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Shinichiro Kato

Nagoya Local Meteorological Observatory, Japan Meteorological Agency

Fumiaki Ogawa

`fumiaki.ogawa@bio.mie-u.ac.jp`

Mie University

Yoshihiro Tachibana

Mie University

Satoru Kasuga

Hokkaido University

Shota Watanabe

Gifu Local Meteorological Observatory, Japan Meteorological Agency

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A Dynamical Categorization of Cold Air Outbreaks for Weather Impacts in East Asia

Shinichiro Kato¹

Fumiaki Ogawa^{2,3*}

ORCID id: 0000-0003-4079-9518

*Corresponding author: Fumiaki Ogawa (email: fumiaki.ogawa@bio.mie-u.ac.jp)

Yoshihiro Tachibana²

Satoru Kasuga^{2,4}

Shota Watanabe⁵

Author details

1 Nagoya Local Meteorological Observatory, Japan Meteorological Agency, 2-18 Hiyori-

cho, Chikusa-ku, Nagoya, Aichi, Japan

2 Faculty of Bioresources, Mie University, 1577 Kurimamachiya-cho, Tsu City, Mie,

Japan

3 Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1,

Komaba, Meguro-ku, Tokyo, Japan

4 Faculty of Environmental Earth Science, Hokkaido University, N10W5, Kita-ku,

19 Sapporo, Hokkaido, Japan

20 5 Gifu Local Meteorological Observatory, Japan Meteorological Agency, 6 Kano-

21 Ninomaru, Gifu, Japan

22

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25

Abstract

The winter climate in Japan is closely linked to large-scale atmospheric circulation patterns, and heavy snowfall often occurs during cold air outbreaks (CAOs). Cold air fluxes associated with CAOs towards Japan are strongly influenced by the complex topography of the East Asian continent. This topographic effect leads to various CAO patterns, which have distinct impacts on the snowfall distribution in Japan. When the Japan-Sea Polar airmass Convergence Zone (JPCZ) forms, heavy snowfall often occurs mainly along the Sea of Japan coast. However, the CAO's spatial patterns and quantitative diagnostics for such cases have not yet been established.

Therefore, in this study, we introduce a new quantitative index to objectively characterize CAOs over East Asia based on the distribution in the flux of cold airmass (FLCA). We obtained the new index by first calculating FLCA and then applying Self-Organizing Maps (SOM), a machine-learning technique, to classify CAO cases.

The new index enables a physically consistent categorization of CAOs into three patterns bounded by Mt. Baitoushan. In the first category, CAO originates mainly from the western side of the mountain and extends into western Japan (the *Western Group*). In the second, CAO is mainly on the eastern side of the mountain, reaching northern Japan (the *Northern Group*). The third category (the *Intermediate Group*) is characterized by

broadly distributed FLCA on both sides of the mountain, reaching Japan without a strong regional preference.

We further discuss the implications of these CAO categories for the JPCZ characteristics and the precipitation distribution.

Keywords

cold air outbreak; flux of cold airmass; Japan-Sea Polar airmass Convergence Zone; snowfall; Self-Organizing Maps

Statements and Declarations

Competing interests

The authors declare that they have no competing interests.

1 Introduction

The East Asian Winter Monsoon is a dominant component of the global climate system during boreal winter. It is characterized by episodic cold air outbreaks (CAOs) originating from the Siberian High, which transport cold airmasses southward to mid- and low latitudes (e.g., Zhang et al. 1997; Iwasaki et al. 2014). These CAOs pose serious risks to society in East Asia through severe weather events, including extreme low temperatures and heavy snowfall, which disrupt transportation, agriculture, and daily life.

Fluxes of cold airmass (FLCA) associated with CAOs towards Japan are strongly influenced by the complex topography of the East Asian continent (Fig. 1). In the lower troposphere, FLCA exhibits variability in its pathway, with two preferred routes on either side of the Changbai Mountains on the Korean Peninsula: the *western* and *northern routes*. The Japan-Sea Polar airmass Convergence Zone (JPCZ) is often formed over the Sea of Japan, where strong heat and moisture fluxes from the Sea of Japan create a favorable environment for the development of mesoscale convective systems (e.g., Nagata et al. 1986; Tachibana et al. 2022; Watanabe et al. 2022). Yamazaki et al. (2024) demonstrated that the *western route* of FLCA is often associated with JPCZ development and subsequent heavy snowfall events, whereas the *northern route* originates in the Sea of Okhotsk and runs via the northern Sea of Japan.

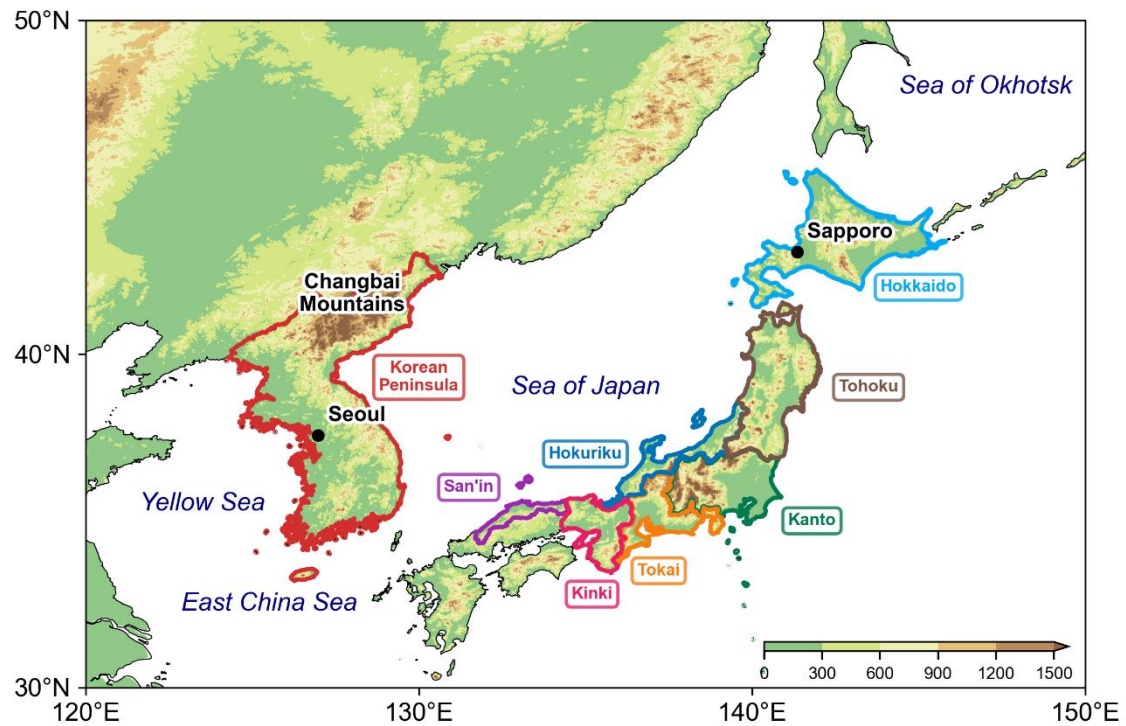


Fig. 1 Topography of East Asia around the Sea of Japan (shading; m). The map indicates key geographical features discussed in this study, including the Changbai Mountains, the Korean Peninsula, and surrounding seas (Sea of Japan, Yellow Sea, Sea of Okhotsk, and East China Sea). Black dots represent the observation stations at Seoul and Sapporo. Specific Japanese regions analyzed in this study (Hokkaido, Tohoku, Hokuriku, Kanto, Tokai, Kinki, and San'in) are highlighted with colored outlines.

However, Yamazaki et al. (2024) focused primarily on specific severe events, leaving the climatological and statistical robustness of the relationship between FLCA pathways and JPCZ formation unclear. Because snowfall distributions and JPCZ occurrences are expected to depend not only on the FLCA intensity but also on the FLCA pathway, a pathway-based perspective is essential for understanding regional weather impacts. Nevertheless, previous studies have primarily focused on FLCA intensity rather than its pathway. For example, Kawaguchi and Kato (2023) evaluated the absolute magnitude of FLCA for local heavy snowfall but did not explicitly classify its horizontally two-dimensional pathways. Consequently, comprehensive climatological studies linking FLCA pathways to JPCZ occurrence and regional weather impacts remain scarce.

Previous studies have also attempted to classify CAOs using FLCA. Analyzing FLCA with respect to the isentropic surface is useful for diagnosing CAOs (Iwasaki et al. 2014). Applying this method, Liu et al. (2021) categorized CAOs into three types based on their meridional extent and discussed their different influences on temperature and precipitation across East Asia. Still, previous studies have only studied either latitudinal classifications of CAOs or specific CAO events (e.g., Yamaguchi et al. 2019; Shoji et al. 2014). Spatial variations in horizontal CAO patterns remain unclear, which hampers our understanding of the link between synoptic patterns and local weather.

Therefore, considering FLCA pathways can improve understanding of snowfall areas and the winter climate of East Asia, including Japan, thereby helping to evaluate local disaster potential and improve regional disaster prevention strategies. To unravel the complex links among the FLCA pathways, JPCZ formation, and local snowfall, it is essential to objectively characterize the CAO spatial patterns.

This study examines the atmospheric circulations associated with CAOs to identify dynamical relationships among CAO patterns, favorable conditions for JPCZ occurrence, and precipitation distributions. To this end, we objectively classify the two-dimensional horizontal FLCA patterns associated with CAOs and characterize their typical spatial patterns. We further develop a new dynamical index for objectively categorizing the major pathways of cold air mass outflows based on the characteristic distribution of FLCA around Mt. Baitoushan. The characteristic CAO spatial pattern identified based on the index reveals a sequence of atmospheric responses, suggesting links to JPCZ occurrence and the associated distribution of snowfall around Japan.

The simple new index proposed in this study provides a climatological perspective on the pathways of cold air mass outflows and their regional weather impacts, with potential applications to winter weather forecasting and disaster preparedness in Japan.

2 Data and Method

(a) Data

The dataset analyzed in this study is the Japanese Reanalysis for Three Quarters of a Century (hereafter JRA-3Q; Kosaka et al. 2024), with a horizontal resolution of $1.25^\circ \times 1.25^\circ$ and a 6-hourly temporal resolution (03, 09, 15, and 21 JST). We used this reanalysis data from 1979 onwards, corresponding to the modern satellite era, to ensure temporal homogeneity in data quality. The analysis period covers winter months (December, January, and February) from 1979/80 to 2023/24 (16,248 time steps at 6-hourly intervals). The surface variables used in our analyses are sea level pressure and net upward latent heat flux, while the variables on isobaric surfaces are temperature, geopotential height, and the zonal and meridional wind components. The climatological mean value was defined as the average for each calendar day and time over the analysis period. Additionally, the daily climatology (Fig. 2a) and its standard deviation (Fig. 2b) were calculated according to JRA-3Q definition, i.e., by first averaging for each calendar day over the 1991-2020 base period, and then applying a Lanczos low-pass filter with a 60-day cutoff to remove high-frequency variations.

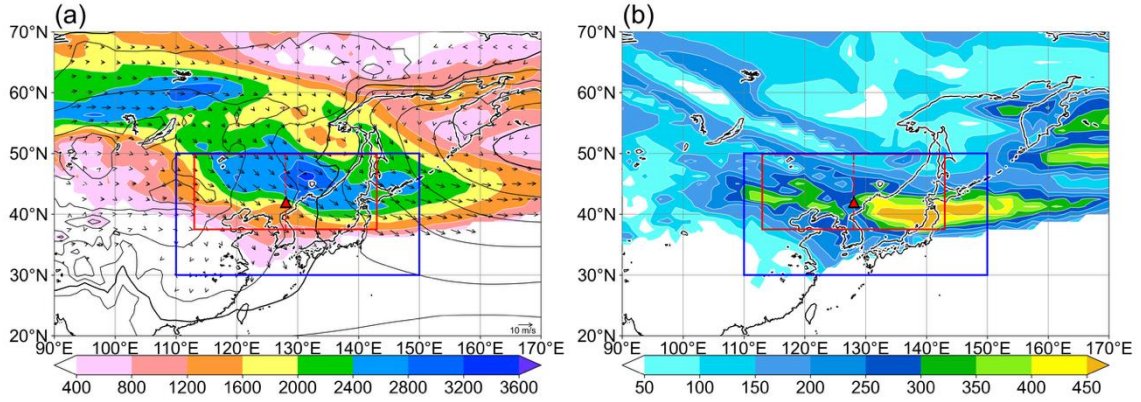


Fig. 2 (a) Spatial distribution of the magnitude of $|\text{FLCA}|$ (color; hPa m s^{-1}), VEL (vectors; m s^{-1}), and mean sea level pressure (contours; hPa) based on the daily mean smooth climatological normals for the period 1991–2020. (b) Spatial distribution of the standard deviation of $|\text{FLCA}|$ (color; hPa m s^{-1}) based on the daily mean smooth climatological normals for the period 1991–2020. The region outlined in blue indicates the domain used for extracting CAO cases. The regions outlined in red indicate the areas used to calculate the indices of FLCA from the west (I_w) and north (I_N). The red triangle denotes Mt. Baitoushan.

For the mean sea level pressure in Sapporo, a surface observation dataset from the Japan Meteorological Agency (JMA) was used. We used hourly data available on the JMA website (<https://www.data.jma.go.jp/risk/obsdl/index.php>). For the mean sea level pressure in Seoul, a surface observation dataset from the Korea Meteorological Administration (KMA) was used. We used hourly data available on the KMA website (<https://data.kma.go.kr/data/grnd/selectAsosRltmList.do?pgmNo=36>).

For the preceding 1-hour precipitation, a rain gauge observation dataset from the Automated Meteorological Data Acquisition System (AMeDAS) operated by the JMA was used.

(b) Extraction of Cold Air Outbreak cases

Following the definitions by Iwasaki et al. (2014) and Kawaguchi and Kato (2023), we calculated the cold air mass (Delta Pressure: DP [hPa]), the flux vector of cold airmass (Flux of Cold Airmass: FLCA [hPa m s⁻¹]), and the velocity of the cold air mass (Velocity: VEL [m s⁻¹]). Here, DP is defined as the pressure difference between the surface pressure and the pressure at a specific isentropic surface with a threshold potential temperature; VEL represents the representative wind vector associated with the FLCA vector. Mathematically, DP, FLCA, and VEL are defined as follows:

$$DP = p_s - p(\theta_T)$$

$$FLCA = \int_{p(\theta_T)}^{p_s} \boldsymbol{v} dp$$

$$VEL = FLCA \cdot DP^{-1}$$

Here, p_s is the surface pressure [hPa], θ_T is the threshold potential temperature [K], and $\boldsymbol{v}$ is the horizontal wind vector [m s^{-1}] at each pressure level. θ_T was set to 280 K, corresponding to the temperature of -6 °C at the 850 hPa pressure level, an operational criterion for snowfall in lowland areas outside mountainous terrain (e.g., Iwasaki et al. 2014; Kawaguchi and Kato 2023).

Fig. 2a illustrates the climatology of the magnitude of $|FLCA|$, VEL , and mean sea level pressure. In this study, we defined CAO events as cases that simultaneously satisfied two conditions. First, the area-averaged $|FLCA|$ around Japan (30°N-50°N, 110°E-150°E; corresponding to the region outlined in blue in Fig. 2a) was at least one standard deviation above its climatological mean. Second, its pressure difference between Seoul and Sapporo was equal to or greater than the climatological mean over the analysis period (10.75 hPa). The latter criterion was applied to exclude cases with cyclones over the Sea of Japan or non-winter monsoon patterns (Shinoda et al. 2021). The 2,052 cases satisfying both criteria were hereafter referred to as "CAO cases".

(c) Three characteristic FLCA pathways

As seen in Fig. 2a and 2b, the |FLCA| climatology and standard deviation show notable double peaks located on both sides of Mt. Baitoushan, the highest mountain in the Changbai Mountains. Two distinct peaks are located near 120°E and to the east of 130°E, with the mountain range located between them. These facts suggest that the mountain acts as a topographic boundary that alters the FLCA pathways, with cold air preferentially passing to either the western or eastern sides of the mountain depending on the event. Thus, the FLCA pathway can be characterized by the relative strength of the FLCA to the west and east of Mt. Baitoushan. When organized FLCA on the west side of Mt. Baitoushan was substantially stronger than that on the east side, the pathway was defined as the *western route*. Conversely, when organized FLCA on the east side of Mt. Baitoushan was substantially stronger than that on the west side, the pathway was defined as the *northern route*. Although the classification depends on whether the FLCA is stronger west or east of Mt. Baitoushan, we refer to the eastern-side pattern as the *northern route*, following the naming convention (e.g. Yamazaki et al. 2022) reflecting the dominance of the northerly wind component in this pattern. When FLCA was broadly distributed on both sides of Mt. Baitoushan, we classified the pathway as *Intermediate*.

Individual CAOs can be characterized by evaluating the ratio of FLCA amounts

through the *western* and *northern routes*. Calculating rectangular averages of **|FLCA|** for (37.5°N-50°N, 113°E-128°E) and (37.5°N-50°N, 128°E-143°E) as I_W and I_N , respectively, I_N/I_W gives a simple dynamical measure indicating whether a CAO event is characterized by FLCA through the *western* and *northern routes*. Furthermore, taking the logarithm of the ratio reduces the reciprocal relationship to a simple sign reversal. In this study, we propose the FLCA Pathway Index (FPI), defined as following:

$$FPI = \log_2(I_N/I_W)$$

to characterize the FLCA pathway for individual CAO cases. Based on FPI, each CAO event falls into one of the three groups: the *Western Group*, *Northern Group*, and *Intermediate Group*.

(d) Self-Organizing Maps (SOM) and Pattern Classification details

CAO patterns can be statistically classified using Self-Organizing Maps (SOM; Kohonen 1990). The SOM is an unsupervised artificial neural network that projects multidimensional data onto a two-dimensional space where fields transition smoothly to adjacent nodes, and is widely used in meteorological data analysis and studies of the winter climate of Japan (e.g., Inatsu et al. 2021; Ohba and Sugimoto 2022). The method follows that described in Doan et al. (2021), using S-SIM to identify the Best-Matching

219 Unit (BMU).

220 Applying the SOM to |FLCA|, we identified 25 CAO patterns. To categorize these
221 25 nodes into the *Western Group*, *Northern Group*, and *Intermediate Group*, we applied
222 the following procedure:

223 Step 1: The 25 nodes were sorted in ascending order of FPI (from lowest to highest),
224 where their ranks were denoted as t ($t = 1, \dots, 25$). FPI value for the node at rank t
225 was defined as $N(t)$. A lower $N(t)$ stronger FLCA through the *western route*.

226 Step 2: To categorize the 25 nodes into the three groups, we calculated differences in
227 $N(t)$ between adjacent ranks: $D(t) = N(t + 1) - N(t)$. Accordingly, several t ranks
228 showing local $D(t)$ maxima become candidates to bound the nodes into different groups.

229 Step 3: Two bounding t ranks were finally selected to ensure that the resulting three
230 groups contain a reasonable number of nodes.

231 Fig. 3 presents $N(t)$ and $D(t)$ for $t = 1$ to 25. Following the local $D(t)$
232 maxima, $t = 6$ (between #11 and #22) was selected as the boundary between the
233 *Western Group* and the *Intermediate Group*. Similarly, the *Intermediate Group* and the
234 *Northern Group* were bounded at $t = 19$ (between #21 and #04).

235

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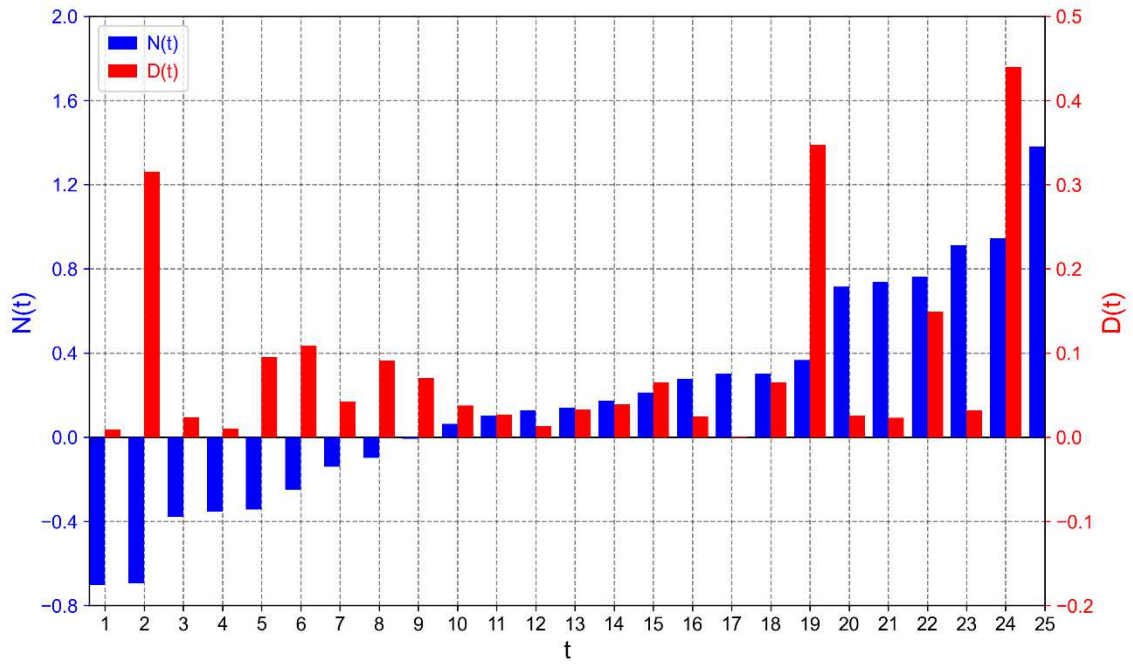


Fig. 3 Bar charts of $N(t)$ and $D(t)$ across the sorted node rank t ($t = 1 - 25$). The blue bars indicate $N(t)$, representing the value of FPI for the node at ascending rank t (left axis). The red bars indicate $D(t)$, defined as the difference between adjacent ranks, $N(t + 1) - N(t)$ (right axis). The prominent peaks in $D(t)$ at $t = 6$ and $t = 19$ were used to objectively determine the boundaries separating the *Western Group*, *Intermediate Group*, and *Northern Group*.

(e) Near-surface convergence/divergence of horizontal wind at the southwestern Sea of Japan

Shinoda et al. (2021) defined the area-averaged 925 hPa horizontal wind convergence over a specific region of the Sea of Japan as an appropriate measure to extract JPCZ events. Following their approach, we evaluated the horizontal convergence intensity over the Sea of Japan. Fig. 4 shows the composite map of 925 hPa horizontal wind streamlines and their convergence/divergence for the extracted CAO cases. This composite map reveals that a strong convergence zone tends to develop over the Sea of Japan, specifically at the 10 grid points indicated by open circles. Given the similarity of the location of these 10 grid points to the observed JPCZ locations, the area-averaged values of horizontal wind convergence/divergence at 925 hPa imply the likelihood of JPCZ occurrence for each CAO case.

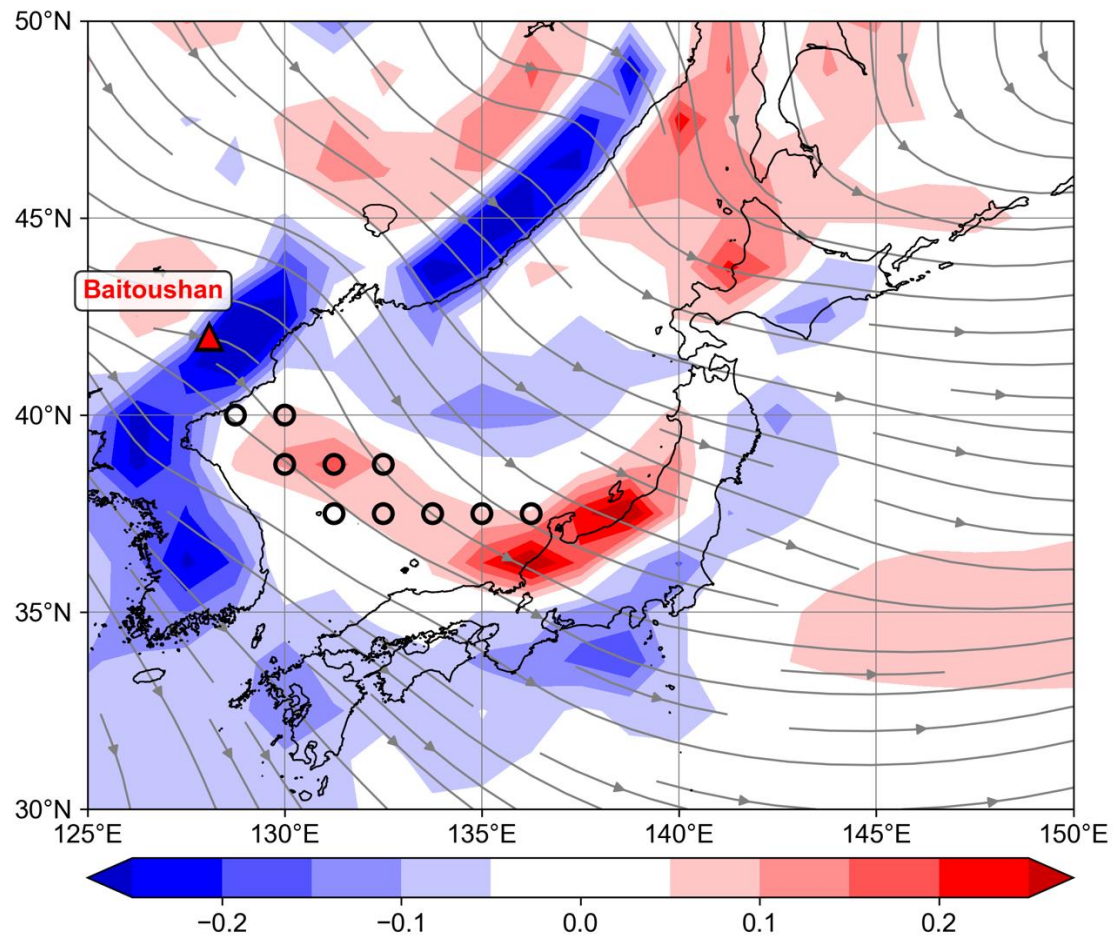


Fig. 4 Composite of 925 hPa horizontal wind (streamlines; m s^{-1}) and its convergence/divergence (shading; 10^{-4} s^{-1}) for CAO cases. The 10 grid points with particularly large convergence over the Sea of Japan are plotted with open circles (white circles with black outlines). The red triangle denotes Mt. Baitoushan. The convergence/divergence values in Fig. 14 were calculated over this area.

3 Results and Discussion

3.1 Spatial Pattern Classification of |FLCA|

Fig. 5 shows the spatial |FLCA| patterns and corresponding mean sea level pressure composited for individual 25 nodes (i.e., 5×5 nodes) classified by the SOM. The number in parentheses at the top of each panel represents the number of CAO cases classified into that node. Values of I_N , I_W , and FPI calculated for each node are summarized in Table 1. This time, the nodes of *Western group* correspond to a FPI value of -0.249 or smaller, while the nodes of *Northern group* correspond to a FPI value of 0.740 or larger, and the other nodes with FPI values in between falls into *intermediate group*.

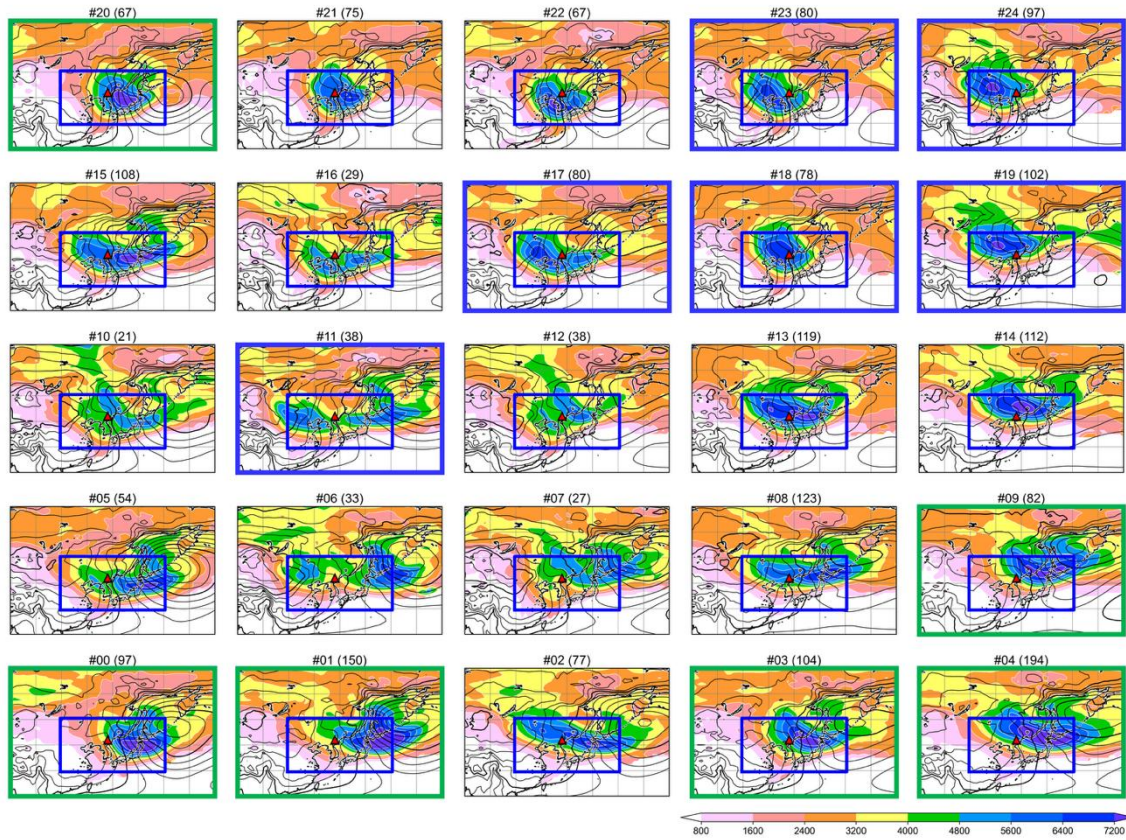


Fig. 5 Classification results of SOM for $|\text{FLCA}|$ (shading; hPa m s^{-1}), and composite of $|\text{FLCA}|$ (shading; hPa m s^{-1}) and mean sea level pressure (contours; hPa) at the times classified into each node. The number in parentheses at the top of each node represents the number of cases classified into that node. The SOM was performed in the region outlined in blue (30°N - 50°N , 110°E - 150°E). The red triangle denotes Mt. Baitoushan.

#20 (t=23) 5950 3163 0.912	#21 (t=19) 5257 4075 0.367	#22 (t=7) 4205 4634 -0.140	#23 (t=1) 3452 5616 -0.702	#24 (t=2) 3761 6083 -0.694
#15 (t=13) 5563 5046 0.140	#16 (t=9) 4231 4252 -0.007	#17 (t=3) 4325 5620 -0.378	#18 (t=4) 4322 5486 -0.344	#19 (t=5) 4283 5475 -0.354
#10 (t=12) 4478 4099 0.128	#11 (t=6) 3872 4601 -0.249	#12 (t=11) 4642 4329 0.101	#13 (t=10) 5796 5548 0.063	#14 (t=16) 5593 4615 0.277
#05 (t=18) 4771 3868 0.303	#06 (t=8) 4087 4735 -0.098	#07 (t=17) 4640 3764 0.302	#08 (t=15) 5291 4568 0.212	#09 (t=24) 5825 3029 0.944
#00 (t=25) 5976 2291 1.383	#01 (t=21) 5482 3282 0.740	#02 (t=14) 5340 4737 0.173	#03 (t=22) 6001 3536 0.763	#04 (t=20) 6467 3941 0.715

Table 1 Values of I_N , I_W , and FPI for each node of the SOM, listed in order from top to bottom. The number in parentheses (t=XX) next to the node number indicates the ascending order based on the value of FPI. The background colors of the cells indicate their assigned groups: blue for the *Western Group*, green for the *Northern Group*, and unshaded for the *Intermediate Group*.

291 Fig. 6 shows the monthly frequencies of each node for December, January, and
292 February. Table 2 summarizes the total monthly frequency for the three groups. As shown
293 in Table 2, the *Intermediate Group* exhibits the highest total frequency, followed by the
294 *Northern Group* and the *Western Group*. CAO patterns grouped as the *Western Group*
295 tend to occur more in early winter (December) and gradually decrease toward February.
296 In contrast, CAO patterns categorized as either the *Northern Group* or the *Intermediate*
297 *Group* tend to occur more in mid-winter (January).
298

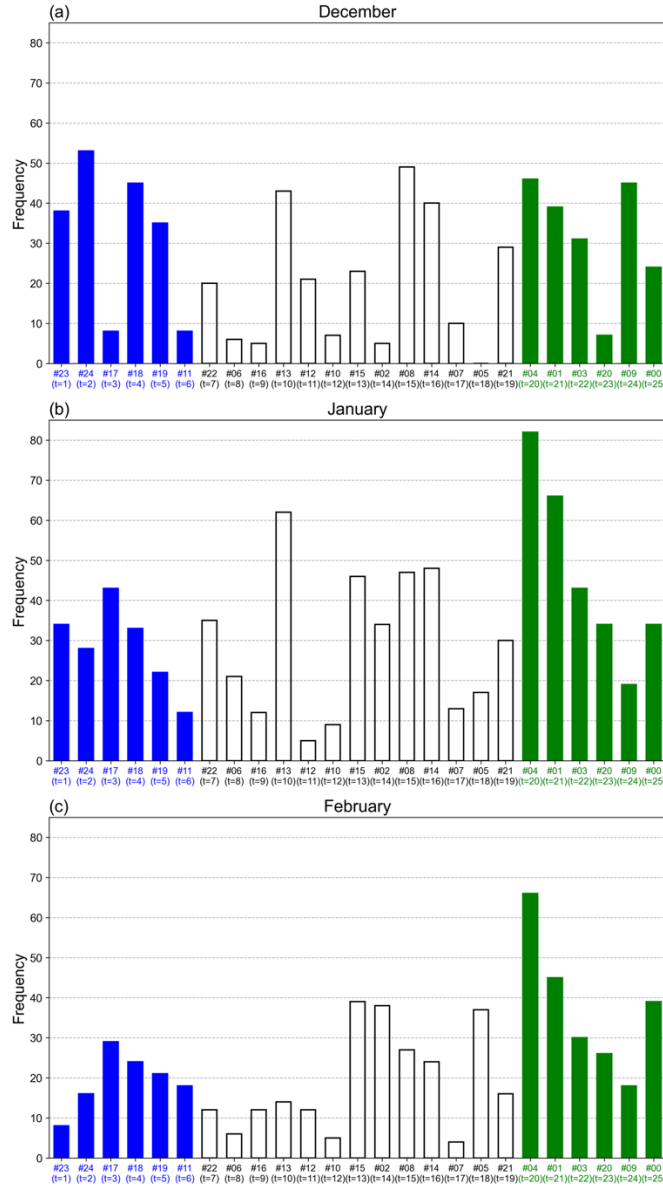


Fig. 6 Monthly frequencies of occurrence for each SOM node in (a) December, (b) January, and (c) February. The bars and numbers colored in blue, black (with uncolored bars), and green indicate the nodes classified into the *Western Group* ($t \in \{1, \dots, 6\}$), the *Intermediate Group* ($t \in \{7, \dots, 19\}$), and the *Northern Group* ($t \in \{20, \dots, 25\}$), respectively. The number in parentheses ($t=XX$) below the node number indicates the ascending order based on the value of FPI.

Group Month	Western Group	Intermediate Group	Northern Group	Total
12	187 (4.15)	258 (5.73)	192 (4.27)	637 (14.2)
1	172 (3.82)	379 (8.42)	278 (6.18)	829 (18.4)
2	116 (2.58)	246 (5.47)	224 (4.98)	586 (13.0)
Total	475 (10.6)	883 (19.6)	694 (15.4)	2052 (45.6)

Table 2 Monthly frequency of occurrence (December, January, and February) for the three categorized CAO groups: the *Western Group*, *Intermediate Group*, and *Northern Group*. The numbers in parentheses represent the number of occurrences per year. The background colors in the header correspond to the color-coding of each group (blue for the *Western Group* and green for the *Northern Group*).

3.2 CAO characteristics of individual groups

To investigate the detailed characteristics of each SOM node, we first created composite maps of 925 hPa horizontal wind convergence/divergence (Fig. 7), latent heat net flux from sea surface with 925 hPa wind convergence/divergence (Fig. 8), and preceding 1-hour precipitation (Fig. 9) for all SOM nodes.

We aggregated the cases belonging to each group and constructed group-averaged composite maps to clarify their differences from a macroscopic perspective, rather than comparing individual nodes. Specifically, we focused on the differences between the *Western Group* and the *Northern Group* with respect to the magnitude of **FLCA**, **VEL**, mean sea-level pressure (Fig. 10), 925 hPa horizontal wind convergence/divergence and streamlines (Fig. 11), latent heat net flux (Fig. 12), and preceding 1-hour precipitation (Fig. 13).

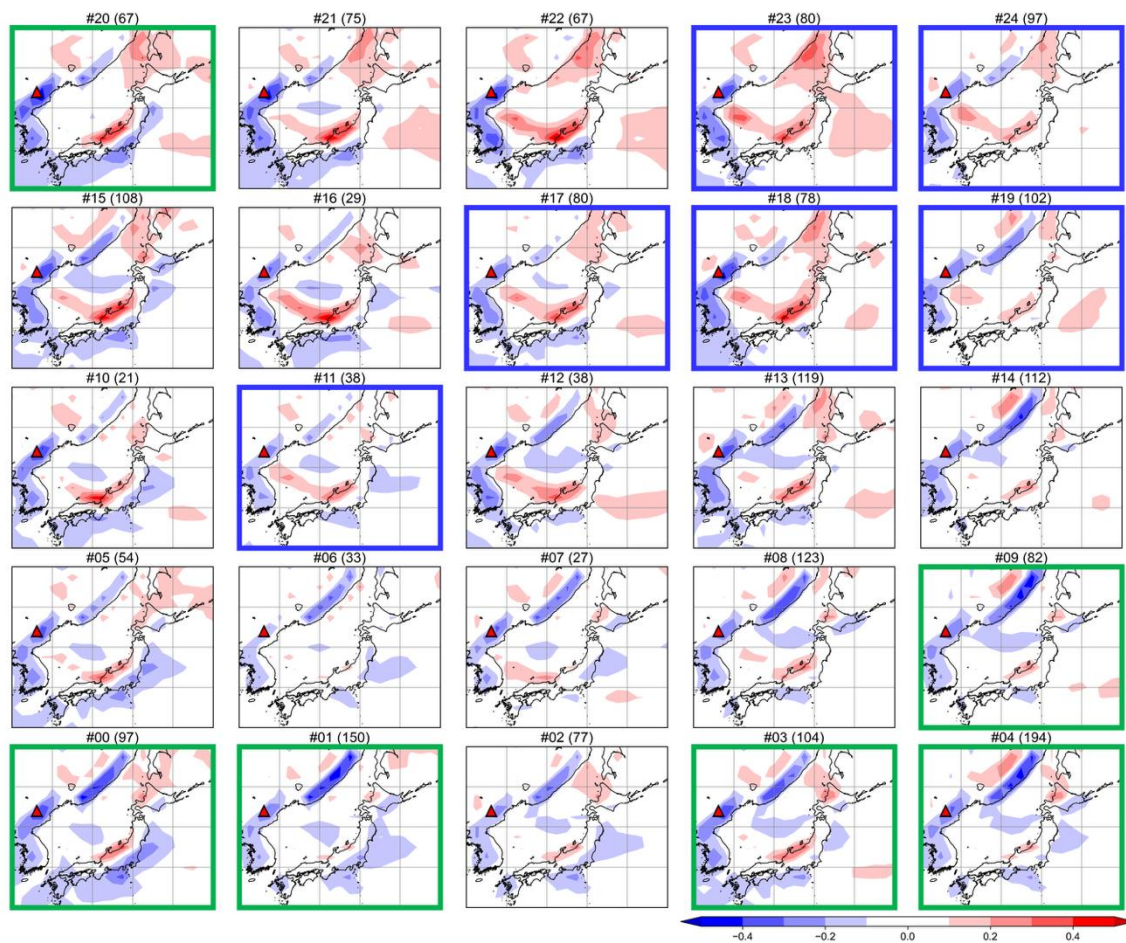


Fig. 7 Composite of 925 hPa horizontal wind streamlines and its convergence/divergence (shading; 10^{-4} s^{-1}) at the times classified into each SOM node. The number in parentheses at the top of each node represents the number of cases classified into that node. The red triangle denotes Mt. Baitoushan.

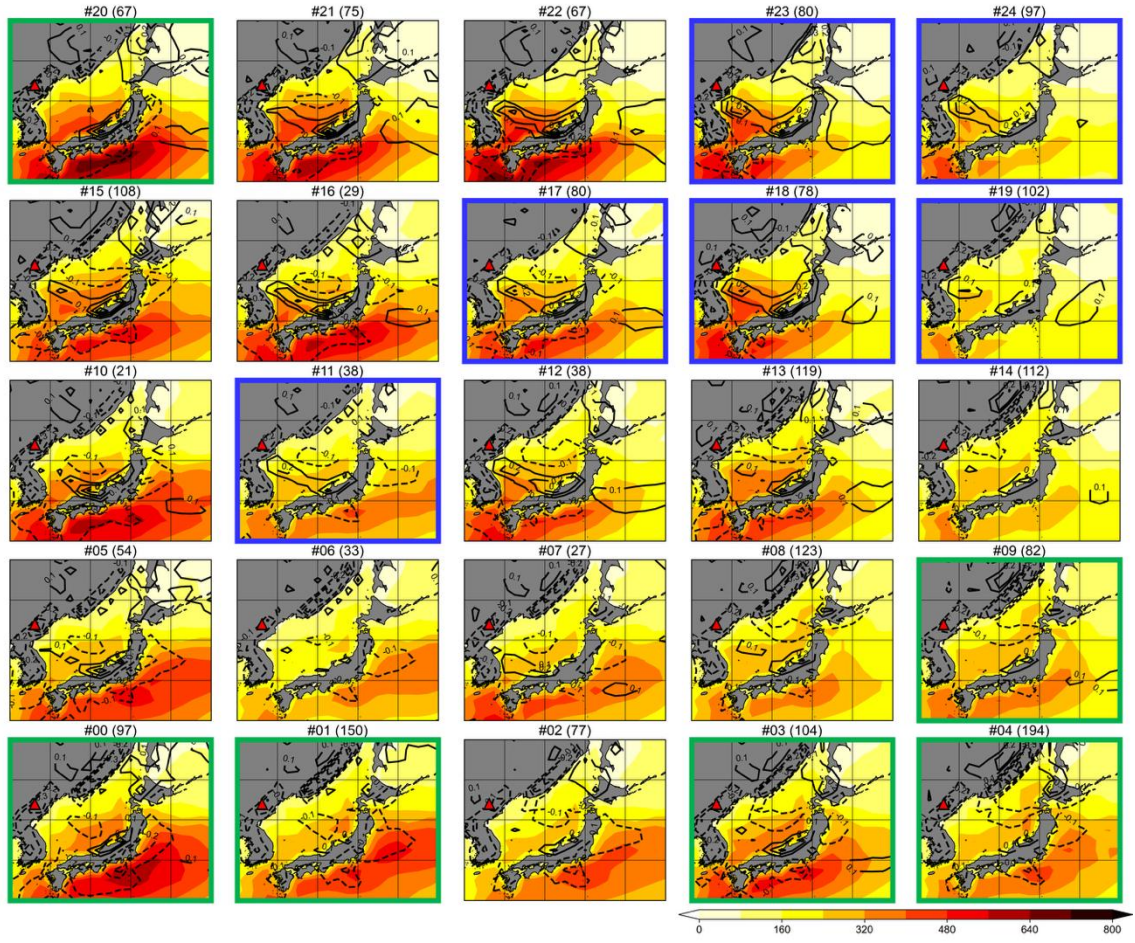


Fig. 8 Composite of latent heat net flux (shading; W m^{-2}) and 925 hPa horizontal wind convergence/divergence (contours; 10^{-4} s^{-1}) at the times classified into each SOM node. The number in parentheses at the top of each node represents the number of cases classified into that node. The red triangle denotes Mt. Baitoushan.

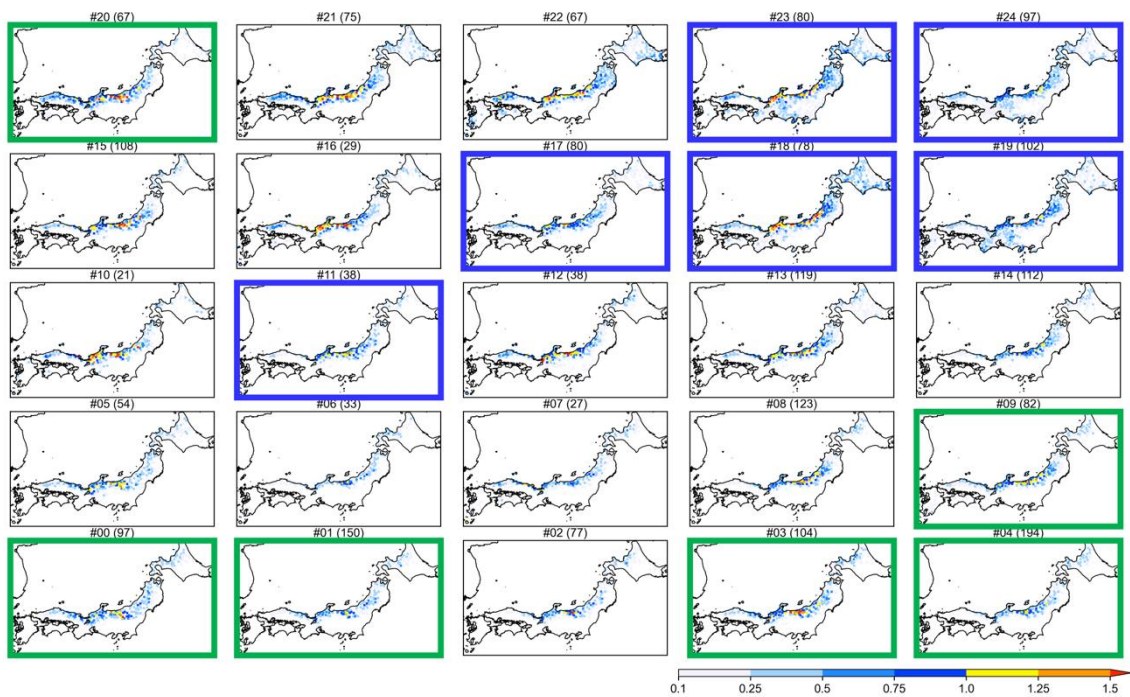


Fig. 9 Composite of preceding 1-hour precipitation (colored dots; mm h^{-1}) at each observation station at the times classified into each SOM node. The number in parentheses at the top of each node represents the number of cases classified into that node.

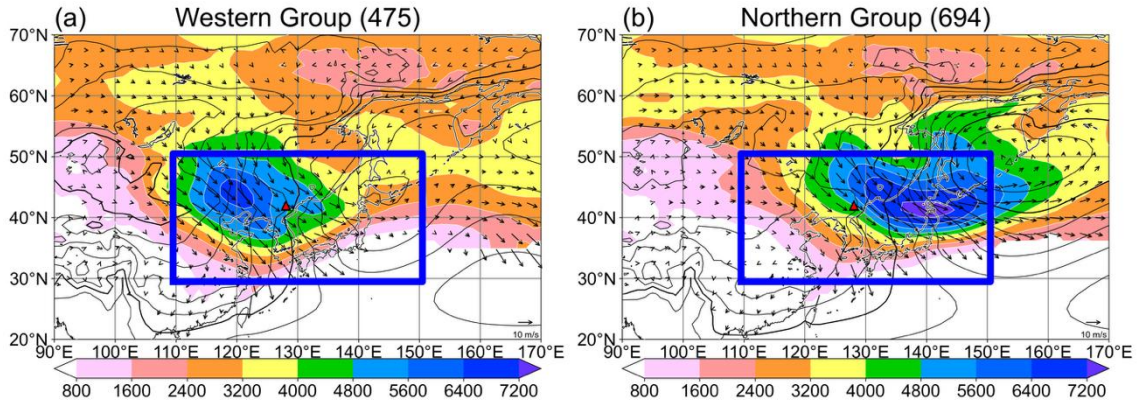


Fig. 10 Composite of the magnitude of $|\text{FLCA}|$ (shading; hPa m s^{-1}), VEL (vectors; m s^{-1}), and mean sea level pressure (contours; hPa) for (a) the *Western Group* and (b) the *Northern Group* based on the SOM classification in Fig. 6. The red triangle denotes Mt. Baitoushan.

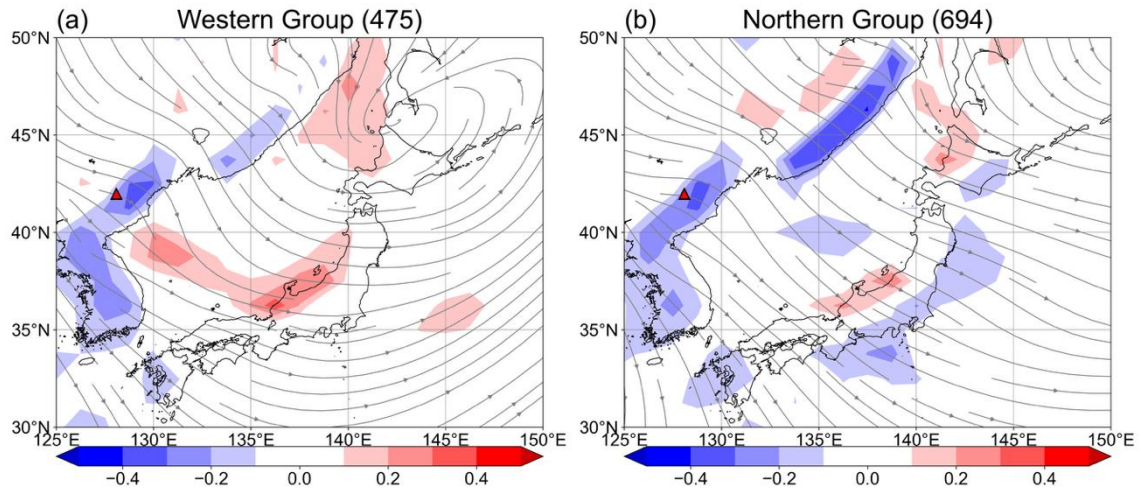


Fig. 11 Composite of 925 hPa horizontal wind streamlines and its convergence/divergence (shading; 10^{-4} s^{-1}) for (a) the *Western Group* and (b) the *Northern Group* based on the SOM classification in Fig. 6. The red triangle denotes Mt. Baitoushan.

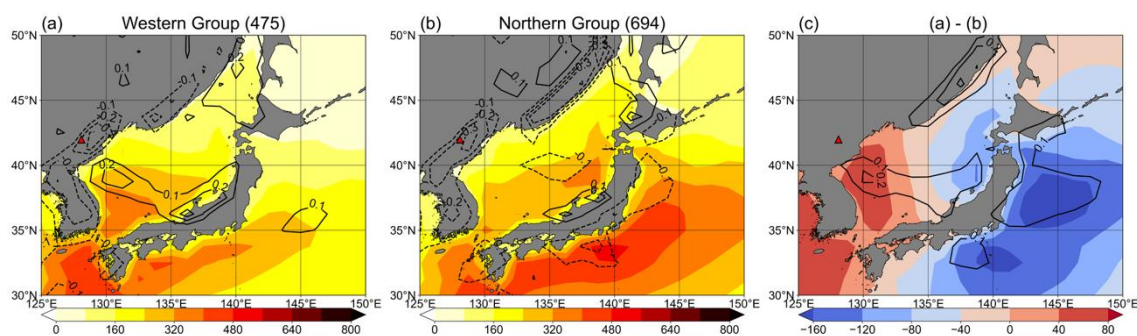


Fig. 12 Composite of latent heat net flux (shading; W m^{-2}) and 925 hPa horizontal wind convergence/divergence (contours; 10^{-4} s^{-1}) for (a) the *Western Group* and (b) the *Northern Group* based on the SOM classification in Fig. 8. (c) Difference between the *Western Group* and the *Northern Group* ((a) minus (b)). The red triangle denotes Mt. Baitoushan.

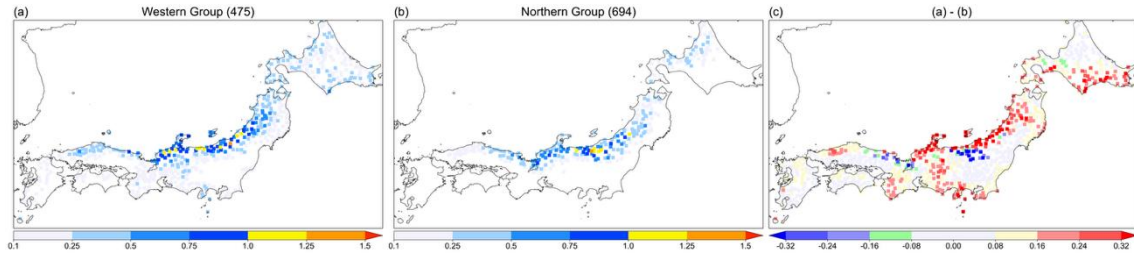


Fig. 13 Composite of preceding 1-hour precipitation (colored dots; mm h⁻¹) for (a) the *Western Group* and (b) the *Northern Group* based on the SOM classification in Fig. 9. (c) Difference between the *Western Group* and the *Northern Group* ((a) minus (b)).

The red triangle denotes Mt. Baitoushan.

Using these composite maps, we compared the spatial characteristics among the (1) *Western Group*, (2) *Northern Group*, and (3) *Intermediate Group*.

(1) *Western Group* (#11,#17,#18,#19,#23,#24)

A low-pressure area is located around Hokkaido, and strong westerly wind components broadly dominate over the Sea of Japan. Furthermore, the FLCA from the west of 128°E is strong (Figs. 5, 10a). Common to most nodes (e.g., #11, #17, #18, #23, and #24) in this group, a convergence zone extends from the western Sea of Japan to the Tohoku region, and another convergence area exists from the northern Sea of Japan to the west coast of Hokkaido (Figs. 7, 11a). Around the convergence zone stretching toward Tohoku and to its west, the latent heat net flux is large (Figs. 8, 12a, 12c). Regarding precipitation, larger amounts of precipitation were observed along the coasts of the Hokuriku and Tohoku regions, and in the San'in region compared to the *Northern Group* (Figs. 9, 13a, 13c). This is consistent with the findings of Takemura et al. (2022), who demonstrated that heavy snowfall occurs in the Hokuriku and San'in regions when cold air mass tends to intrude via the western route along the periphery of a cyclonic circulation anomaly centered near Japan. In addition, it is implied that the larger amounts of precipitation along the coasts of the Hokuriku and Tohoku regions are due to the convergence zone, while the larger amounts of precipitation in the San'in region are due

to the latent heat flux.

(2) *Northern Group* (#00,#01,#03,#04,#09,#20)

A low-pressure area is located far east of Hokkaido, and northerly wind components prevail from the east of Mt. Baitoushan to the northern Sea of Japan. Furthermore, the FLCA from the east of 128°E is strong, which characterizes the flow of cold air mass from the north (i.e., the *northern route*) (Figs. 5, 10b). The convergence zone extending from the western Sea of Japan to the Tohoku region, which was observed in many nodes of the *Western Group*, is absent in all nodes of this group (Figs. 7, 11b). The latent heat net flux is large over the ocean east or south of the Kanto region (Figs. 8, 12b, 12c). Larger amounts of precipitation were observed in the inland Kanto, northern Kinki, and the border between the Hokuriku and Kanto regions compared to the *Western Group* (Figs. 9, 13b, 13c).

(3) *Intermediate Group* (#02,#05,#06,#07,#08,#10,#12,#13,#14,#15,#16,#21,#22)

While some nodes show a large pressure gradient and strong cold air transport (e.g., #05, #15, #21, and #22), others exhibit a small pressure gradient and weak cold air transport (e.g., #06, #07, and #12). However, strong FLCA is observed on both the

western and eastern sides of 128°E across this group (Fig. 5). Nodes of relatively low FPI values (e.g., #12, #16, and #22) tend to show a convergence zone extends from the western Sea of Japan to the Tohoku region, and another convergence area exists from the northern Sea of Japan to the west coast of Hokkaido. Around this convergence zone and to its west, the latent heat net flux is large, suggesting an abundant supply of water vapor (Figs. 7, 8). Regarding precipitation, large amounts of precipitation were observed along the coasts of the Hokuriku and Tohoku regions, and in the San'in region (Fig. 9). On the other hand, nodes of relatively high FPI values (e.g., #02 and #05) tend to show the convergence zone extending from the western Sea of Japan to the Tohoku region is absent, and large amounts of precipitation were observed in the inland Kanto, northern Kinki, and the border between the Hokuriku and Kanto regions (Figs. 7, 9).

3.3 Relationship between FLCA and the JPCZ

The horizontal wind convergence zone over the Sea of Japan, suggestive of JPCZ activity, is evident in the *Western Group* but not in the *Northern Group*. We quantify this contrast by examining a linear relationship between FPI and the wind convergence.

The relationship between FPI and the area-averaged horizontal wind convergence at 925 hPa over the central Sea of Japan is shown in Fig. 14. In this scatter plot, individual CAO cases are color-coded based on their assigned SOM node numbers.

A statistically significant negative correlation was found between the two variables ($r = -0.51$, $p \ll 0.01$). Linear regression analysis, indicated by the solid black line ($y = -0.0986x + 0.1160$), further confirms this trend, demonstrating that the convergence significantly decreases as FPI increases. The mean values for the Western, Intermediate, and Northern Groups (plotted in blue, yellow, and green rectangles, respectively) are generally on the regression line, suggesting the classification of the three groups are consistent with JPCZ activity.

Therefore, it is implied that the *western route* characterizes CAO cases leading to the formation of JPCZ. The importance of CAOs for the formation and maintenance of the JPCZ lies not only in their absolute intensity. This study suggests that the CAO pathway is also an essential factor.

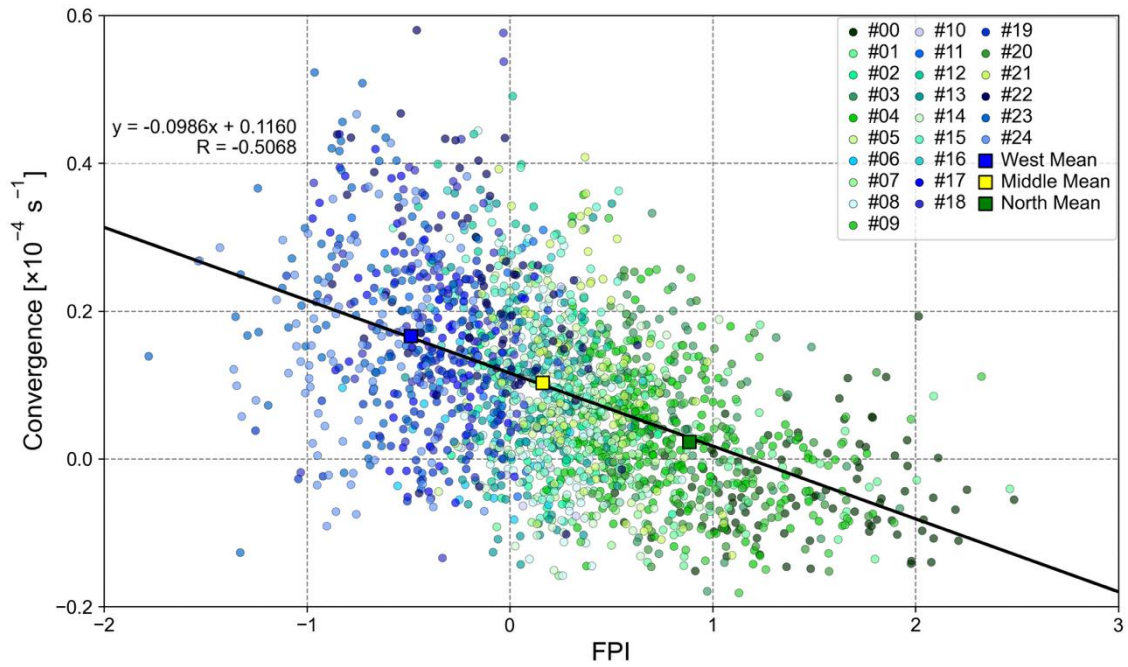


Fig. 14 Scatter plot showing the relationship between FPI and the area-averaged 925 hPa horizontal wind convergence (10^{-4} s^{-1}). Individual CAO cases are color-coded according to their assigned SOM nodes: blue tones for the *Western Group*, yellowish tones for the *Intermediate Group*, and green tones for the *Northern Group*. The blue, yellow, and green squares represent the group averages for the *Western Group*, *Intermediate Group*, and *Northern Group*, respectively. The solid black line indicates the linear regression fit.

4 Conclusions

This study aimed to reveal the dependence of winter weather in Japan on the horizontally two-dimensional distribution of the Cold-Air Outbreak (CAO) in East Asia. Using the JRA-3Q reanalysis data and the SOM clustering method, we statistically classified CAO spatial patterns. We further developed a new dynamical index, the FLCA Pathway Index (FPI), based on the ratio of the flux of cold air amounts (FLCA) from the western and eastern sides of Mt. Baitoushan in the Changbai Mountains. We then investigated the atmospheric circulations associated with the CAO patterns to suggest a dynamical relationship among CAO patterns, JPCZ occurrence, and precipitation distribution in the vicinity of Japan. Our findings are summarized as follows.

The CAO patterns were grouped into three types according to the main FLCA routes: *the Western Group, the Northern Group, and the Intermediate Group.*

The *Western Group* was characterized by the FLCA from the west side of Mt. Baitoushan (i.e., the *western route*). CAOs of this group occur most frequently in December. Being associated with strong westerly wind components over the Sea of Japan, a convergence zone suggestive of JPCZ is organized from the western Sea of Japan to the Tohoku region. Large amounts of precipitation were observed along the coasts of the Hokuriku and Tohoku regions, and in the San'in region.

In contrast, regarding the monthly frequency of occurrence, the *Northern Group* tended to appear more frequently in January and February. This group was dominated by the FLCA from the east side of Mt. Baitoushan (i.e., the northern route), where strong northerly wind components prevail from the east of Mt. Baitoushan to the northern Sea of Japan. In this group, the convergence zone from the western Sea of Japan to the Tohoku region was absent. Instead, larger amounts of precipitation were observed in the inland Kanto, northern Kinki, and the border between the Hokuriku and Kanto regions compared to the *Western Group*.

As for the *Intermediate Group*, the monthly frequency of occurrence peaked in January. This group was characterized by broadly distributed FLCA on both sides of the mountain, reaching Japan without a strong regional preference.

We found a significant negative correlation between FPI and the amount of horizontal wind convergence at 925 hPa. This means that a larger fraction of FLCA in the western side of Mt. Baitoushan against the eastern side tends to be associated with a more organized convergence zone over the Sea of Japan, suggestive of a JPCZ formation. This result supports the working hypothesis based on a case study by Yamazaki et al. (2024) that the blocking effect of the Changbai Mountains enhances the western FLCA and develops the JPCZ, providing climatological and statistical evidence for this mechanism.

The academic significance of this study lies in establishing a new dynamical index, FPI, for classifying horizontally two-dimensional CAO patterns and diagnosing their climatological relevance to the JPCZ and snowfall over Japan. While these relationships had previously been addressed through CAO categorization by latitude or individual CAO case studies, this study introduced a new index based on a simple ratio of area-averaged FLCA in East Asia to diagnose the potential for JPCZ formation from complex synoptic fields.

Prospects include applying this method to future climate projection data (e.g., d4PDF). Under global warming, understanding the relationship between CAO patterns and the frequency and intensity of the JPCZ could aid policymakers with disaster prevention and mitigation, such as future projections of snow disaster risk. Furthermore, since the reanalysis data used here lacks enough resolution for mesoscale convection, it is necessary to conduct further investigations using high-resolution data to clarify detailed lifecycle of more realistic JPCZ under CAO and explicitly verify whether it reaches the convergence zone extending from the western Sea of Japan to the coast of the Tohoku region. Future changes in CAOs should be investigated in a separate study.

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Author contributions

Sh. K. and Y. T. co-initiated this study; F. O. and Y. T. supervised the study. Sh. K. conducted the analysis and led the writing of the main text. Sa. K. guided the assembly of the study and helped revise the paper. S. W. discussed the study with Sh. K. for refinement.

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Data availability

The JRA-3Q reanalysis dataset is available on the Dataset Search and Analysis System (DIAS) website (<https://search.diasjp.net/en/dataset/JRA3Q>). The surface observation dataset from the Japan Meteorological Agency (JMA) is available on the JMA website (<https://www.data.jma.go.jp/risk/obsdl/index.php>). The surface observation dataset from the Korea Meteorological Administration (KMA) is available on the KMA website (<https://data.kma.go.kr/data/grnd/selectAsosRltnList.do?pgmNo=36>). The rain gauge observation dataset from the Automated Meteorological Data Acquisition System (AMeDAS) operated by the JMA is available on the JMA website (<https://www.data.jma.go.jp/stats/etrn>).

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