Decrease of winter cyclone passage over northern Japan due to the reduction in the regional cyclogenesis associated with cold air outbreak

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Abstract

In East Asia, a strong winter monsoon and high baroclinicity cause enhanced cyclone activity, which has been the subject of intensive study. Despite the high frequency of genesis of mesoscale cyclones in this area, most of the studies on the decadal timescale have focused only on synoptic-scale cyclones. To clarify the interannual variation of the passage of winter cyclones including synoptic-scale and mesoscale cyclones over and around Japan, a tracking algorithm was applied to 62 winter seasons (December–March) from 1958/1959 to 2019/2020. During the study period, the passage of cyclones around northern Japan showed a decreasing trend. Most cyclones that pass around northern Japan are generated over the northern part of the Sea of Japan, which is an area where cyclogenesis has decreased during the study period. Weather pattern classification based on synoptic scale atmospheric conditions revealed that passage of upper-level troughs and occurrence of lower-level cold air outbreaks are the preferential conditions for cyclogenesis in this region. In addition, the intensity of the cold air outbreak in this region was weakened during the study period. These results suggest that changes in atmospheric conditions due to climate change have reduced mesocyclone genesis over the northern Sea of Japan, resulting in the reduction in the number of cyclones passing over and around northern Japan.

KEYWORDS

extratropical cyclone, long-term trend, mesocyclone, weather patterns, winter cyclone

1 | INTRODUCTION

In winter, extratropical cyclones frequently pass over and around Japan, accompanied by strong winds and precipitation (e.g., Adachi and Kimura, 2007). Major genesis locations of such extratropical cyclones include the northwestern Pacific Ocean, Sea of Japan, and eastern Eurasian Continent (e.g., Chung et al., 1976; Chen et al., 1991). Among these regions, the Sea of Japan, located downstream of the Eurasian continent and under the influence of strong cold air outbreaks that originate from the cold Siberian High, has a remarkable rate of genesis of intense maritime mesocyclones (e.g., Asai, 1988; Ninomiya, 1991; Yanase et al., 2016). While the horizontal...
scale of the extratropical cyclone is typically >1,000 km, mesocyclones observed in the Sea of Japan have various horizontal scales ranging from meso-α (200–2,000 km) to meso-β (20–200 km) scale (e.g., Asai and Miura, 1981; Ninomiya et al., 1990; Tsuboki and Wakahama, 1992; Watanabe and Niino, 2014). Such mesocyclones generated over high-latitude oceans are called polar mesocyclones (Rasmussen and Turner, 2003). The development of the mesocyclone is contributed by multiple mechanisms (Yanase and Niino, 2007) such as baroclinic instability (e.g., Reed and Duncan, 1987) and lower-level thermal instability induced by the relatively warm ocean (e.g., Rasmussen, 1979). Intense mesocyclones tend to cause localized but heavy snowfall and strong winds (e.g., Muramatsu et al., 1975; Ninomiya et al., 1993) over western coastal areas of mainland Japan and across the island of Hokkaido (Figure 1). Therefore, a mesocyclone represents an essential component of winter cyclonic activity that can trigger severe weather events in Japan.

Global climate models have projected reduction of the total number of winter cyclones in the Northern Hemisphere in response to human-induced climate change, but the tendency of this decrease varies with region and cyclone intensity (Mizuta et al., 2011). Regional variations of this tendency of decrease have also been captured in reanalysis datasets. For example, the frequency of occurrence of extratropical cyclones has decreased in parts of East Asia, although the change is not statistically significant (Lee et al., 2020). Conversely, increase in the frequency of occurrence of explosive cyclones over ocean areas to the east of Hokkaido (Tsukijihara et al., 2019) is indicative of recent change in cyclone intensity. These changes revealed in reanalysis datasets imply that regional cyclone activity has already altered owing to ongoing climate change.

Related studies have focused mainly on the activities of extratropical cyclones (e.g., Lee et al., 2020). Yet the mesocyclones generated in East Asia have not been the target of intensive research despite their substantial impact on regional climate. Research has shown that the lifecycle of a mesocyclone is sensitive to regional geographical factors such as topography and local atmospheric conditions (e.g., Tamura and Sato, 2020). Therefore, mesocyclones might represent suitable indicators of climate change because the response of a mesocyclone to regional climate change can differ from that of an extratropical cyclone. For example, Stoll et al. (2018) investigated the global climatology of mesocyclones and found the frequency of occurrence of mesocyclones over the offshore region south of Svalbard in recent years (2001–2016) was higher than that of past years (1979–1994). We expect analysis that considers mesocyclones to provide new insight regarding the winter climatology of cyclone activity. Specifically, interannual variation of winter cyclone activity over northern Japan appears highly affected by mesocyclones because mesocyclone genesis is concentrated over the offshore area west of Hokkaido (e.g., Fujiyoshi et al., 1988; Watanabe et al., 2017; Tamura and Sato, 2020).

Climatological studies for each synoptic-scale and mesoscale cyclone suggest that these winter cyclones are essential components to characterize the regional climate around Japan (e.g., Chung et al., 1976; Chen et al., 1991; Adachi and Kimura, 2007; Yanase et al., 2016). Although the interannual variations of the cyclone activity in this region have been studied, related studies have focused on either the synoptic-scale cyclone (e.g., Tsukijihara et al., 2019; Lee et al., 2020) or mesoscale cyclones (Stoll et al., 2018). Therefore, a comprehensive understanding of winter cyclone activity, including synoptic-scale and mesoscale cyclones, is still lacking. The objective of this study is to clarify the interannual variation of both synoptic-scale and mesoscale cyclone activities over northern Japan. In addition, possible reasons for the decreasing tendency in the number of cyclone passages were discussed based on the result of synoptic scale weather pattern classifications.

Using a reanalysis dataset, this study examined the interannual variation of winter cyclone activity and investigated the mechanism behind recent changes. The remainder of this article is organized as follows. Section 2 describes the methodology of the study, that is, the tracking of cyclones and classification of synoptic scale weather patterns. In section 3, the geographical and interannual variations of cyclone passage over East Asia are presented, revealing a significant trend of decrease in the passage of cyclones over and around Hokkaido. The analysis using weather pattern classification was presented to figure out under what synoptic condition the decreasing trend was observed. Finally, section 4 provides a discussion and our conclusions.
DATA AND METHODS

2.1 Algorithm for tracking cyclones

This study used the Japanese 55-year Reanalysis dataset (JRA-55), obtained from the Japan Meteorological Agency (Kobayashi et al., 2015), for the detection and tracking of cyclones and for the analysis of synoptic scale conditions. This dataset has 1.25° horizontal resolution and a 6-hourly time interval. The analysis was performed for 62 winters (December–March) from 1958/1959 to 2019/2020. Cyclone tracking follows Adachi and Kimura (2007) with slight modifications to detect the synoptic-scale cyclone and small but discriminable cyclone systems. In brief, the algorithm first detects a grid point with a local minimum sea level pressure (SLP) which must be lower than any neighbouring eight grids. This step aims to find all low-pressure centres detectable by 1.25° mesh reanalysis data, which roughly corresponds to the cyclones in meso-α scale or greater. The second step eliminates topographically anchored SLP minima. A cyclone centre is designated only when an anomalous SLP minimum remains at least 0.5 hPa lower than that at the neighbouring eight grids after removal of the 31-days running mean SLP field. A cyclone track is created by connecting the positions of the nearest cyclone centre at each 6-hourly time interval. If there are no cyclone centres within the search area (i.e., four grids to the north, six grids to the east, four grids to the south, and three grids to the west relative to the current cyclone centre) in the subsequent time step, cyclone tracking is terminated. This algorithm is capable of detecting intense but small cyclones that were previously removed through spatial filtering in the study on decadal trend of cyclone activity (Lee et al., 2020); hence, our algorithm makes it possible to investigate the decadal trend of the winter cyclone, including synoptic-scale and meso-α scale cyclones. Due to the limitation in the resolution of JRA-55 dataset, cyclones smaller than meso-α scale are not investigated. In this study, the algorithm was applied to the region 0°–80°N, and 90°–180°E, and cyclones that persisted for more than 24 h were analysed.

2.2 Classification of pressure patterns

The synoptic scale atmospheric conditions related to interannual variation of cyclone activities were examined using the classification method based on self-organizing maps (SOMs; Kohonen, 1982). The SOM approach offers visualization of high-dimensional datasets via reduction to a two-dimensional map through neural network techniques. In meteorological studies, this technique has been used widely in classification of temporally varying atmospheric conditions such as SLP patterns (e.g., Lennard and Hegerl, 2015; Ohba et al., 2015; Kawazoe et al., 2020). In this study, the SOM method was used to classify the SLP patterns leading to cyclogenesis. The SOM was trained using 6-hourly standardized SLP fields over northern Japan (35°–55°N, 127°–157°E). The training was performed using 30,072 input vectors (4 times daily × 121/122 winter days × 62 years).

RESULTS

3.1 Cyclone genesis and passage

Figure 2a shows the number of cyclone passages in winter (December–March) over Japan from 1958–2019. The number of cyclone passages means the number of individual cyclones, that is, a cyclone that remained longer or passed over the same grid multiple times was counted as one. The number of cyclone passages was high over the Sea of Japan and the northwestern Pacific, consistent with the findings of related studies (e.g., Chen et al., 1991; Adachi and Kimura, 2007; Lee et al., 2020). Figure 2 shows that the number of cyclone passages around Hokkaido was also relatively high. This result is a feature not seen in Lee et al. (2020) that investigated only synoptic-scale cyclones. Therefore, this high passage frequency implies that mesocyclones make substantial contribution to the climatology of cyclonic activity in the studied area.

The distribution of the number of occurrences of cyclogenesis is shown in Figure 2b. The large number of occurrences of cyclogenesis evident over the western Sea of Japan might reflect topographic effects of the Changbai Mountains, which are located in the region of the border between China and North Korea (Chung et al., 1976; Shimizu et al., 2017; Watanabe et al., 2018; Shinoda et al., 2021). Over the offshore area east of Japan, cyclogenesis occurred predominantly along the track of the Kuroshio Current (Chen et al., 1991; Yoshida and Asuma, 2004; Tsukijihara et al., 2019). The concentration of cyclogenesis over the offshore area west of Hokkaido (Figure 2b) may reflect the predominant genesis of the mesocyclones in this area (e.g., Asai, 1988; Yanase et al., 2016; Tamura and Sato, 2020). Figure 2c shows the linear trends of the number of cyclone passages. The number of cyclone passages increased along the eastern and southern coasts of Japan but decreased around Hokkaido. We confirmed that these trends are significant even if the tracking algorithm used in Adachi and Kimura (2007) was adopted. This tendency of increase along the eastern and southern coasts of Japan
appears consistent with the increase in explosive cyclone activity reported in Tsukijihara et al. (2019).

The factors controlling the tendency of decrease of cyclone passages around Hokkaido were investigated. The area in which the number of cyclone passages decreased substantially (41.25°–46.25° N, 138.75°–146.25° E; rectangle in Figure 2c) was defined as the target area and formed the subject of the following analysis. Figure 2d illustrates the pathways of cyclones reaching the target area. Many cyclones that passed over the target area developed over nearby upwind seas, that is, the offshore area west of Hokkaido and the western Sea of Japan (Figure 2d, broken lines). Cyclones also reached Hokkaido from other regions (Eurasian Continent and other oceans). The following sections examine their contribution to the trend of decline in the number of cyclone passages across northern Japan.

### 3.2 | Interannual variation of cyclone activities

Cyclones that pass over and around Hokkaido are generated mainly over the offshore area west of Hokkaido and the western Sea of Japan (Figure 2d). Cyclones are classified into four types and are designated based on their genesis location as followings (see also Figure 3): Local-cyclones for those generated over and around Hokkaido including the offshore area west of Hokkaido, Remote-cyclones for those generated over the Sea of Japan region except for the Local-cyclone,
Continental-cyclones generated over the land except for Japanese Islands, and Oceanic-cyclones generated over other oceans. Horizontal size of each cyclone type is shown in Figure 3. Here, the horizontal size of the cyclones is defined as the vortex area determined using relative vorticity at 900 hPa (Figure S1, Supporting Information). It can be seen that more than half (55%, 264 cases) of the Local-cyclones have small vortex areas of less than $20 \times 10^4 \text{ km}^2$ (Figure 3). The area $20 \times 10^4 \text{ km}^2$ is approximately equivalent to 2.5 times the land area of Hokkaido ($7.8 \times 10^4 \text{ km}^2$). Proportions of cyclones that have such small vortex area are less for other cyclone types (Remote-cyclone: 22% (61 cases); Continental-cyclone: 25% (111 cases); Oceanic-cyclone: 20% (39 cases)). This implies that most of the Local-cyclones did not develop as large as other cyclone types.

Here, this study describes the characteristics of the Local-cyclone. Figure 4a shows the duration of the cyclones. All cyclone (white bars) and Local-cyclone (red bars and white dot) tend to have shorter lifespan. The short duration cyclones ($\leq 2$ days) occupies 39%
(572 cases) for all cyclone and 63% (301 cases) of the Local-cyclones. In contrast, majority (70%, 190 cases) of the Remote-cyclones have duration longer than 2 days. Figure 4b shows the relation between the duration and horizontal size of the cyclones. Cyclones with a short duration were relatively small. These results clearly show that most of the Local-cyclones were relatively short-lived and small-scale cyclones.

Figure 5 shows the interannual variation of the number of cyclones passing over and around Hokkaido (rectangle in Figure 2c), and the number of occurrences of cyclogenesis. Quantitative comparison of the interannual variation is summarized in Table 1. The total number of all cyclones passing over and around Hokkaido decreased significantly at a rate of −1.0 decade\(^{-1}\) (black line with filled circle in Figure 5a). The highest number of cyclone passages occurred in 1985/1986 when a strong winter monsoon brought a cold winter to East Asia (Jhun and Lee, 2004). Interannual variation of the number of occurrences of Local-cyclone genesis (red line with open circle in Figure 5b) was almost identical to the number of cyclone passages over Hokkaido (Figure 5a), and both showed significant trends of decrease (genesis: −0.65 decade\(^{-1}\), passage: −0.62 decade\(^{-1}\)). This decrease in the passage of Local-cyclone is thought to be caused by the decrease of cyclogenesis and the weakening of the cyclones which results in the reduction of detectable cyclones. In contrast, interannual variation of the Remote-cyclone genesis (blue line with filled rhombus in Figure 5b) and passage (Figure 5a) did not show significant trends (genesis: −0.06 decade\(^{-1}\), passage: −0.17 decade\(^{-1}\)). Continental-cyclones (−0.13 decade\(^{-1}\)) and Oceanic-cyclones (−0.09 decade\(^{-1}\)) also showed no significant trends (Figure 5a). The observed rate of decrease in Local-cyclones (−0.62 decade\(^{-1}\)) corresponds to 60% of that for all cyclones passing over and around Hokkaido (−1.0 decade\(^{-1}\)). Furthermore, the interannual variation of all cyclone passages over Hokkaido and the genesis of Local-cyclones are correlated (correlation coefficient of 0.62). The number of passages of Continental-cyclones is also correlated (correlation coefficient of 0.59) with All passages, but its trend of passages is not statistically significant (−0.13 decade\(^{-1}\)). These results suggest that the contribution of the reduction in Local-cyclone genesis to the observed decrease in the

### Table 1: Number of cyclone passage and cyclogenesis, and linear trends shown in Figure 5

|                      | All passages | Local-cyclones | Remote-cyclones | Continental-cyclones | Oceanic-cyclones |
|----------------------|--------------|----------------|-----------------|-----------------------|-----------------|
|                      | Annual mean  | 22.4           | 8.52            | 13.68                 | 4.40            |
|                      | Trend (decade\(^{-1}\)) | −1.0**         | −0.65**         | −0.06                 | −0.17           |
|                      | Correlation coefficient | 0.57***        | 0.62***         | 0.14                  | 0.47***         |

**Note:** All passages refer to all cyclones that passed over the target area (rectangle in Figure 2c). Local-cyclone, Remote-cyclone, Continental-cyclone, and Oceanic-cyclone genesis are the cyclone generated in each area defined in Figure 5. Passage means those cyclones that passed over the Hokkaido area. Correlation coefficients are calculated against the interannual variation of All passages (Figure 5a). Trends and the correlation coefficients exceeding the 99% and 99.9% confidence levels are marked by superscripts ** and ***, respectively.
number of cyclone passages over and around Hokkaido was larger than the other cyclone types.

Synoptic scale conditions at the time of Local-cyclones genesis were investigated by the pressure pattern classification. Figure 6 shows standardized SLP patterns produced by the SOM method. To focus on the synoptic scale pressure patterns around Hokkaido, the analysis targets the domain from Northeast Asia to the Sea of Okhotsk and the part of the northwestern Pacific. Each panel in the SOM map (hereafter referred to as nodes) is denoted by a number (column) and an alphabet (row), e.g., the node in the upper-left corner was written as (1,a) in this paper. The number presented in each node indicates the number of days (winter$^{-1}$) that belong to each node. The definitions of Cluster 1, Cluster 2, and Cluster 3 are documented in section 3.2 [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 6](wileyonlinelibrary.com)

**Figure 6** Composite map of standardized SLP patterns on 5 × 4 SOM. The classification is based on standardized 6-hourly SLP snapshots around Hokkaido (35°-55°N, 127°-157°E) for December–March during 1958/1959–2019/2020. Solid contour lines indicate positive value, and dotted contour lines indicate negative value. Number shown in each panel indicates the number of days (winter$^{-1}$) that belong to each node. The definitions of Cluster 1, Cluster 2, and Cluster 3 are documented in section 3.2 [Colour figure can be viewed at wileyonlinelibrary.com]

To ensure the above interpretation is reasonable, trained 5 × 4 SLP patterns were classified by K-means clustering and three clusters were obtained: left-hand 12 nodes in columns 1–3 (3 × 4 nodes), upper-right four nodes (2 × 2 nodes), and lower-right four nodes (2 × 2 nodes) (Figure 6). We defined these clusters as Cluster 1, Cluster 2, and Cluster 3 as indicated by red, blue, and green rectangles in Figure 6, respectively. We also confirmed that this classification consisting of left-hand columns, upper-right nodes, and bottom-right nodes, is robust regardless of SOM settings (4 × 4, 4 × 5, and 5 × 5 settings were tested; not shown).

![Figure 7](wileyonlinelibrary.com)

**Figure 7** Number of occurrences of Local-cyclone genesis (colour and numbers) in each SOM node illustrated in Figure 6. Colour rectangles indicate the clustering defined in Figure 6 [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 7 summarizes the counts of Local-cyclone genesis for every 6-hourly snapshot categorized into each SOM node (Figure 6). The average number of occurrences of Local-cyclone genesis under the typical winter pressure pattern (Cluster 1) is 28 cases, while that of the remainder of the pattern, upper-right nodes (Cluster 2) is 16 cases, and lower-right nodes (Cluster 3) is 19 cases, respectively. Hereafter, Local-cyclones generated under synoptic conditions corresponding to Cluster 1, Cluster 2, and Cluster 3 are defined as C1-cyclones, C2-cyclones, and C3-cyclones, respectively. The probability of cyclogenesis at each node can be obtained from the total number of occurrences of cyclogenesis (Figure 7) divided by the number of days (Figure 6). There is no significant difference in the probability of Local-cyclone genesis with respect to the background surface pressure pattern (C1-cyclones: 6.6%, C2-cyclones: 6.2%, C3-cyclones: 6.5%).

Pressure and western high pressure, is higher than that in the two right-hand columns (4.9 days-winter$^{-1}$). This clear low–high-pressure pattern with high frequency indicates that the nodes in the three left-hand columns represent the typical winter surface pressure pattern of northeast Asia, comprising the Aleutian Low and the Siberian High.

To ensure the above interpretation is reasonable, trained 5 × 4 SLP patterns were classified by K-means clustering and three clusters were obtained: left-hand 12 nodes in columns 1–3 (3 × 4 nodes), upper-right four nodes (2 × 2 nodes), and lower-right four nodes (2 × 2 nodes) (Figure 6). We defined these clusters as Cluster 1, Cluster 2, and Cluster 3 as indicated by red, blue, and green rectangles in Figure 6, respectively. We also confirmed that this classification consisting of left-hand columns, upper-right nodes, and bottom-right nodes, is robust regardless of SOM settings (4 × 4, 4 × 5, and 5 × 5 settings were tested; not shown).

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Figure 8a–c shows the synoptic conditions when Local-cyclone was generated. Here, we focus on the nodes classified as Cluster 1 in which the SLP anomaly fields (Figure 8a) include the western high-pressure anomaly (Siberian High) and the eastern low-pressure anomaly (Aleutian Low). The upper-level pressure patterns are characterized by the low-pressure anomaly (upper-level trough) located over the western offshore area of Hokkaido, except for node (1,d) (Figure 8b). The lower-level temperature fields show strong cold air advection over the Sea of Japan, which reflects the cold air outbreaks from the continent induced by the Siberian High and the Aleutian Low (Figure 8c). These atmospheric conditions coincide with the synoptic scale conditions known to enhance mesocyclone genesis over the offshore area west of Hokkaido (e.g., Ninomiya et al., 1996; Watanabe et al., 2017). Therefore, Local-cyclones generated under the synoptic scale conditions assigned in the Cluster 1 (C1-cyclones) are likely to represent mesocyclones produced by cold air outbreaks from the continent.

Considering the SOM nodes aligned in the two right-hand columns in Figure 8a, the surface low-pressure anomaly is located close to Hokkaido or over the Eurasian Continent. The upper-level trough extends over eastern parts of the Eurasian Continent to Hokkaido (Figure 8b). Lower-level temperature fields show warm advection from the Pacific Sea or the Sea of Japan toward Hokkaido (Figure 8c). Especially in the nodes classified in Cluster 2 (upper-right four nodes), the synoptic-scale low pressure over Hokkaido (Figure 8a) encourages warm advection from the Pacific Sea and cold advection from the Eurasian Continent over the offshore area west of Hokkaido (Figure 8c). These advections intensify the lower-level temperature gradient within the northwestern quadrant of the synoptic-scale low pressure. Low-level disturbance triggered by the horizontal wind shear and temperature gradient is further intensified by the vertical stretching and the vertical coupling of the low-level disturbance and upper-level circulation associated with the mid-tropospheric trough, leading to the development of the cyclone over the offshore area west of Hokkaido (e.g., Ninomiya et al., 1993). The nodes in Cluster 2 show relatively large surface low pressure over the offshore area west of Hokkaido, and a corresponding mid-tropospheric trough is evident to the west of the surface low pressure (Figure 8a,b). These are similar to the atmospheric conditions of mesoscale cyclogenesis developed by baroclinic instability (Yanase et al., 2016). On the basis of the evaluations mentioned above, it is considered that the C2-cyclones are likely to be the cyclones that develop in baroclinic instability.

A possible cyclone-formation process that might be relevant in the synoptic scale atmospheric conditions in C3-cyclones genesis is lee-cyclogenesis, which is found to dominate the offshore area west of Hokkaido owing to the presence of mountains on the eastern coast of the

![Composite map of (a) SLP (hPa), (b) geopotential height at 500 hPa (m), and (c) 850-hPa temperature (K) and wind fields averaged for cases having Local-cyclone genesis (contours and vectors). Shading indicates the deviation of cyclone genesis cases relative to their corresponding daily climatology (1958/1959–2019/2020 winters). Hatching indicates the significant difference at the 0.05 confidence level (Welch’s t test). Colour rectangles indicate the clustering defined in Figure 6 [Colour figure can be viewed at wileyonlinelibrary.com]
Eurasian Continent (Sikhote-Alin in Figure 1) (e.g., Chung et al., 1976). Low-level westerly winds that pass over the mountains on the eastern coast of the Sikhote-Alin mountain (Figure 8c) and mid-tropospheric troughs located over the continent (Figure 8b) can induce cyclogenesis over the lee side of the mountain.

The characteristics of the atmospheric conditions leading to the Local-cyclone genesis are summarized in Figure 9. A C1-cyclone is characterized as a small cyclone feature generated locally over the offshore area west of Hokkaido, as evidenced by the northwestward extension of the low-pressure area (contours in Figure 9a) shown in Figure 9a. C1-cyclone tends to develop between the synoptic-scale low-pressure anomaly located over the Kamchatka Peninsula and the Siberian High (Figure 9a). Upper-level trough (Figure 9b) and the cold air advection (Figure 9c) exist over the offshore area west of Hokkaido. These are the typical conditions of mesoscale cyclogenesis developed in the northerly wind caused by the synoptic-scale cyclone to the east of Hokkaido and northwesterly winter monsoon (Yanase et al., 2016; Watanabe et al., 2017). Because C1-cyclones are short-lived and small-scale (Figure 4), many of them are seemed to be mesocyclone associated with the cold air outbreaks. In contrast, a C2-cyclone is characterized as a relatively large-scale cyclone close to the high-pressure anomaly located over the south of the Kamchatka Peninsula (Figure 9d) and an upper-level trough over the continent (Figure 9e). These conditions are similar to the mesocyclones developing through baroclinic instability (Yanase et al., 2016). Since there is a surface low-pressure anomaly located over the continent at the time of C3-cyclone genesis (Figure 9g), it is possible that C3-cyclone is a cyclone associated with lee cyclogenesis (e.g., Chung et al., 1976). These classifications show that Local-cyclone occurs under various synoptic scale atmospheric conditions.

Interannual variation of the cyclogenesis for each cluster (Figure 10a) reflects that the number of

![Composite map of SLP (hPa) (a, d, g), geopotential height at 500 hPa (m) (b, e, h), and 850-hPa temperature (K) and wind (c, f, i) fields for C1- (top), C2- (middle), and C3-cyclone (bottom) created by averaging the nodes for each cluster in Figure 8. Drawing conventions are as in Figure 8 [Colour figure can be viewed at wileyonlinelibrary.com]]
occurrences of C1-cyclone genesis (red with open circle) is significantly decreased (−0.54 decade⁻¹; p = 0.003), while the change in C2-cyclone genesis (blue with open rhombus) (−0.08 decade⁻¹; p = 0.26) and C3-cyclone genesis (green with triangle) (0.002 decade⁻¹; p = 0.98) are not significant. It is also confirmed that only the significant trend of C1-cyclone genesis is robust regardless of the SOM settings (tested for 4 × 4, 4 × 5, and 5 × 5 SOM settings). Interestingly, the linear trend for the number of cases that correspond to the weather pattern of Cluster 1 is not significant (−0.70 decade⁻¹; p = 0.18). However, the ratio of C1-cyclone genesis to the number of cases of Cluster 1 (Figure 10b, red with open circle), that is, C1-cyclone number divided by the number of Cluster 1 snapshots, shows a significant tendency of decrease (−0.15 decade⁻¹; p = 0.003). This tendency was confirmed to be robust regardless of the SOM settings. These results suggest that the decrease in the number of occurrences of cyclogenesis over the offshore area west of Hokkaido (C1-cyclones) is not attributable to changes in the frequency of the favourable pressure pattern.

C1-cyclones occur in association with an upper-level trough and lower-level cold air outbreaks (Figure 9a–c). Considering the fact, the following analysis aims at the investigation of the interannual variation of cold air outbreak over the offshore area west of Hokkaido. This study utilized a CAO-index defined as follows:

$$\text{CAO-index}_{850} = \theta_{\text{skt}} - \theta_{850},$$

where $\theta_{850}$ and $\theta_{\text{skt}}$ represent the potential temperature at 850 hPa and surface skin, respectively. This index is widely utilized in the studies on cold air outbreaks over relatively warm oceans (Papritz et al., 2015; Kolstad, 2017;...
Because C1-cyclones occur in the lower-level northwesterly wind (Figure 9c), the high CAO-index \( \text{index}_{850} \) means that the air from the continent is cold or sea surface temperature is high. Here, the count (6 hr\(^{-1} \)) of cold air outbreaks was investigated using the number of events when CAO-index \( \text{index}_{850} \) averaged over the sea in the target area (map in Figure 3, red shading and white dot) is larger than its standard deviation computed for 1958/1959–2019/2020. Similarly, the frequency of upper-level trough event was defined as the number of events when 500-hPa geopotential height averaged over the target area is less than \(-1\) standard deviation. Figure 10c indicates the number of occurrences of cold air outbreaks (light blue line and filled circle) and upper-level trough (purple line and cross) for Cluster 1. The frequency of the cold air outbreaks showed weak decrease (\(-2.2\) decade\(^{-1} \); \( p = 0.13 \)). The frequency of the upper-level trough event also decreases (\(-0.62\) decade\(^{-1} \); \( p = 0.68 \)), but both trends are not statistically significant. However, the averaged CAO-index \( \text{index}_{850} \) (i.e., the magnitude of vertical instability) at the events of cold air outbreak (black line and open circle) decreased significantly at the 95% confidence level (0.05 decade\(^{-1} \); \( p < 0.001 \)). Significant decreasing trends were also observed in the results by using other SOM settings. It suggests that the intensity of the cold air outbreak in this region has weakened in recent years. The correlations of the interannual variation of C1-cyclones genesis (red and open circle in Figure 10a) against the frequency of cold air outbreaks (correlation coefficient of 0.19; \( p = 0.14 \)), the trough events (correlation coefficient of 0.09; \( p = 0.5 \)), and the CAO-index \( \text{index}_{850} \) (correlation coefficient of 0.23; \( p = 0.07 \)) are not significant. These trends and their significance were similar even if the SOM settings were changed. Although decisive factors for their changes need further investigation, the decrease and weakening in the cold air outbreak events on the west–east high and low surface pressure pattern might have suppressed cyclogenesis or development of mesoscale cyclones in this region, resulting in the reduction in the number of cyclones passing over and around Hokkaido.

4 | DISCUSSION AND CONCLUSIONS

This study examined the factors behind the interannual variation in the number of winter cyclones that pass over and around Japan. Cyclone tracking including synoptic-scale and mesoscale cyclones revealed that the number of cyclones passing over and around Hokkaido has decreased significantly since the 1960s. Of the major areas of genesis of cyclones that pass over and around Hokkaido, the number of cyclones generated over the offshore area west of Hokkaido has decreased significantly. Synoptic scale weather pattern classification based on the SOM approach showed that cyclogenesis is affected by cold air outbreaks from the Eurasian continent and upper-level troughs located over the offshore area west of Hokkaido. Mesocyclones tend to form preferentially in an area with a low-level horizontal temperature gradient induced by cold air outbreaks, and they develop in association with instabilities triggered by upper-level intrusion of cold air when the trough migrates (e.g., Ninomiya et al., 1996; Kolstad, 2011; Watanabe et al., 2017). Hence, weakening of the cold air outbreaks associated with climate change is probably the reason for the significant reduction in the number of cyclones passing over and around Hokkaido over the past 60 years. The weakening of the cold air outbreaks can be attributed to the fact that the continental warming is greater than the ocean warming (e.g., Manabe et al., 1991).

The intensity of the cold air outbreaks (CAO-index \( \text{index}_{850} \)) is significantly decreased (Figure 10c, black line with open circle) and the interannual variation in the frequency of cold air outbreaks showed a weak tendency of decrease (Figure 10c, light blue line with filled circle). It was also found that the correlation coefficient of the frequency of cold air outbreaks (\( r = 0.19 \)) was higher than that of the upper-level troughs (\( r = 0.09 \)). Therefore, cold air outbreaks might have stronger impact than upper-level troughs on cyclogenesis or development of the mesoscale cyclone in the offshore area west of Hokkaido. The trend of decrease in cold air outbreaks is likely related to global warming.

Enhanced heat and moisture fluxes associated with high sea surface temperature (SST) promote the development of mesocyclones (Watanabe et al., 2017). Despite SST warming in recent years (not shown), the number of occurrences of cyclogenesis has decreased over the offshore area west of Hokkaido. Therefore, possible clues are in the decadal changes in dynamic and thermodynamic atmospheric conditions. Meanwhile, the coincidence of high SST and strong CAO can cause stronger mesocyclones if other conditions remain the same. Hence, it is undeniable that the number of stronger mesocyclones will increase in the future as SST experiences further warming. To evaluate the various effects of SST on mesocyclones, sensitivity experiments using a numerical model will be conducted in following studies.

A mesocyclone is a crucial winter disturbance that can trigger extreme weather events such as local severe snowstorms. Ongoing climate change is projected to decrease the amount of snowfall in Hokkaido (Matsumura and Sato, 2011). The decrease in mesocyclone genesis revealed in this study is likely to contribute to...
to the further reduction of snowfall in this area. The key environmental factors including synoptic scale atmospheric conditions and SST are found to respond to climate change (e.g., Gan and Wu, 2013), which could potentially lead to substantial modification of the behaviour of mesocyclones. From the perspective of predicting future changes in regional climate, our study highlights the climate change signal apparent in mesoscale weather systems. Further studies on historical and future changes of mesoscale phenomena should be conducted in other regions of the world.

ACKNOWLEDGEMENTS
This research was funded by Grants-in-Aid for Scientific Research (KAKENHI; Grant Nos. JP19H05697 and JP19H05668), the Arctic Challenge for Sustainability II (ArCSII; Grant No. JPMXD142031885), and the Integrated Research Program for Advancing Climate Models (TOUGOU; Grant No. JPMXD0717935561) from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan. The SOM analysis is based on the python package “somoclu” (Wittek et al., 2017). We thank James Buxton MSc of Edanz (https://jp.edanz.com/ac) for editing a draft of this manuscript.

AUTHOR CONTRIBUTIONS
Kenta Tamura: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; validation; visualization; writing – original draft. Tomonori Sato: Funding acquisition; project administration; resources; supervision; validation; writing – review and editing.

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How to cite this article: Tamura, K., & Sato, T. (2022). Decrease of winter cyclone passage over northern Japan due to the reduction in the regional cyclogenesis associated with cold air outbreak. *International Journal of Climatology*, 42(15), 7598–7610. https://doi.org/10.1002/joc.7667