalies. It is assumed that the decomposition is time-independent and
175 exhibits zonal symmetry. Consequently, for the purpose of this analysis, $a(x, y, p, t) = \overline{a(y, p)} + a'(x, y, p, t)$ where a is any field of interest like u , v , w (Tamarin and Kaspi, 2016), and the $\overline{a(y, p)}$ is the time and zonal mean. The meridional background flow represents a contribution to the PV tendency that is an order of magnitude smaller, so the PV tendency equation can be decomposed into mean and anomaly to gain better insight into variation in ASMA intensification:

$$\frac{\partial q}{\partial t} = \frac{\partial q'}{\partial t} = -\bar{u} \frac{\partial q'}{\partial x} - v' \frac{\partial \bar{q}}{\partial y} - \bar{u}' \frac{\partial q'}{\partial x} - v' \frac{\partial q'}{\partial y} - w \frac{\partial q}{\partial p} + Q \quad (8)$$

180 Here, the $-\bar{u} \partial q' / \partial x$ represents the advection of the PV perturbation by the background zonal mean flow, the $-v' \partial \bar{q} / \partial y$ term is the meridional advection of the background vorticity by the perturbation velocity associated with anticyclone. The next



two terms $-u'\partial q'/\partial x, -v'\partial q'/\partial y$ represents the nonlinear perturbation advection terms, and $-w\partial q/\partial p$ represents the vertical advection.

However, on an isentropic surface (like the 370 K surface), the potential temperature θ is constant by definition. This means the horizontal gradients of θ are zero: $\partial\theta/\partial x = 0$ and $\partial\theta/\partial y = 0$. Therefore, the second term (the tilting term) vanishes, and the expression simplifies to:

$$q = -g(\zeta_\theta + f) \frac{\partial\theta}{\partial p} \quad (9)$$

where ζ_θ is the relative vorticity calculated using winds on the 370 K surface. The rate of change of PV due to the wind blowing different values of PV across the point. Here, u and v are the eastward and northward wind components on the 370 K surface, and $\partial q/\partial x$ and $\partial q/\partial y$ are the horizontal gradients of PV on that same surface. This is typically the dominant term. And the rate of change of PV due to air moving vertically across the 370 K surface (diabatic motion) where a vertical gradient of PV ($\partial q/\partial\theta$) exists. The PV tendency equation on 370 K is

$$\frac{\partial q}{\partial t} = -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - \dot{\theta} \frac{\partial q}{\partial \theta} + Q_\theta \quad (10)$$

where $\dot{\theta} = d\theta/dt$ is the diabatic heating rate (e.g., from latent heat release or radiation). Q_θ is diabatic heating, the source/sink term that generates or destroys PV through differential diabatic heating.

4 Vortex tracking and PV tendency analysis

4.1 Movements of ASMA

The MSF, relative vorticity, and zonal wind are involved in the multi-center vortex tracking of ASMA, the tracking domain is $0^\circ - 180^\circ\text{E}$ and $15^\circ - 45^\circ\text{N}$ in the period of 2000–2020. Figure 2 shows the vortex tracking on 370 K isentropic surface by the method as discussed in section 3. Figure 2 reveals a relationship between zonal wind u , relative vorticity ζ , and MSF ψ , the vortex center locates at the intersection of maximum ψ and zero-zonal wind line, with $\zeta < 0$. Figure S1 shows the number and frequency of occurrence of ASMA centers from May to August. The centroid locations agree well among three reanalysis data, even the results by JRA-3Q and ERA5 are much closer. The three modes are obvious in frequency-longitude histogram, the Iranian Plateau (IP) mode near 50°E , Tibetan Plateau (TP) mode near 90°E , and Western Pacific (WP) mode around $135^\circ - 150^\circ\text{E}$ which are similar to Honomichl and Pan (2020) and Siu and Bowman (2020). These three modes are often referred to the Iranian, Tibetan and Bonin (Ogasawara) highs (Enomoto et al., 2003; Enomoto, 2004), also the relationship between TP and WP high is often referred to as South Asian high, the IP and TP mode also have an interaction relationship with the spatial distribution of Fig. S1, some WP mode are caused by eastward eddy shedding. Nützel et al. (2016) have found occurrence frequencies of IP and TP modes are concentrated in $25^\circ - 35^\circ\text{N}$, $45^\circ - 100^\circ\text{E}$, and Siu and Bowman (2020) find an

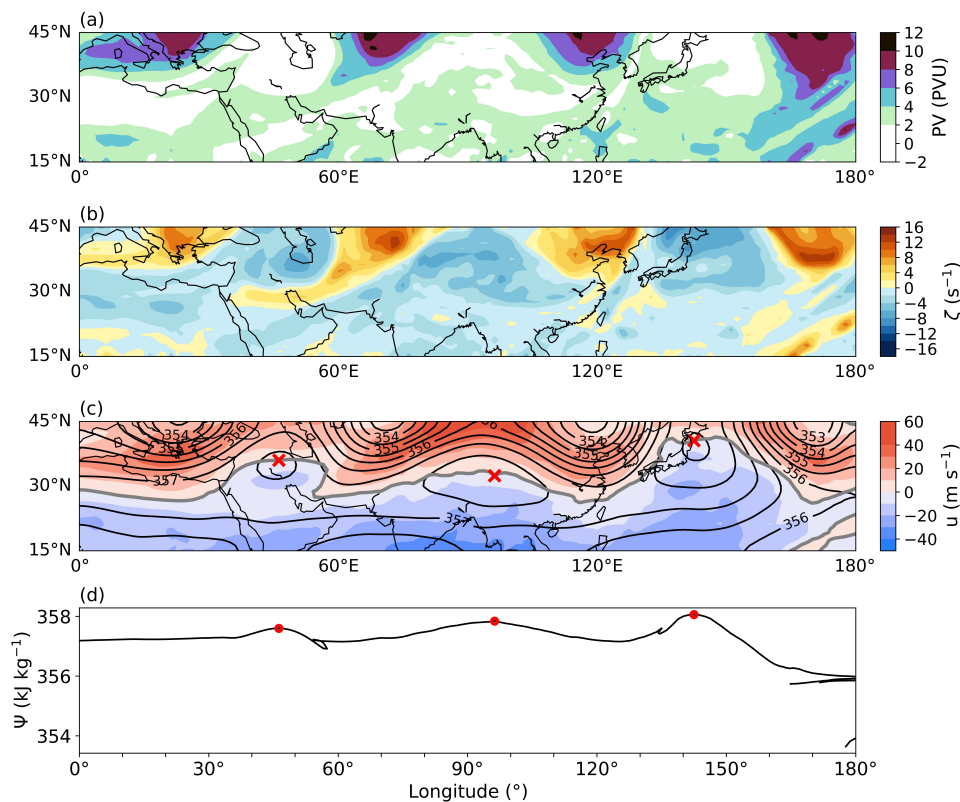


Figure 2. An illustrative example of vortex center identification of ASMA at 370 K on UTC 00:00 August 17, 2019. (a) PV (q); (b) relative vorticity, ζ ; (c) zonal wind, u , the zero-wind, $u = 0$ contour (gray line), the identified vortex centres (red crosses), the MSF, ψ (black contour); (d) MSF along the zero-wind line versus longitude, the corresponding vortex center (red dots).

expansive area of frequent in Bonin High (BH) between 120°–180°E, these vortices are weaker than those in TP and IP. Our results of vortex tracking are consistent with the above publications both in distribution and histogram.

To enhance our understanding of the variations in the ASMA, particularly the observed trimodality from May to September, we plot Hovmöller diagrams to illustrate the spatiotemporal evolution of vortex movements. It shows the locations of the anticyclone relating to time, latitude, and longitude. The trimodal structure, comprising the IP, TP, and WP modes is obvious in panels (a)-(c) of Fig. 3. The detailed ranges of the vortex centers can be identified, with the climatological centers of the IP, TP, and WP located at approximately 45°–65°E, 85°–100°E, and 135°–145°E, respectively. Additionally, the ASMA exhibits a strong latitudinal dependency for both persistent and transient type that the anticyclone moves northward (slightly) during the beginning of boreal summer and southward later, then reaching its north latitude of approximately 40°N between July 15 and August 14, which is similar to Nützel et al. (2016, 2022) results. The persistent vortex identified by ERA5 and JRA-3Q

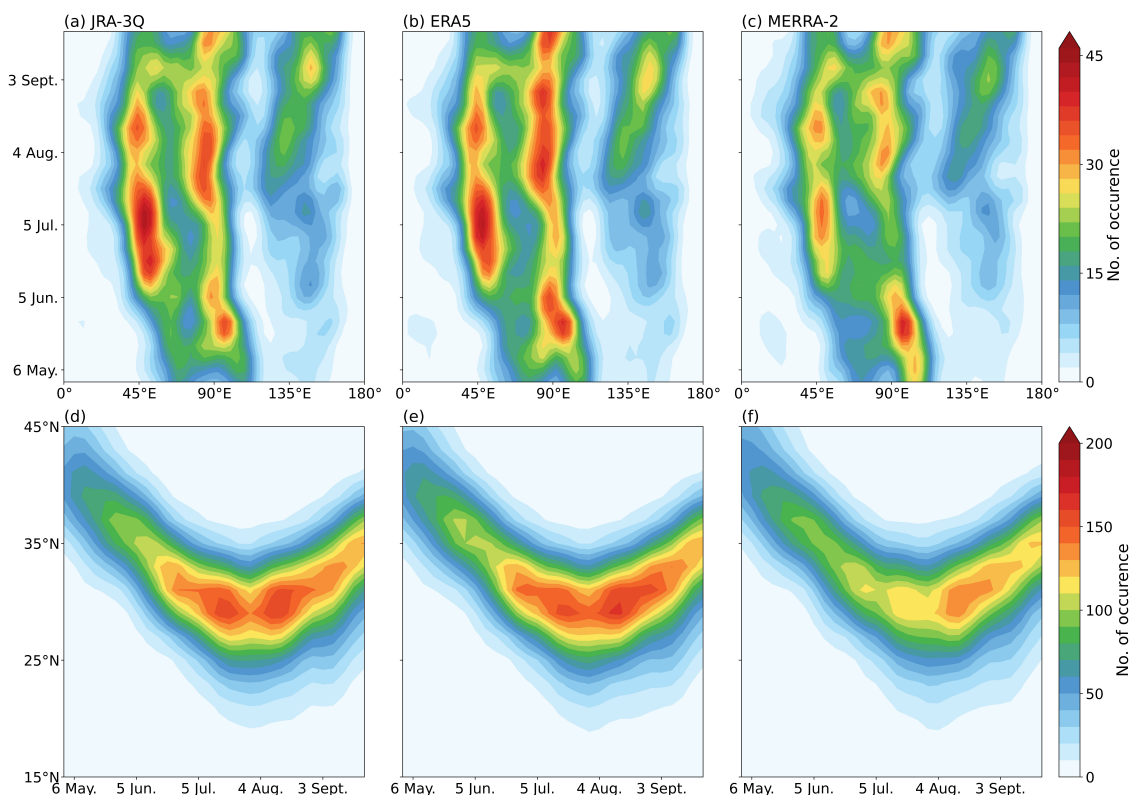


Figure 3. The evolution of vortex occurrence counts by vortex tracking at 100 hPa from 2000 to 2020 in (a, b, c) time-longitude and (d, e, f) time-latitude plots. Shown are (a, d) JRA-3Q, (b, e) ERA5 and (c, f) MERRA-2 reanalysis results

reanalysis constitutes over 65% of the overall vortex centers, while the transient vortex is relatively rare comparing to the persistent vortex, as illustrated in Table S1.

Figure 4 shows the four examples of anticyclone movements from May to September in 2000, 2005, 2010, 2015, and 2020, respectively, where the PV fields during the summer on the isentropic surface at 370 K, with color shading values ranging from 0 to 2 PVU. The low PV patterns observed in the JRA-3Q exhibit a high degree of consistency with the locations of anticyclone. Additionally, most of the features of anticyclone moving westward and eastward coexisted with the almost stationary low PV area, and these are actually eddy shedding events (Popovic and Plumb, 2001), also the vortices have relative larger PV in September. The western Pacific is located in the southward-flowing eastward flank of the anticyclone, which transports high-PV air from the extratropical lowermost stratosphere equatorward, which may lead to larger PV (Wang et al., 2022). Although the vortices mainly move in the east-west direction or shedding, movement in the north-south direction can also occur.

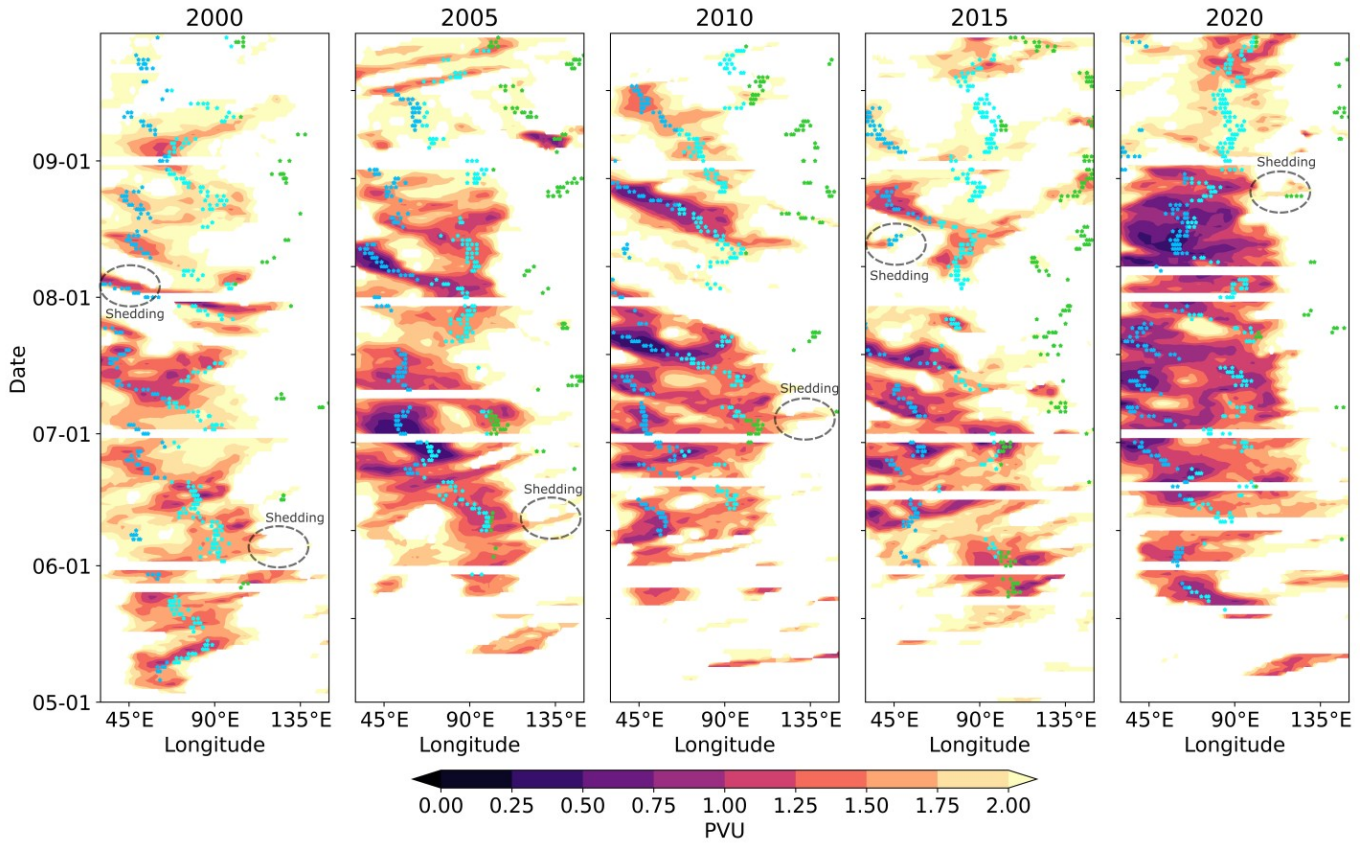


Figure 4. Time-longitude plots of 6 hourly PV at 370 K over the latitudinal band between 20°N and 40°N in 2000, 2005, 2010, 2015 and 2020 (from JRA-3Q). The light blue, cyan, and green represents the locations of persistent anticyclone over IP, TP, and BH regions. The gray and dashed circle indicates the eddy shedding events.

230 4.2 Development process of the ASMA

The vertical cross section from Eq. (7) are calculated separately in each term and shown in Fig. 5 and the longitudinal and latitudinal extents are set of $\pm 30^\circ$ and $\pm 15^\circ$ from the center of anticyclone. The positive and negative dipolar tendencies occur in Eq. (7), the $-u\partial q/\partial x$ and $-v\partial q/\partial y$ can cancel out approximately. The zonal advection of PV is more responsible for the positive PV tendency in the upper level (> 300 hPa), while the vertical advection leads to a positive PV tendency closed to the center of anticyclone and negative PV tendency remote from the center eastwardly. The contributions of diabatic heating that is dominated by the latent and radiative heating to the PV tendency are important for anticyclonic process. The association between the release of latent heating and the updraft motion of warm air in the anticyclone sector is illustrated in Fig. 5(e1)-(e3). Since latent heating is not explicitly provided in ERA5 data, a non-radiative heating component dominated by latent heating is used here, which can reflect the characteristics of latent heating to a certain extent. As the warm and moist air travels



upward, it cools and condenses, releasing latent heat, which produces positive PV tendency in lower level and negative PV anomaly and tendency in upper level. At the level higher than 200 hPa, the background radiation (longwave and shortwave heating) dominates the total diabatic heating, thus, resulting in positive PV tendency for cyclonic flow. The sum of each term in Eq. (7) shows a tripole PV tendency pattern, which is positive closed to the center of anticyclone and negative in eastward and westward. The findings from ERA5, JRA-3Q, and MERRA-2 exhibit minor discrepancies. Specifically, the potential temperature recorded in MERRA-2 is higher than that observed in both ERA5 and JRA-3Q across all levels. Additionally, the region characterized by PV anomalies, which indicates the core of the anticyclone, is also shown in Fig. 5.

The latent heat released during the formation of an anticyclone results in an expansion of the isentropes at higher altitudes while simultaneously causing a contraction of the isentropes at lower altitudes. This phenomenon leads to an increase in static stability at lower levels, thereby enhancing the potential temperature gradient, while the gradient diminishes at upper levels. The resultant warming effect elevates the geopotential height at higher altitudes, which in turn generates an outward pressure gradient force that induces divergence at these levels (Ahmadi-Givi et al., 2004; Tamarin and Kaspi, 2016). This divergence facilitates upward vertical motion and convergence at lower altitudes, as illustrated in Fig. 5(c1)-(c3), ultimately contributing to an increase in potential vorticity.

Figure 6 shows the PV tendencies induced by different diabatic heating components—radiative heating (Q_{rad}), latent heating (Q_{LH}), and total diabatic heating (Q) which are associated with the IP, TP, and BH, three major modes of the ASMA. Background radiative heating (top row) produces positive PV tendencies to the north of the anticyclone core, indicating that upper-tropospheric radiation acts to increase PV and weaken the circulation. In contrast, latent heating (middle row) generates strong negative PV tendencies south of the core, especially over the BH, where monsoonal convection and latent heat release are most intense. This PV reduction enhances the anticyclonic vorticity and contributes to ASMA intensification. The total diabatic heating (bottom row), which combines both radiative and latent effects, shows a net negative PV tendency around the southern flank of each high, the latent heating drives the strengthening of the ASMA, while radiative processes provide a weak damping influence, with the most pronounced diabatic enhancement occurring over the BH region. Additionally, this phenomenon is not so obvious in IP. Probably the IP differs in terms of the intensity of terrain dynamic forcing, the magnitude and concentration of diabatic heating (predominantly latent heat), the characteristics of large-scale circulation coupling, and the significant differences in the thermal properties of the underlying surface, it is still to be determined.

Given that the tendency of PV is directly related to the product of absolute vorticity and the rate of change in static stability, this process results in an increase in potential vorticity at lower levels and a decrease at upper levels. When examining the core of the anticyclone at 200 hPa, it is likely that diabatic heating exerts a direct influence on the southward movement of PV tendency. This is illustrated in Fig. 6, which indicates that both latent heating and background radiation contribute to a small or negative PV tendency to the south of the anticyclone. But the magnitude of diabatic heating is even smaller than the horizontal advection, the vertical advection acts to enhance the PV tendency to the south of the anticyclone, resulting in significant upward motion on the southern side, see Fig. S2(a)-(c). Collectively, the interactions among vertical advection, horizontal advection, and total diabatic heating give rise to a tripole pattern associated with the anticyclone, characterized by convergence to the north and divergence to the northeast and northwest, as shown in Fig. S2(g)-(i). The warm and humid air located to the south



275 and west of the anticyclone moves northward and upward. As this air cools, latent heat is released at lower levels, resulting in a positive PV tendency in these lower levels. Concurrently, an imbalance in the pressure gradient force at upper levels generates a negative PV tendency, leading to divergence, the anticyclone exhibits a tendency to propagate in both the northwest and northeast directions.

The PV tendency provides a useful tool on how the intensification and locations of ASMA change within 6 hours interval.
280 To better quantify the intensification and contributions of each term, the minimum PV inside each box (red and blue box in Fig. S2 is considered as the value representing the ASMA development and is noted as q_{dev} . But the q_{dev} is not directly related to the anticyclone intensification as propagation leads to positive or negative PV tendencies aligned to its movement, and intensification makes the anticyclone stronger, so the propagation and intensification are both account for the anticyclone development. The q_{dev} in westward and eastward is decomposed as

$$\begin{aligned} q_{dev}^W &= q_{int}^W + q_{prop}^W \\ q_{dev}^E &= q_{int}^E + q_{prop}^E \end{aligned} \quad (11)$$

where q_{int} and q_{prop} are the PV tendencies due to anticyclone intensification and propagation. The foundation of this methodology is the tripole pattern of PV tendency. The PV tendency is an indicator of anticyclonic migration, while the tripole pattern indicates a process of intensification. The q_{int} can be defined as

$$\begin{aligned} q_{int}^W &= [q_{int}^W] + [q_{int}^{center}] \\ q_{int}^E &= [q_{int}^E] + [q_{int}^{center}] \end{aligned} \quad (12)$$

290 where $[q_{int}^W]$ and $[q_{int}^E]$ is the PV tendency averaged within the box centered at westside and eastside (negative PV tendency, the blue box), respectively, $[q_{int}^{center}]$ is the averaged PV tendency inside the red box for positive PV tendency. The geographical ranges of the western blue box, the eastern blue box, and the red box in three modes are shown in Table 3.

To simplify the interpretation of the vertical advection terms, the PV tendency is converted from the pressure level coordinate to 370 K isentropic surface, as shown in Fig. 7. Since air parcels generally flow along isentropic surfaces (in the absence of
295 diabatic heating), the advection is a much more accurate representation of how PV is actually being transported by the wind. The diabatic term Q is often the most crucial for understanding the intensification of anticyclone. By analyzing the PV tendency on 370 K, you can directly isolate and quantify the impact of latent heat release (from convection) or radiative cooling on the PV structure in three modes. The strong convective heating beneath the 370 K surface will create a strong positive PV tendency on that surface, directly linking vapor processes to large-scale dynamics. The diabatic heating term (Q) generates negative PV
300 tendencies south of the anticyclone centers, e.g. consistent with strong latent heating from deep monsoon convection in BH, as shown in Fig. 7. The negative PV tendency strengthens the anticyclonic circulation, the horizontal PV advection (middle row) introduces a tripole patterns.

The contributions of each term in Eq. 8 to intensification of anticyclone are shown in Fig. 8. The larger positive PV tendency is specifically in relation to the weakening of the anticyclone, otherwise, the negative or smaller PV tendency means

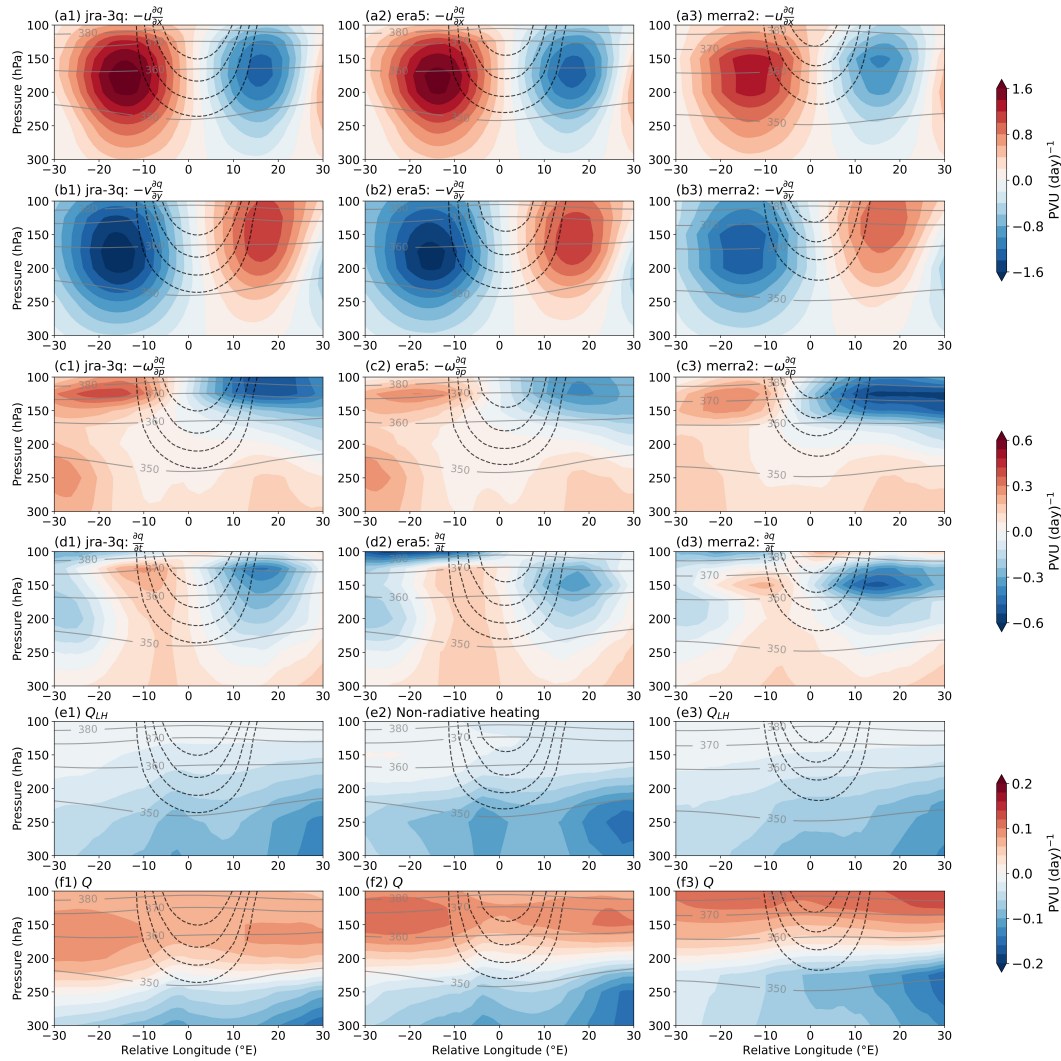


Figure 5. The PV tendency from (a1)-(a3) zonal advection ($-u\partial q/\partial x$), (b1)-(b3) meridional advection ($-v\partial q/\partial y$), (c1)-(c3) vertical advection ($-w\partial q/\partial p$), (d1)-(d3) PV tendency ($\partial q/\partial t$), (e1)-(e3) latent heating (Q_{LH}), and (f1)-(f3) total diabatic heating (Q). The PV anomaly is contoured in black dashed line with -0.1 PVU interval from -0.1 to -0.5 PVU and potential temperature is plotted in gray line. The longitudinal extent of anticyclone is denoted by relative longitude. The first, second, and third column is the calculation from JRA-3Q, ERA5, and MERRA-2 respectively.

Table 3. The relative geophysical ranges (relative longitude and latitude), the eastward direction is defined as positive, while the northward direction is taken as negative in the tripole patterns of three modes.

Mode	Western box (blue)	Center box(red)	Eastern box (blue)
IP	5° to 15°; -30° to -25°	5° to 15°; -20° to -5°	5° to 15°; -3° to 20°
TP	5° to 15°; -30° to -20°	5° to 15°; -15° to 0°	5° to 15°; 5° to 25°
BH	5° to 15°; -30° to -20°	5° to 15°; -15° to 2°	0° to 15°; 10° to 30°

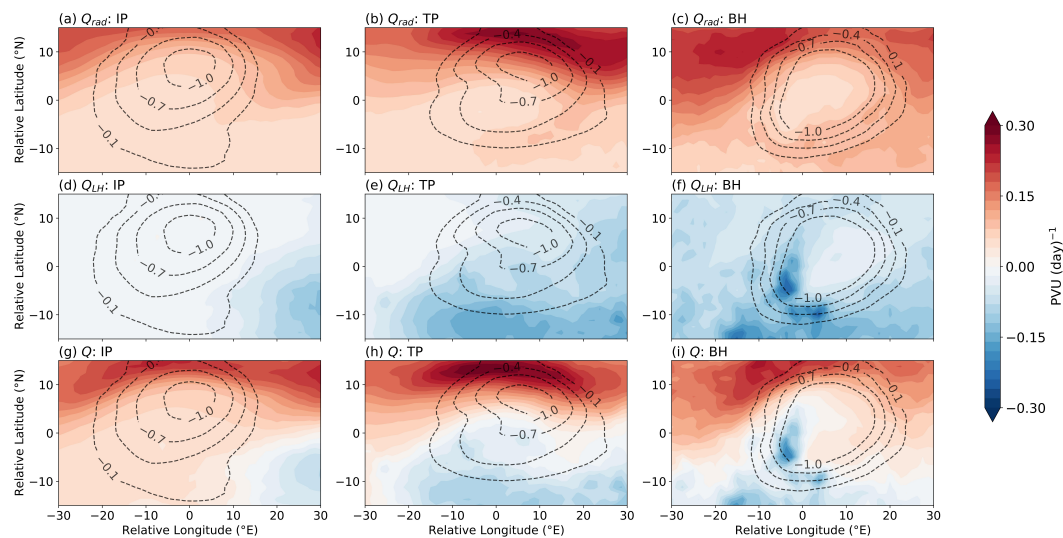


Figure 6. The PV tendency from (a)-(c) background radiation Q_{rad} , (d)-(f) latent heating Q_{LH} , and (g)-(i) total diabatic heating Q in IP, TP, and BH regions (from left to right) on 200 hPa. The black dashed contours show the PV anomaly at 100 hPa which contours from -1 to 0 PVU with interval of 0.3 PVU. The longitudinal and latitudinal extents are the main area of anticyclone. All analyzed patterns feature dashed contours (representing anticyclonic circulation) and shaded regions indicating PV tendency (units: PVU day^{-1}), with axes defined by relative longitude ($^{\circ}\text{E}$) and latitude ($^{\circ}\text{N}$) centered on each anticyclone.

305 the strengthens of anticyclone. Analysis of PV tendencies reveals that the anticyclone exhibits greater intensification in the eastward compared to the westward propagation in IP, but is weaker in TP and BH. The effect of mean zonal advection on the anticyclone differs markedly between these two directions: during westward propagation, mean zonal advection acts to weaken the anticyclone, whereas during eastward propagation, it strengthens it in IP, but still weakens it in TP and BH. In contrast, the effect of mean advection opposes that of mean zonal advection; specifically, mean advection intensifies cyclones in the west
310 while diminishing anticyclones in the east. However, these opposing effects largely cancel out each other, although one term tends to predominate when their combined effect is considered. The contribution of the nonlinear horizontal advection term is very small comparing to the horizontal advection. Given that the anticyclone is situated at an altitude corresponding to the 200 hPa to 100 hPa pressure levels, the water vapor content is substantially low, thereby rendering the effect and vertical gradient

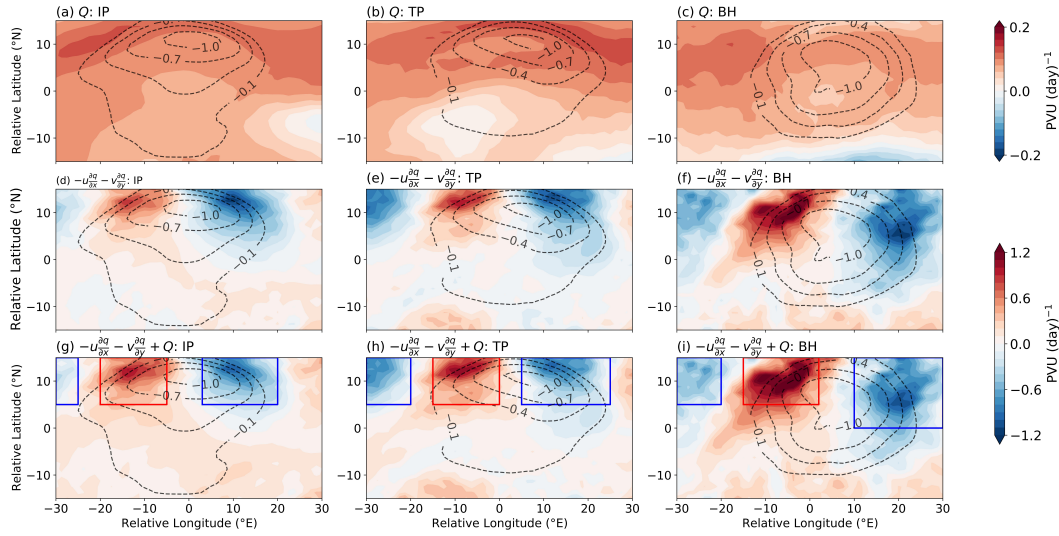


Figure 7. The PV tendency from (a)-(c) vertical advection, (d)-(f) horizontal advection, and (g)-(i) sum of each term from three modes on 370 k isentropic level. The black dashed contours show the PV anomaly at 370 K which contours from -1 to 0 PVU with interval of 0.3 PVU. The longitudinal and latitudinal extents are the main area of anticyclone, with the red box indicating the main area of divergence, while the blue boxes signify additional zones of divergence.

of latent heat release comparatively insignificant relative to the total diabatic heating. Within the non-adiabatic heating components, longwave and shortwave radiation referred to as background radiation in Fig. S2 predominate, leading to the attenuation of the ASMA. The q_{dev} , q_{int} , and q_{prop} from reanalysis data are shown in Fig. 9, the eastward development, propagation of ASMA is stronger than in eastward in TP and BH modes. Both the intensification and propagation are negative PV tendency, but the intensification is positive due to the positive PV tendency pole in the center as illustrated in Fig. S2 and Fig. 7.

5 Discussion

Our findings on the ASMA's trimodal structure, PV dynamics, and eddy-shedding behavior build directly on foundational work by Siu and Bowman (2020), while resolving key discrepancies and quantifying previously unaddressed mechanisms. A central debate in ASMA research revolves around its modality, Nützel et al. (2016) proposed a dominant bimodal structure (IP and TP of South Asian High) based on 100 hPa geopotential height from former reanalysis products (JRA-25, ERA-I, and MERRA, etc.), neglecting the Western Pacific/BH mode. In contrast, our analysis uses three modern, high-resolution reanalysis datasets (ERA5, JRA-3Q, MERRA-2) and the 370 K isentropic surface to track the vortex. We discover the BH (135°–150°E) as a third mode, this consistency across datasets aligns with Siu and Bowman (2020), who first documented BH's frequent occurrence using MSF. The discrepancy with Nützel et al. (2016) stems from their reliance on coarser pressure-level data (100 hPa), where

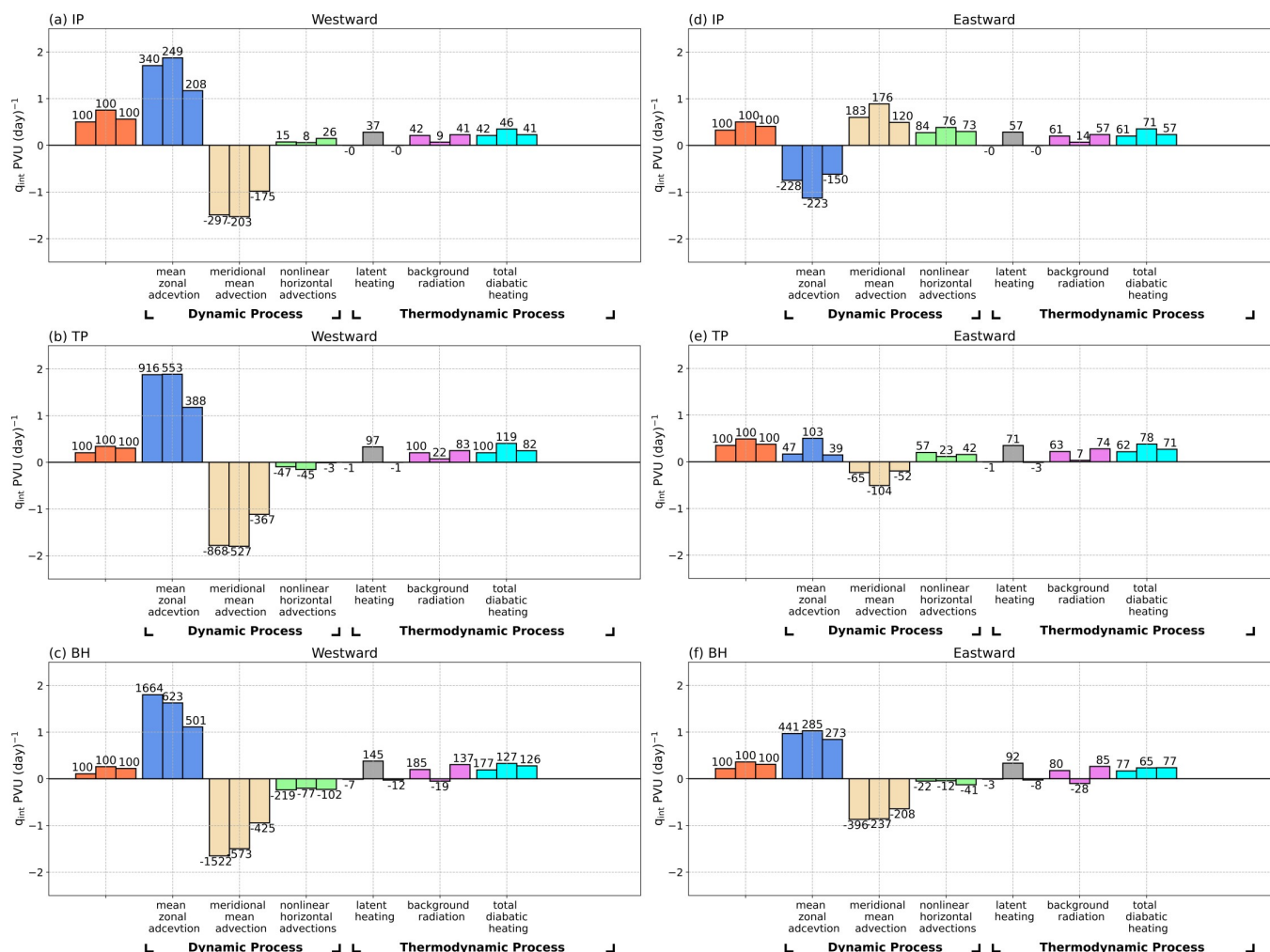


Figure 8. The values representing the PV tendency on 370 K for (a-c) westward and (d-f) eastward, the intensification of anticyclone, as attributed to various terms, are depicted in terms of their relative contributions (%). The bars for each term, organized in groups of three reanalysis products (JRA-3Q, ERA5, MERRA-2) from left to right. The numbers on the bar chart represent the percentages (%) of component contributions

BH signals are masked by zonal flow, whereas our isentropic analysis isolates the UTLS region where weak anticyclonic centers are most distinct.

330 The PV tendency diagnostic in this study advances the work pioneered by Garny and Randel (2013), who linked low-PV regions to convective heating but did not quantify the processes driving PV temporal changes. Garny and Randel (2013) noted that preexisting low-PV over the Asian monsoon domain complicates separating intrinsic ASMA intensification from background variability, a challenge we address by decomposing PV tendency into dynamical (horizontal/vertical advection) and thermodynamic (latent heating, radiation) components. Our results show mean zonal and meridional advection are the

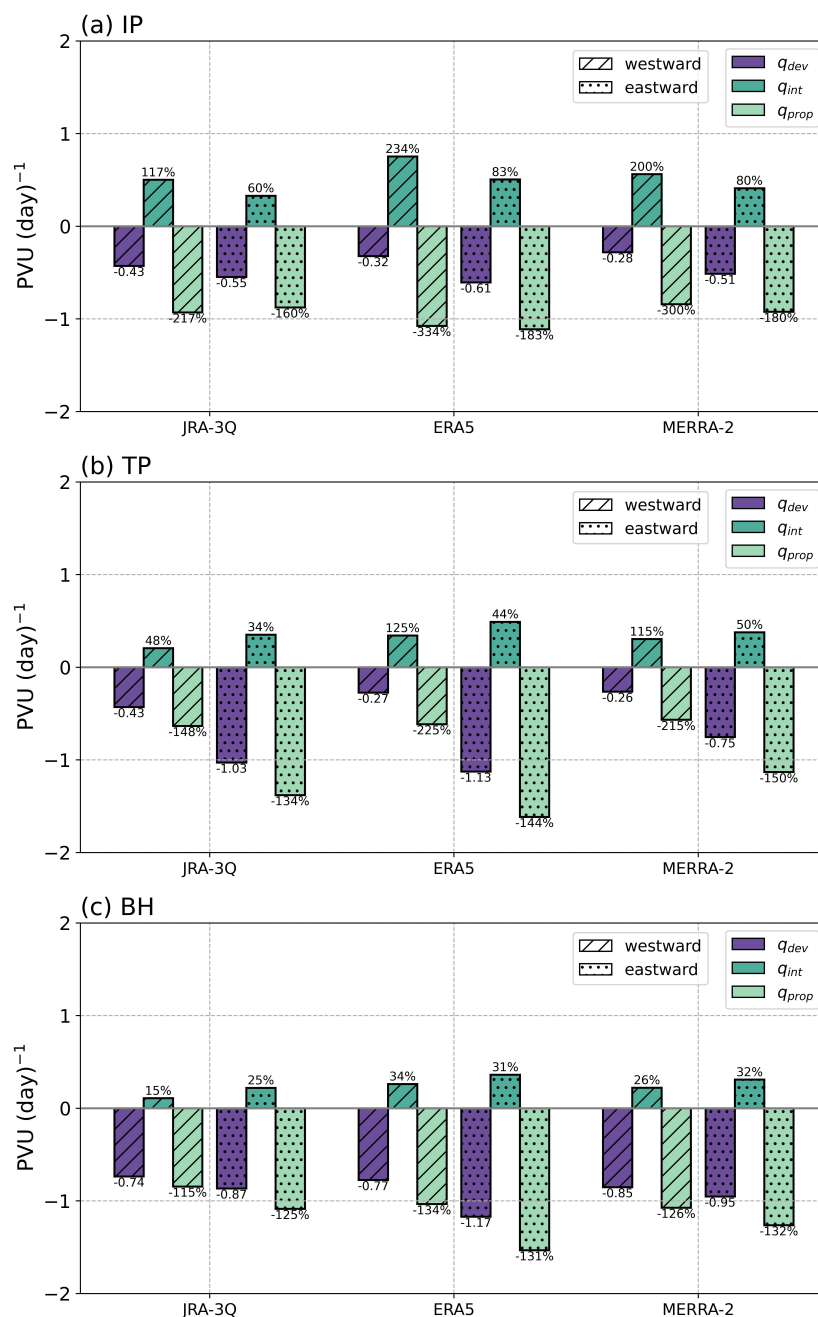


Figure 9. The q_{dev} , q_{int} , and q_{prop} from reanalysis. The values denoted to each bar refer to the relative contribution (%) and PV tendency. The westward and eastward of anticyclone propagation and intensification is represented by the diagonal and dot texture, respectively.



335 primary drivers of PV tendency, with diabatic heating as a critical modulator (Fig. 8a). Manney et al. (2021) documented the ASMA's core on 350–410 K isentropic surfaces but did not explore PV dynamics, our work fills this gap by demonstrating how tripole PV tendency patterns (positive at the center, negative eastward/westward) drive the anticyclone's eastward and westward propagation across its three modes.

Eddy shedding is an important driver of ASMA intraseasonal variability, it further highlights the interplay between our findings and prior studies. Popovic and Plumb (2001) first identified westward eddy shedding of ASMA, attributing it to baroclinic instability, while Siu and Bowman (2020) linked eastward shedding to BH formation without quantifying underlying mechanisms. Our PV tendency analysis clarifies these processes, westward-shedding eddies (primarily from the IP mode) are driven by mean zonal advection (positive PV tendencies that weaken the anticyclone) and background radiation (damping effects), explaining their transient nature (Table S1). In contrast, eastward shedding (from the TP mode) is sustained by latent heating over the Western Pacific, which generates strong negative PV tendencies (enhancing anticyclonic vorticity) that convert shed eddies into persistent BH centers (Fig. 10 and 11). This directional dependence aligns with Garny and Randel (2013)'s focus on PV transport but extends it by showing how horizontal advection and diabatic heating collaborate to shape shedding behavior with eastward shedding vortices strengthened by mean zonal advection in the IP mode and latent heating in the BH mode.

350 Regional characteristics (continental vs. marine) further modulate ASMA dynamics, as reflected in the distinct drivers of each mode. The IP mode is shaped by continental-scale wind advection and moderate diabatic forcing; the TP mode is distinguished by plateau-enhanced latent heating (Fig. 6e), which amplifies PV tendency anomalies (Fig. 10 and 11); and the BH mode is governed by strong convective diabatic heating over the Western Pacific and marine dynamical-advective interactions. Future work should explore how teleconnections (e.g. ENSO; Yan et al. 2018) modulate these modal interactions and eddy-shedding frequencies, as well as the impact of anthropogenic forcing (Zhang et al., 2024; Qie et al., 2025) on ASMA's stability and variability directions that build on Manney et al. (2021)'s work for a more comprehensive understanding of UTLS circulation drivers.

6 Conclusions

This study systematically clarifies the key dynamical mechanisms of the ASMA through comprehensive analyses of three state-of-the-art reanalysis datasets and a PV tendency diagnostic, thereby contributing to resolving ASMA's intensification, development, propagation, and temporal evolution. A definitive finding is the trimodal structure of the ASMA during boreal summer, characterized by persistent anticyclonic centers over the IP, TP, and BH. This finding complements the bimodality perspective reported by Nützel et al. (2016). By leveraging the 370 K isentropic surface identified as the climatological core of the ASMA and a multi-center vortex tracking algorithm, this study discovers that the BH constitutes a persistent mode rather than transient atmospheric noise. This trimodal signature is consistent across the three datasets, with only minor discrepancies observed in MERRA-2, which may be attributed to differences in data assimilation schemes and vertical resolution among reanalysis products.

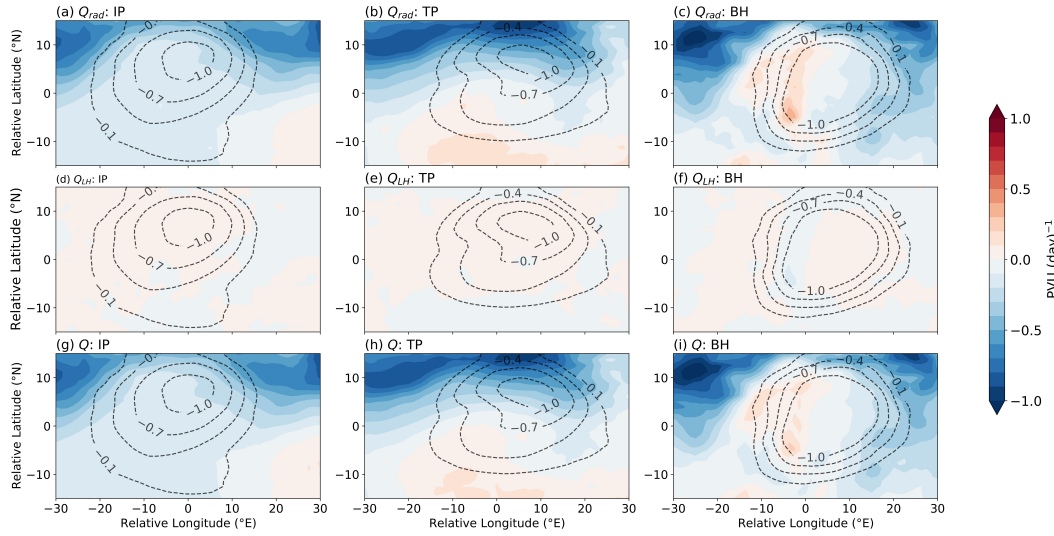


Figure 10. The PV tendency anomalies from (a)-(c) background radiation Q_{rad} , (d)-(f) latent heating Q_{LH} , and (g)-(i) total diabatic heating Q in IP, TP, and BH regions (from left to right) on 200 hPa. The black dashed contours show the PV anomaly at 100 hPa which contours from -1 to 0 PVU with interval of 0.3 PVU.

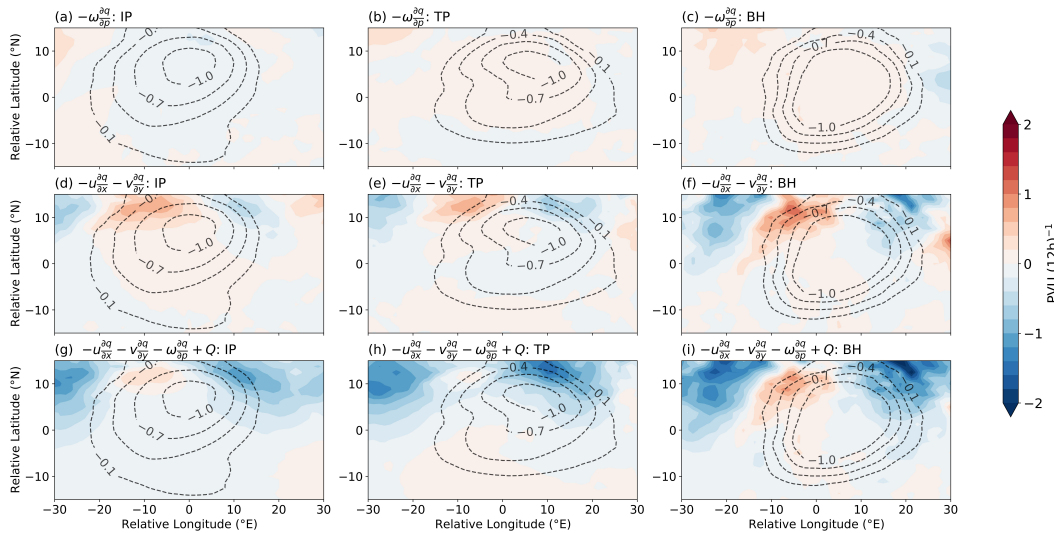


Figure 11. The PV tendency anomalies from (a)-(c) vertical advection, (d)-(f) horizontal advection, and (g)-(i) sum of each term from three modes on 200 hPa. The black dashed contours show the PV anomaly at 100 hPa which contours from -1 to 0 PVU with interval of 0.3 PVU.

The ASMA-specific PV tendency diagnostic developed herein extends the PV-based analytical method pioneered by Garny and Randel (2013) by quantitatively disentangling the dynamical and thermodynamical drivers of ASMA evolution. Results demonstrate that mean zonal and meridional advection work as the predominant drivers of PV tendency, while total diabatic



heating (encompassing latent heating and background radiation) exerts a critical modulating effect. This diagnostic effectively captures a characteristic tripole PV tendency pattern with positive anomalies at the anticyclonic core and negative anomalies to the east and west which enables the decoupling of ASMA intensification from zonal propagation, addressing a notable limitation of conventional PV analysis approaches. Specifically, latent heating enhances the BH mode via negative PV tendencies, whereas background radiation induces weakening effects on the ASMA as a whole, highlighting the mode-specific regulatory role of thermodynamic processes.

Furthermore, eddy shedding dynamics exhibit intrinsic links to the ASMA's trimodal structure, with distinct directional drivers governing the persistence of each mode. Eastward eddy shedding from the TP mode, sustained by intense latent heating associated with deep convection over the western Pacific, facilitates the conversion of transient eddies into persistent BH centers. In contrast, westward eddy shedding from the IP mode is primarily driven by mean zonal advection and background radiation. These directional differences are inherently tied to regional underlying surface characteristics: the IP and TP modes are dominated by continental scale dynamical processes and moderate diabatic forcing, while the BH mode is shaped by marine influenced convective heating. Collectively, these findings establish a unified theoretical framework for understanding ASMA variability, underscoring the intricate interplay between dynamical advection, thermodynamic forcing, and modal structure. This work not only advances the scientific understanding of UTLS circulation dynamics but also provides a robust physical basis for improving the predictability of monsoon-related regional climate variability and UTLS tracer transport.



390 *Author contributions.* Ninghui Li contributed to conceptualization, data analysis, and drafting the original manuscript; Jonathon Wright provided supervision, participated in data analysis, and curated the data; Philip Rupp Alison Ming and Shenglong Zhang were involved in data analysis and manuscript review/editing; Jie Gao contributed to result analysis, provided supervision on the research, and participated in manuscript review/editing.

Code and data availability.

The ERA5, JRA-3Q, and MERRA-2 dataset can be downloaded from <https://climate.copernicus.eu/climate-reanalysis>, <https://disc.gsfc.nasa.gov/datasets?project=MERRA-2> and <https://www.data.jma.go.jp/jra/html/index.html>. Python scripts used to produce the analyses and figures in this study are available on request from the authors.

395 *Competing interests.* The authors declare that they have no conflict of interest.

Acknowledgements. We would like to thank Dr. Leong Wai Siu and Xiangliang Zhang for the advice in vortex tracking. And the paper is benefited a lot from the discussion with Dr. Shenglong Zhang and YuanRui Chen. This research is supported by the Department of Science and Technology of Shandong Province (ZR2024QD136).



References

- 400 Ahmadi-Givi, F., Graig, G. C., and Plant, R. S.: The dynamics of a midlatitude cyclone with very strong latent-heat release, *Quarterly Journal of the Royal Meteorological Society*, 130, 295–323, <https://doi.org/10.1256/qj.02.226>, 2004.
- Amemiya, A.: Dynamics of the quasi-biweekly variability of the Asian monsoon anticyclone, Ph.D. thesis, The University of Tokyo, 2018.
- Amemiya, A. and Sato, K.: A Two-Dimensional Dynamical Model for the Subseasonal Variability of the Asian Monsoon Anticyclone, *Journal of the atmospheric sciences*, 75, 3597–3612, <https://doi.org/10.1175/JAS-D-17-0208.1>, 2018.
- 405 Andrew, D. G., Holton, J. R., and Leovy, C. B.: *Middle atmosphere dynamics*, Academic Press Inc., Orlando, FL, <https://www.osti.gov/biblio/5936274>, 1986.
- Davis, S. M., Hegglin, M. I., Fujiwara, M., Dragani, R., Harada, Y., Kobayashi, C., Long, C., Manney, G. L., Nash, E. R., Potter, G. L., Tegtmeier, S., Wang, T., Wargan, K., and Wright, J. S.: Assessment of upper tropospheric and stratospheric water vapor and ozone in reanalyses as part of S-RIP, *Atmospheric Chemistry and Physics*, 17, 12 743–12 778, <https://doi.org/10.5194/acp-17-12743-2017>, 2017.
- 410 Enomoto, T.: Interannual Variability of the Bonin High Associated with the Propagation of Rossby Waves along the Asian Jet, *Journal of the Meteorological Society of Japan. Ser. II*, 82, 1019–1034, <https://doi.org/10.2151/jmsj.2004.1019>, 2004.
- Enomoto, T., Hoskins, B. J., and Matsuda, Y.: The formation mechanism of the Bonin high in August, *Quarterly Journal of the Royal Meteorological Society*, 129, 157–178, <https://doi.org/https://doi.org/10.1256/qj.01.211>, 2003.
- Fairlie, T. D., Vernier, J. P., Natarajan, M., and Bedka, K. M.: Dispersion of the Nabro volcanic plume and its relation to the Asian summer monsoon, *Atmospheric Chemistry and Physics*, 14, 7045–7057, <https://doi.org/10.5194/acp-14-7045-2014>, 2014.
- 415 Garny, H. and Randel, W. J.: Dynamic variability of the Asian monsoon anticyclone observed in potential vorticity and correlations with tracer distributions, *Journal of Geophysical Research: Atmospheres*, 118, 13,421–13,433, <https://doi.org/10.1002/2013JD020908>, 2013.
- Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., Silva, A. M. D., Gu, W., Kim, G.-K., Koster, R.,
- 420 Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M., and Zhao, B.: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), *Journal of Climate*, 30, 5419–5454, <https://doi.org/10.1175/JCLI-D-16-0758.1>, 2017.
- Gill, A. E.: Some simple solutions for heat-induced tropical circulation, *Quarterly Journal of the Royal Meteorological Society*, 106, 447–462, <https://doi.org/10.1002/qj.49710644905>, 1980.
- 425 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- 430 Honomichl, S. B. and Pan, L. L.: Transport From the Asian Summer Monsoon Anticyclone Over the Western Pacific, *Journal of Geophysical Research: Atmospheres*, 125, e2019JD032 094, <https://doi.org/10.1029/2019JD032094>, 2020.
- Hoskins, B. J. and Rodwell, M. J.: A Model of the Asian Summer Monsoon. Part I: The Global Scale, *Journal of Atmospheric Sciences*, 52, 1329 – 1340, [https://doi.org/10.1175/1520-0469\(1995\)052<1329:AMOTAS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<1329:AMOTAS>2.0.CO;2), 1995.



- 435 Hoskins, B. J., McIntyre, M. E., and Robertson, A. W.: On the use and significance of isentropic potential vorticity maps, *Quarterly Journal of the Royal Meteorological Society*, 111, 877–946, <https://doi.org/10.1002/qj.49711147002>, 1985.
- Hsu, H.-H., Terng, C.-T., and Chen, C.-T.: Evolution of Large-Scale Circulation and Heating during the First Transition of Asian Summer Monsoon, *Journal of Climate*, 12, 793–810, [https://doi.org/10.1175/1520-0442\(1999\)012<0793:EOLSCA>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<0793:EOLSCA>2.0.CO;2), 1999.
- Joseph, P.: *Geophysical Fluid Dynamics*, Springer, 1981.
- 440 Kang, J. M. and Son, S.-W.: Development Processes of the Explosive Cyclones over the Northwest Pacific: Potential Vorticity Tendency Inversion, *Journal of the Atmospheric Sciences*, 78, 1913 – 1930, <https://doi.org/10.1175/JAS-D-20-0151.1>, 2021.
- Kosaka, Y., Kobayashi, S., Harada, Y., Kobayashi, C., Naoe, H., Yoshimoto, K., Harada, M., Goto, N., Chiba, J., Miyaoka, K., Sekiguchi, R., Deushi, M., Kamahori, H., Nakaegawa, T., Tanaka, T. Y., Tokuhira, T., Sato, Y., Matsushita, Y., and Onogi, K.: The JRA-3Q Reanalysis, *Journal of the Meteorological Society of Japan. Ser. II*, 102, 49–109, <https://doi.org/10.2151/jmsj.2024-004>, 2024.
- 445 Lackmann, G.: *Midlatitude Synoptic Meteorology: Dynamics, Analysis, and Forecasting*, *Quarterly Journal of the Royal Meteorological Society*, 2011.
- Lorensen, W. E.: History of the Marching Cubes Algorithm, *IEEE Computer Graphics and Applications*, 40, 8–15, <https://doi.org/10.1109/MCG.2020.2971284>, 2020.
- Manney, G. L., Santee, M. L., Lawrence, Z. D., Wargan, K., and Schwartz, M. J.: A Moments View of Climatology and Variability of the Asian Summer Monsoon Anticyclone, *Journal of Climate*, 34, 7821 – 7841, <https://doi.org/10.1175/JCLI-D-20-0729.1>, 2021.
- 450 Nützel, M., Dameris, M., and Garny, H.: Movement, drivers and bimodality of the South Asian High, *Atmospheric Chemistry and Physics*, 16, 14 755–14 774, <https://doi.org/10.5194/acp-16-14755-2016>, 2016.
- Nützel, M., Brinkop, S., Dameris, M., Garny, H., J Ockel, P., Pan, L. L., and Park, M.: Climatology and variability of air mass transport from the boundary layer to the Asian monsoon anticyclone, *Atmospheric Chemistry and Physics*, 22, 15 659–15 683, <https://doi.org/10.5194/acp-22-15659-2022>, 2022.
- 455 Pan, L. L., Kinnison, D., Liang, Q., Chin, M., Santee, M. L., Flemming, J., Smith, W. P., Honomichl, S. B., Bresch, J. F., Lait, L. R., Zhu, Y., Tilmes, S., Colarco, P. R., Warner, J., Vuvan, A., Clerbaux, C., Atlas, E. L., Newman, P. A., Thornberry, T., Randel, W. J., and Toon, O. B.: A Multimodel Investigation of Asian Summer Monsoon UTLS Transport Over the Western Pacific, *Journal of Geophysical Research: Atmospheres*, 127, e2022JD037 511, <https://doi.org/10.1029/2022JD037511>, 2022.
- 460 Ploeger, F., Gottschling, C., Griessbach, S., Groo Ss, J. U., Guenther, G., Konopka, P., M Uller, R., Riese, M., Stroh, F., Tao, M., Ungermann, J., Vogel, B., and von Hobe, M.: A potential vorticity-based determination of the transport barrier in the Asian summer monsoon anticyclone, *Atmospheric Chemistry and Physics*, 15, 13 145–13 159, <https://doi.org/10.5194/acp-15-13145-2015>, 2015.
- Popovic, J. M. and Plumb, R. A.: Eddy Shedding from the Upper-Tropospheric Asian Monsoon Anticyclone, *Journal of the Atmospheric Sciences*, 58, 93–104, [https://doi.org/10.1175/1520-0469\(2001\)058<0093:ESFTUT>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<0093:ESFTUT>2.0.CO;2), 2001.
- 465 Qian, Y., Zhang, Q., Yao, Y., and Zhang, X.: Seasonal variation and heat preference of the south asia high, *Advances in Atmospheric Sciences*, 19, 821–836, <https://doi.org/10.1007/s00376-002-0047-3>, 2002.
- Qie, K., Tian, W., Bian, J., Xie, F., and Li, D.: Weakened Asian summer monsoon anticyclone related to increased anthropogenic aerosol emissions in recent decades, *npj Climate and Atmospheric Science*, 8, 140, <https://doi.org/10.1038/s41612-025-01026-8>, 2025.
- Randel, W. J. and Park, M.: Deep convective influence on the Asian summer monsoon anticyclone and associated tracer variability observed with Atmospheric Infrared Sounder (AIRS), *Journal of Geophysical Research: Atmospheres*, 111, <https://doi.org/10.1029/2005JD006490>, 2006.



- Ren, R., Zhu, C., and Cai, M.: Linking quasi-biweekly variability of the South Asian high to atmospheric heating over Tibetan Plateau in summer, *Climate Dynamics*, 53, 3419–3429, <https://doi.org/10.1007/s00382-019-04713-4>, 2019.
- Rupp, P. M.: On the structure and dynamics of the Asian monsoon anticyclone, Ph.D. thesis, University of Cambridge, 2018.
- 475 Rupp, P. M. and Haynes, P. H.: Spatio-temporal stability analysis applied to monsoon anticyclone flow, *Quarterly Journal of the Royal Meteorological Society*, 146, 1861–1879, <https://doi.org/10.1002/qj.3771>, 2020.
- Rupp, P. M. and Haynes, P. H.: Zonal scale and temporal variability of the Asian monsoon anticyclone in an idealised numerical model, *Weather and Climate Dynamics*, 2, 413–431, <https://doi.org/10.5194/wcd-2-413-2021>, 2021.
- Santee, M. L., Manney, G. L., Livesey, N. J., Schwartz, M. J., Neu, J. L., and Read, W. G.: A comprehensive overview of the climatological
 480 composition of the Asian summer monsoon anticyclone based on 10 years of Aura Microwave Limb Sounder measurements, *Journal of Geophysical Research: Atmospheres*, 122, 5491–5514, <https://doi.org/10.1002/2016JD026408>, 2017.
- Siu, L. W. and Bowman, K. P.: Unsteady Vortex Behavior in the Asian Monsoon Anticyclone, *Journal of the Atmospheric Sciences*, 77, 4067–4088, <https://doi.org/10.1175/JAS-D-19-0349.1>, 2020.
- Tamarin, T. and Kaspi, Y.: The Poleward Motion of Extratropical Cyclones from a Potential Vorticity Tendency Analysis, *Journal of the
 485 Atmospheric Sciences*, 73, 1687–1707, <https://doi.org/10.1175/JAS-D-15-0168.1>, 2016.
- Vernier, J. P., Fairlie, T. D., Natarajan, M., Wienhold, F. G., Bian, J., Martinsson, B. G., Crumeyrolle, S., Thomason, L. W., and Bedka, K. M.: Increase in upper tropospheric and lower stratospheric aerosol levels and its potential connection with Asian pollution, *Journal of Geophysical Research: Atmospheres*, 120, 1608–1619, <https://doi.org/10.1002/2014JD022372>, 2015.
- Wang, X., Randel, W., Pan, L., Wu, Y., and Zhang, P.: Transient Behavior of the Asian Summer Monsoon Anticyclone Associated With
 490 Eastward Eddy Shedding, *Journal of Geophysical Research: Atmospheres*, 127, e2021JD036090, <https://doi.org/10.1029/2021JD036090>, 2022.
- Wei, W., Zhang, R., Wen, M., Rong, X., and Li, T.: Impact of Indian summer monsoon on the South Asian High and its influence on summer rainfall over China, *Climate Dynamics*, 43, 1257–1269, <https://doi.org/10.1007/s00382-013-1938-y>, 2014.
- Xue, X., Chen, W., and Hou, S.: The long-term variation in the South Asia High intensity measured by 150-hPa eddy geopotential height,
 495 *Meteorology and Atmospheric Physics*, 132, 833–844, <https://doi.org/10.1007/s00703-020-00723-8>, 2020.
- Yan, R.-C., Bian, J.-C., and Fan, Q.-J.: The Impact of the South Asia High Bimodality on the Chemical Composition of the Upper Troposphere and Lower Stratosphere, *Atmospheric and Oceanic Science Letters*, 4, 229–234, <https://doi.org/10.1080/16742834.2011.11446934>, 2011.
- Yan, X., Konopka, P., Ploeger, F., Tao, M., M Uller, R., Santee, M. L., Bian, J., and Riese, M.: El Nino Southern Oscillation influence on the Asian summer monsoon anticyclone, *Atmospheric Chemistry and Physics*, 18, 8079–8096, <https://doi.org/10.5194/acp-18-8079-2018>,
 500 2018.
- Zarrin, A., Ghaemi, H., Azadi, M., and Farajzadeh, M.: The spatial pattern of summertime subtropical anticyclones over Asia and Africa: A climatological review, *International Journal of Climate*, 30, 159–173, <https://doi.org/10.1002/joc.1879>, *international Journal of Climatology*, 2010.
- Zhang, D., Huang, Y., Zhou, B., and Wang, H.: Is There Interdecadal Variation in the South Asian High?, *Journal of Climate*, 34, 8089–8103, <https://doi.org/10.1175/JCLI-D-21-0059.1>, 2021.
- 505 Zhang, Q., Wu, G., and Qian, Y.: The Bimodality of the 100 hPa South Asia High and its Relationship to the Climate Anomaly over East Asia in Summer, *Journal of the Meteorological Society of Japan. Ser. II*, 80, 733–744, <https://doi.org/10.2151/jmsj.80.733>, 2002.
- Zhang, S., Wright, J. S., Guo, Z., Huang, W., and Peng, Y.: Effects of Anthropogenic Aerosols on the East Asian Winter Monsoon, *Journal of Geophysical Research: Atmospheres*, 129, e2023JD040305, <https://doi.org/10.1029/2023JD040305>, 2024.



- 510 Zhou, N., Yu, Y., and Qian, Y.: Simulations of the 100-hPa South Asian High and precipitation over East Asia with IPCC coupled GCMs, Advances in Atmospheric Sciences, 23, 375–390, <https://doi.org/10.1007/s00376-006-0375-9>, 2006.