Contributions of the climate regime shift and historical global warming to explosive cyclone activity around Japan according to large-ensemble simulations

Abstract
Using the Database for Policy Decision-Making for Future Climate Change (d4PDF), this study examined the impact of a tropical climate regime shift around 1998/1999 on explosive cyclone activity around Japan in boreal winter, highlighting cyclones moving along the Kuroshio Current (KC cyclones), especially northward-migrating (N-type, as defined in Tsukijihara et al., 2019) KC cyclones. Wave-train patterns along the Asian jet affect the track and rapid development of N-type cyclones, and the frequency of the top 10% of pronounced wave-train patterns using a teleconnection index (NI10%) has increased since 1998/1999. Tropical precipitation in the region close to the Bay of Bengal increased with the climate regime shift, leading to the increased frequency of NI10%. The downstream development of wave packets tends to form a ridge with a barotropic structure east of Japan that is able to force the northward shift of the KC cyclone. In reality, there are high correlations between the inter-annual variations in the ensemble mean frequencies of NI10%, N-type cyclones, and tropical precipitation around the Bay of Bengal, and all three indices have increased since 1998/1999. Furthermore, the above results are nearly the same in both historical and non-warming experiments, indicating that recent changes in the frequency of N-type cyclones are not directly related to historical global warming.

KEYWORDS
climate regime shift, d4PDF, explosive cyclone, large-ensemble simulations, tropical precipitation, wave train

1 INTRODUCTION
Explosively developing extratropical cyclones frequently appear around the Kuroshio/Kuroshio Extension in the northwestern Pacific and the Gulf Stream in the northwestern Atlantic during the boreal cold season (e.g., Sanders and Gyakum, 1980; Roebber, 1984; Gyakum et al., 1989; Lim and Simmonds, 2002; Black and Pezza, 2013). Previous studies have reported that important factors in the development of explosive cyclones include baroclinic instability, vertical coupling of the upper and lower tropospheric vortices
(e.g., Hoskins et al., 1985; Takayabu, 1991; Shapiro et al., 1999), and latent heat release near the cyclone centre (e.g., Kuo et al., 1991a; 1991b; Reed et al., 1993; Kuwano-Yoshida and Asuma, 2008; Heo et al., 2015). From the viewpoint of large-scale circulations, the wave packets propagating eastward along the northern Eurasian and South Asian waveguides also contribute to the further enhancement of cyclone development over the northwestern Pacific (Chang, 2005). Yamashita et al. (2012) noted that a subtropical teleconnection pattern forms a barotropic ridge east of an explosive cyclone, which could cause the northward shift of the cyclone.

Tsukijihara et al. (2019, hereafter T2019) focused on inter-decadal explosive cyclone activity and possible interaction between the wave trains and explosive cyclones. They examined explosive cyclone activity around Japan in boreal winters from 1979/1980 to 2016/2017, mainly utilizing the Japanese 55-year Reanalysis (JRA-55) data (Kobayashi et al., 2015). The extreme events of both strong winds and heavy precipitation have increased in Hokkaido, the northernmost island of Japan, since the late 1990s, which is consistent with the recent tendency of the cyclones moving along the Kuroshio Current (KC cyclones) to approach the Hokkaido region. In the composite analyses of northward-migrating (N-type) KC cyclones, wave-train patterns dominated along the polar front jet and the Asian jet over the continent, thereby inducing an upper-level trough (ridge) to the west (east) of the cyclone. An upper-level divergence related to the rapidly developing N-type cyclone excited the downstream development of wave packets as a Rossby wave source, causing further amplification of the upper-level ridge east of the cyclone. The amplified ridge with a barotropic structure plays a significant role not only in forcing the northward shift of the cyclone, but also in importing a moisture flux near the cyclone centre from lower latitudes.

T2019 also discussed the relationship between the climate regime shift and inter-decadal change in explosive cyclone activity around Japan. A North Pacific regime shift is known to have occurred in the winter of 1998/1999 (e.g., Minobe, 2002; Bond et al., 2003; Overland et al., 2008; Jo et al., 2013). The regime shift accompanied an inter-decadal change in the sea surface temperature (SST) with warming in the equatorial western Pacific and cooling in the equatorial central and eastern Pacific. The distribution indicates a recent La Niña–like mean state (e.g., Zhang et al., 2011; Kosaka and Xie, 2013; Jo et al., 2014; Hong et al., 2016). According to previous studies, the La Niña condition enhances the tropical convection in the vicinity of the South China Sea and Philippine Sea, and its Rossby wave response induces anomalous anticyclonic circulation around the upper-level subtropical jet over southern China, the so-called Asian jet (e.g., Sakai and Kawamura, 2009; Sakai et al., 2010). T2019 suggested that increased tropical precipitation relevant to the climate regime shift around 1998/1999 facilitated the eastward propagation of stationary waves along the Asian jet, which may have contributed to the recent increase in the frequency of N-type cyclones.

However, questions remain as to whether the 1998/1999 climate regime shift indeed contributed to the active propagation of wave packets along the Asian jet and consequently increased the frequency of N-type cyclones, and whether historical global warming contributed to these inter-decadal changes. This study utilized the Database for Policy Decision-Making for Future Climate Change (d4PDF) (Mizuta et al., 2017) to answer the above questions. The d4PDF dataset is compiled from the Meteorological Research Institute Atmospheric General Circulation Model, version 3.2 (MRI-AGCM3.2) (Mizuta et al., 2012), which consists of 100 ensemble members from 1951 to 2010. The large-ensemble simulations can extract a large number of N-type cyclones, allowing for detailed assessment of the inter-annual variations in cyclone frequency and associated climate changes. In addition, the d4PDF includes not only the historical (HIST) simulations, but also the non-warming (NonW) simulations. Previous studies based on the d4PDF have reported the impact of historical global warming on meteorological variables, such as temperature and precipitation, by comparing the HIST and NonW simulations (e.g., Shiogama et al., 2016; Hori and Oshima, 2018; Imada et al., 2019; Kawase et al., 2019). The contribution of historical global warming to explosive cyclone activity can also be evaluated by comparing the two experiments.

In this study, we investigate the issues that were not resolved in T2019. The objectives of this study are (a) to investigate the frequency of the pronounced wave-train pattern along the Asian jet as a linking bridge between a tropical climate regime shift and inter-decadal explosive cyclone activity by using a teleconnection index as a new approach, (b) to assess in detail the relationship between the inter-annual and inter-decadal variations in cyclone frequency and the associated climate changes by extracting a large number of N-type cyclones from large-ensemble simulations, and (c) to evaluate the contribution of historical global warming to the frequency of N-type cyclones and the associated climate changes by comparing the HIST and NonW simulations. In this article, Section 2 describes the data and methods. Section 3 gives composite analyses for the wave-train pattern along the Asian jet. Section 4 clarifies the relationship between the climate regime shift around 1998/1999 in the tropics
and the frequency of N-type cyclones. The discussion and summary are presented in Sections 5 and 6, respectively.

2 | DATA AND METHODS

The d4PDF analysis was conducted using MRI-AGCM3.2 with a time interval of 6 hr and a horizontal grid interval of approximately 60 km; however, the data used was smoothed to $1.25^\circ \times 1.25^\circ$. The analysis period for both HIST and NonW simulations consisted of 100 ensemble members of 3,100 winters (December, January, and February; hereafter DJF) from 1979/1980 to 2009/2010. The HIST simulation was conducted by using the observed SST and sea ice based on the Centennial In Situ Observation-Based Estimates of the Variability of SSTs and Marine Meteorological Variables (COBE-SST2; Hirahara et al., 2014) and historical external forcing (greenhouse gases, ozone, and aerosols). The 100 ensemble members were simulated with random initial and SST perturbations. NonW removes the warming trend in the observed SST, with sea ice adjusted to be consistent with the given SST. The external forcing was set at the preindustrial level. The d4PDF is described in detail in Mizuta et al. (2017). We also used JRA-55 data compiled by the Japan Meteorological Agency. The spatial and temporal intervals were $1.25^\circ$ and 6 hr, respectively. The analysis period consisted of 38 winters (DJF) from 1979/1980 to 2016/2017, which was the same period as in T2019. In addition, we used the monthly precipitation data from the Global Precipitation Climatology Project (GPCP), version 2.3 (Adler et al., 2003). The GPCP precipitation data is based on satellite and gauge observations, and the spatial resolution was $2.5^\circ$.

We extracted explosive cyclones from the d4PDF using the same tracking method as in T2019. In the 6-hourly sea level pressure (SLP) field, a local minimum was identified as a cyclone centre over the northwestern Pacific sector ($100^\circ$–$180^\circ$E, $20^\circ$–$60^\circ$N), and the closest cyclone within a radius of 600 km from the expected centre was considered to be the same cyclone. Details of the tracking algorithm are described in Iwao et al. (2012) and T2019. According to Sanders and Gyakum (1980), an extratropical cyclone was identified as an explosive cyclone if the following developing rate ($\epsilon$) exceeded 1 hPa/hr (1 Bergeron):

$$
\epsilon = -\frac{p(t+12) - p(t-12)}{24} \frac{\sin 60^\circ \sin \Phi(t)}{\sin \Phi(t)},
$$

where $t$ is the time in hours, $p$ is the SLP at the cyclone centre, and $\Phi$ is the latitude at the cyclone centre. In

3 | COMPOSITE ANALYSES OF THE WAVE-TRAIN PATTERN

3.1 | Identification of the wave-train pattern based on the JRA-55

Since the stationary wave propagation along the Asian jet affected the track and rapid development of N-type cyclones (T2019), it would be reasonable to focus on the behaviour of such a teleconnection pattern as a linking bridge between a tropical climate regime shift and interdecadal change in explosive cyclone activity around Japan. As a new approach, we define an appropriate index to identify the wave-train pattern along the Asian jet. In this subsection, we investigate the relationship between the upper-level wave-train pattern and a surface cyclone/anticyclone, as well as the long-term change in the frequency of the wave-train pattern. The wave-train pattern is simply identified by the following index (NI), with reference to the composite map for N-type cyclones at a 250 hPa level (fig. 8e in T2019):

$$
NI = Z'(102.5^\circ E, 27.5^\circ N) - Z'(132.5^\circ E, 40.0^\circ N) + Z'(157.5^\circ E, 42.5^\circ N),
$$

(2)

where $Z'$ is the geopotential height anomaly at the 250 hPa level. Note that the anomaly is defined as the 6-hourly data minus the climatological value. The climatological value was not only averaged over the 38-year period, but also smoothed by calculating a 10-day running average; however, the anomaly was not filtered. The NI was calculated every 6 hr during the 38 winters (DJF) from 1979/1980 to 2016/2017, and its peak value was
extracted at time intervals longer than 60 hr to avoid overlapping of wave-train patterns in a short period, which was identified as the mature state of an event. For convenience, hereafter, the top 10% of cases in all NI values extracted are called NI10%, which implies the appearance of pronounced wave-train patterns along the Asian jet. The reason for selecting NI10% as a threshold will be explained later.

NI10% consisted of 53 cases during the 38 winters based on the JRA-55. Figure 1 shows composite maps of the geopotential height and its anomaly at the 250 hPa level for NI10%. Here, $T = 0$ hr denotes the peak time when the NI value reached its maximum. Noticeable wave-train patterns appear along the polar front and Asian jets over the Eurasian continent at $T = -48$ hr, indicating a spatial distribution very similar to the composite map for N-type cyclones (fig. 8a in T2019). It is inferred that the two wave packets propagate eastward through the northern Eurasian and South Asian waveguides. From $T = -24$ to 0 hr, an east–west pair consisting of an upper-level trough and a ridge becomes apparent around Japan. The features show good correspondence with the composite maps for N-type cyclones (fig. 8c,e in T2019). According to T2019, the prominence of wave packets further downstream was caused by an upper-level divergence related to the rapid development of the N-type cyclone as a Rossby wave source.

Figure 2 shows composite patterns of the SLP for NI10% based on the JRA-55. At $T = -24$ hr, there is an east–west pair consisting of a cyclone and anticyclone in the vicinity of Japan. The anticyclone appears to block the eastward movement of the cyclone, thereby forcing the northward shift of the cyclone from $T = -12$ to 0 hr. At $T = 0$ hr, the upper-level trough indicated by the white circle ($132.5^\circ$E, 40.0°N) and the surface cyclone show a westward tilt, suggesting a baroclinic interaction between the lower and upper tropospheres (e.g., Bjerknes and Holmboe, 1944). These features are consistent with the composite maps for N-type cyclones (figs. 6a,c and 9c in T2019), indicating that the pronounced wave-train pattern of NI10% is closely related to N-type cyclones. In addition, the intensities of the cyclone and anticyclone at $T = 0$ hr are almost the same as those of the composite map for N-type cyclones (fig. 6c in T2019). The results show that NI10% has properly extracted the wave-train patterns associated with N-type cyclones.

**FIGURE 1** Composite maps of the 250 hPa geopotential height (grey contours with an interval of 300 m) and its anomaly (shading) at $T = -48$, -24, and 0 hr for NI10% based on the JRA-55. The white circles indicate the points used in the definition of NI. Black dashed contours denote statistically significant regions at a 95% confidence level using Student’s t test [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 2** Composite maps of the SLP (hPa) at $T = -24$, -12, and 0 hr for NI10% based on the JRA-55. The white circles indicate the points used in the definition of NI [Colour figure can be viewed at wileyonlinelibrary.com]
There are 19 and 34 NI10% cases in the earlier (1979/1980–1997/1998) and later (1998/1999–2016/2017) periods, respectively. The difference between the two values denoted statistical significance at a 95% confidence level using Student’s t test, which suggests that the stationary wave propagation along the Asian jet is associated with the climate regime shift. The significant difference at the 95% confidence level was also satisfied in the top 5 and 15% of NI, but not in the top 20%. Therefore, the top 10% of NI was settled as a representative threshold.

### 3.2 d4PDF-based analysis

NI10% was extracted during 3,100 winters from 1979/1980 to 2009/2010 based on 100 ensemble members in the d4PDF. There are 4,347 and 4,362 NI10% cases in the HIST and NonW simulations, respectively. Note that the anomaly is defined as the 6-hourly data minus the climatological value derived from each ensemble member over the 31-year period. Figure 3 shows composite maps of the geopotential height and its anomaly at the 250 hPa level for NI10% based on the 100 members in the HIST and NonW simulations. In both experiments, the wave-train patterns from $T = −48$ to 0 hr are consistent with composite maps based on the JRA-55 (Figure 1).

Composite maps of the SLP for NI10% in both experiments show good correspondence with the results of the JRA-55 in Figure 2 (not shown). Thus, the JRA-55 and d4PDF indicate that the pronounced wave-train pattern of NI10% is closely related to N-type cyclones.

Figure 4 shows inter-annual variations in the ensemble mean frequency of NI10% per winter based on HIST.
and NonW simulations. The inter-annual variations show a recent increase in both experiments, and the difference in the mean values between the earlier 19 winters (1979/1980–1997/1998) and the later 12 winters (1998/1999–2009/2010) satisfied statistical significance at the 95% confidence level using Student’s t test. Note that the later period is shorter than the earlier period because the d4PDF does not include data after 2010. The inter-annual variations in the ensemble mean that the frequency of NI10% is nearly the same in both experiments, suggesting that historical global warming does not affect the frequency of NI10%.

Table 1 reports the number of ensemble members that showed an increase (decrease) in the averaged frequency of NI10% from the earlier (1979/1980–1997/1998) to later (1998/1999–2009/2010) periods based on the 100 members in the HIST and NonW simulations.

|          | All | 90% | 95% |
|----------|-----|-----|-----|
| HIST     | 89  | 31  | 19  |
| NonW     | 78  | 16  | 12  |

Note: Columns 3 and 4, respectively, indicate the number of ensemble members that showed an increase (decrease) in the averaged frequency of NI10% with significant differences between the earlier and later periods at the 90% and 95% confidence levels using Student’s t test.

We also validated the long-term changes in the frequency of NI10% for individual ensemble members. Figure 5 shows composite maps of the precipitation, as well as 250 hPa geopotential height anomalies averaged between T = −72 and 0 hr for NI10% in the earlier and later periods based on the 100 members in the HIST and NonW simulations. Note that the 3-day average is adopted, considering the time lag in the response of the wave-train pattern to tropical forcing. For the earlier period, there are 2,257 and 2,405 NI10% cases in the HIST and NonW simulations, respectively. For the later period, there are 2,090 and 1,957 NI10% cases in the HIST and NonW simulations, respectively. A distinctive positive
precipitation anomaly around Japan was caused by the developing N-type cyclone associated with the wave-train pattern along the Asian jet. In both experiments, a positive precipitation anomaly in the region close to the Bay of Bengal appears in the later period; however, it hardly appears in the earlier period. An upper-level anticyclone anomaly to the north of the Bay of Bengal in the later period is greater than that in the earlier period, reflecting the response of Rossby waves to the positive tropical precipitation anomaly (Sakai and Kawamura, 2009; T2019). Both experiments exhibit similar features in terms of the anomalous precipitation around the Bay of Bengal.

4 | LONG-TERM CHANGES IN TROPICAL PRECIPITATION AND THE FREQUENCY OF N-TYPE CYCLONES

Figure 6 shows the ensemble mean difference in climatological wintertime precipitation between the earlier and later periods (latter minus former) based on HIST and NonW simulations. In both experiments, tropical precipitation exhibits a recent increase in the vicinity of the South China Sea, the Philippine Sea, and the Bay of Bengal, which corresponds well to the result of the GPCP data (fig. 13b in T2019). The increased tropical precipitation is interpreted as a response to SST warming in the equatorial western Pacific associated with the regime shift (Zhang et al., 2011; Gu and Adler, 2013; T2019). Statistically significant regions of increased precipitation around the Bay of Bengal are consistent with the composite maps of the precipitation anomaly for NII10% (Figure 5c,d), which presumably facilitated the eastward propagation of stationary waves along the Asian jet.

Previous studies have reported that the absence of ocean/atm feedback in the model tends to produce an overestimation of precipitation in warm SST regions in the tropics (e.g., Kitoh and Arakawa, 1999; Peings and Magnusdottir, 2015). Since the MRI-AGCM3.2 does not include ocean/atm feedback, we verified the validity of the inter-annual variations in the ensemble mean precipitation around the Bay of Bengal derived from HIST and NonW simulations by comparison with the GPCP data (Figure 7). The inter-annual variations in tropical precipitation are nearly the same in both experiments, which is consistent with the GPCP result, although the model results are slightly higher than the GPCP data. Both experiments well reproduce the precipitation around the Bay of Bengal despite the absence of ocean/atm feedback, suggesting that the potential shortcomings of the experimental design do not significantly affect the results of this study.

Figure 8 presents a synoptic display of the relevant N-type cyclone tracks, with the ensemble mean difference in the climatological wintertime frequency of N-type cyclone tracks between the earlier and later periods (latter minus former) based on HIST and NonW simulations. There are 7,909 and 7,979 N-type cyclones over the period of 1979/1980–2009/2010 in the HIST and NonW simulations, respectively. The frequencies of N-type cyclones per winter are 2.55 and 2.57 in the HIST and NonW simulations, respectively, which are slightly higher than the 2.39 in the JRA-55 (T2019). The mean maximum developing rates of N-type cyclones are 1.63 and 1.62 Bergeron in the HIST and NonW simulations, respectively, which are slightly lower than the 1.67 Bergeron in the JRA-55 (T2019). In the earlier (later) period, the mean maximum developing rates of N-type cyclones are 1.64 (1.63) and 1.62 (1.63) Bergeron in the HIST and NonW simulations, respectively. It is
noteworthy that the mean maximum developing rates are almost the same between the earlier and later periods. The frequency and mean maximum developing rate of N-type cyclones in the d4PDF resemble the results of the JRA-55, although the sample size is quite different. As indicated in Figure 8, the climatological frequency of N-type cyclone tracks extends from the KC to the Kamchatka Peninsula and tends to be concentrated to the east of Hokkaido, the northernmost island of Japan. The frequency of N-type cyclone tracks shows a statistically significant increase in most regions, which is consistent with an increased frequency of NI10%. The above results have very good similarity between the two experiments.

Figure 9 shows the inter-annual changes in the standardized values in the ensemble mean frequencies of
TABLE 2  Correlation coefficient between the inter-annual variations in the ensemble mean frequencies of NI10%, N-type cyclones, and tropical precipitation averaged within the specific domain (80°–105°E, 0°–10°N) based on HIST and NonW simulations during boreal winters (DJF) from 1979/1980 to 2009/2010

|                  | NI10%  | N-type cyclones | Tropical precipitation |
|------------------|--------|----------------|------------------------|
| NI10%            | —      | .83            | .83                    |
| N-type cyclones  | .75    | —              | .67                    |
| Tropical precipitation | .83 | .68            | —                      |

Note: The upper right side of the table represents HIST results, and the lower left side represents NonW results.

NI10%, N-type cyclones, and tropical precipitation averaged within the blue rectangle (80°–105°E, 0°–10°N) in Figure 6. The tropical precipitation in the region close to the Bay of Bengal is related to the active propagation of stationary waves along the Asian jet, as inferred from the results shown in Figures 5 and 6. The three variables tend to have increased since 1998/1999 in both experiments and also correspond well to each other. Table 2 shows the correlation coefficients between their inter-annual variations in Figure 9, indicating high correlation coefficients from .67 to .83. Inter-annual variations in the frequency of N-type cyclones are nearly the same in both experiments, although the NonW simulation removed the warming trend in the observed SST, and the external forcing was set at the preindustrial level, indicating that the inter-annual variations are not directly related to historical global warming. This tendency is consistent with the result regarding the frequency of NI10% and tropical precipitation (Figures 4 and 7).

We also examined the inter-annual variations in the frequencies of eastward-migrating (E-type, as defined in T2019) KC cyclones and all explosive cyclones that recorded their maximum developing rates in the northwestern Pacific sector (100°–180°E, 20°–60°N). The cyclone frequencies showed no significant differences between the earlier and later periods, and these are nearly the same in both experiments (not shown).

5  DISCUSSION

In the previous sections, we explained that the increased tropical precipitation associated with the climate regime shift changes the frequencies of NI10% and N-type cyclones. The results were very similar in the HIST and NonW simulations, which implies that the inter-annual SST variability is primarily driving these phenomena, rather than the warming trend in the observed SST. However, the impact of SST forcing on inter-annual variations, such as tropical precipitation, remains uncertain. Therefore, we would like to discuss this issue in the present section.

In order to investigate the relative magnitude of the SST-forced variability and internal variability, we use a statistical analysis of variance method applied by Rowell et al. (1995) and Sugi et al. (1997). This method decomposes the total variance ($\sigma_T^2$) into the components of SST-forced variability ($\sigma_{SST}^2$) and internal variability ($\sigma_{INT}^2$) by taking advantage of the characteristics in the ensemble simulations. The component of internal variability is calculated from the spread among the ensemble members. The component of SST-forced variability is estimated from the variance of the ensemble mean ($\sigma_{EM}^2$), which is properly corrected because the influence of the internal variability is not necessarily negligible. These variations are calculated as follows:

$$\sigma_{INT}^2 = \frac{1}{N(n-1)} \sum_{i=1}^{N} \sum_{j=1}^{n} (x_{ij} - \bar{x}_i)^2,$$

$$\sigma_{EM}^2 = \frac{1}{N-1} \sum_{i=1}^{N} (\bar{x}_i - \bar{x})^2,$$

$$\sigma_{SST}^2 = \sigma_{EM}^2 - \frac{1}{n} \sigma_{INT}^2,$$

$$\sigma_T^2 = \sigma_{SST}^2 + \sigma_{INT}^2,$$

where $N$ is the number of years, $n$ is the number of ensemble members, $x_{ij}$ is the data of the $i$-th year and $j$-th member of the ensemble, $\bar{x}_i$ is the ensemble mean of the $i$-th year, and $\bar{x}$ is the mean of all data. Finally, we estimate the ratio of the SST-forced variability to the total variability:

$$\hat{R} = \frac{\sigma_{SST}^2}{\sigma_T^2},$$

where $\hat{R}$ is called the variance ratio. It is also noted that small SST perturbations are added to COBE-SST2 for the ensemble simulations in the d4PDF, thus implying that in this study, $\sigma_{INT}^2$ is not due to purely atmospheric internal variability (Endo et al., 2017).

Figure 10 shows the variance ratio for wintertime (DJF) precipitation based on HIST and NonW ensemble simulations. In both experiments, the high-value region of the variance ratio is confined to the tropics, which corresponds well to the recent changes in tropical precipitation (Figure 6). The distribution of the variance ratio
suggests that SST forcing has a relatively high impact on tropical precipitation in the vicinity of the western Pacific and the Bay of Bengal. On the other hand, the variance ratio is small in the extratropics, where the internal variability is larger than the SST-forced variability, which is consistent with the results of Sugi et al. (1997). Since the variance ratio for the tropical precipitation in this study is quite comparable to their estimation, the influence of the added SST perturbations on \( \sigma^2_{\text{INT}} \) could be small. Even though the overestimation of \( \sigma^2_{\text{INT}} \) is not negligible, the corresponding variance ratio could be underestimated in this case, as inferred from Equation (7).

Table 3 shows the variance ratio for the inter-annual variations in three indices in Figure 9. The variance ratios for the tropical precipitation around the Bay of Bengal were 57 and 60% in the HIST and NonW simulations, respectively. The high variance ratio values indicate that the inter-annual variation in tropical precipitation around the Bay of Bengal is largely affected by SST-forced variability. Although the signal of such tropical forcing propagates downstream into the extratropics, the variance ratio is relatively small for the frequencies of NI10% and N-type cyclones, which might also be underestimated, as mentioned above, because the internal variability is predominant in the extratropical atmosphere. This may cause the diversity of each ensemble member, as revealed in Table 1. Nevertheless, the inter-annual variations in three indices correspond well with each other in the ensemble mean terms (Figure 9 and Table 2), indicating that the tropical precipitation associated with SST-forced variability significantly affects the frequency of N-type cyclones through stationary wave propagation along the Asian jet. Particularly, inter-decadal SST change associated with natural variability, rather than the historical warming trend in the observed SST, has a relatively high impact on these phenomena.

6 | SUMMARY

This study examined the impact of the tropical climate regime shift during the 1998/1999 winter on explosive cyclone activity around Japan during 3,100 winters from 1979/1980 to 2009/2010 using the Database for Policy Decision-Making for Future Climate Change (d4PDF), which consists of 100 ensemble members. The major findings in the present study are summarized as follows.

1. Using a teleconnection index as a new approach, we highlighted the top 10% of pronounced wave-train patterns along the Asian jet (NI10%) that affect the track and rapid development of explosive cyclones moving along the KC cyclones, especially northward-migrating (N-type) KC cyclones. The frequency of NI10% has tended to increase since 1998/1999, suggesting that wave packets along the Asian jet were activated by the climate regime shift.

2. Composite analyses for NI10% show the recent prevalence of a tropical precipitation anomaly in the region close to the Bay of Bengal, thereby imposing an upper-level anticyclone anomaly within the South Asian wave-guide north of the Bay of Bengal resulting from the response of Rossby waves to tropical convective heating. The downstream development of wave packets causes the formation of a ridge with a barotropic structure east of Japan that is able to force the northward shift of the KC cyclone, according to Tsukijihara et al. (2019).

3. The inter-annual variations in the ensemble mean frequencies of NI10%, N-type cyclones, and tropical
precipitation around the Bay of Bengal correlate well with each other. The result provides evidence that the stationary wave propagation along the Asian jet was activated by the increased tropical precipitation associated with the 1998/1999 climate regime shift, contributing to the recent increase in the frequency of N-type cyclones. The statistical analysis of variance method indicates that the inter-annual variation in tropical precipitation around the Bay of Bengal was largely affected by SST-forced variability.

4. The above results have good similarity between historical and non-warming experiments, suggesting that the recent increase in the frequency of N-type cyclones is not directly related to historical global warming but is dominated by natural climate variability.

In this study, we found that recent changes in the frequency of N-type KC cyclones were not directly related to historical global warming, but there is also the issue of how regional-scale explosive cyclone activity will be modulated under future climate conditions. The d4PDF also provides +4 K (or 2 K) surface-warming simulations from the preindustrial level. Future climate simulations consist of 90 (or 54) ensemble members based on the six SST warming patterns and perturbations. High-resolution large-ensemble future simulations will help us assess the probabilistic future projections of explosive cyclone activity and separate the relative contributions of global warming and natural climate variability, such as climate regime shift. Further studies are required on this issue.

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AUTHOR CONTRIBUTIONS
Takumi Tsukijihara: Conceptualization; formal analysis; investigation; validation; writing - original draft.
Ryuichi Kawamura: Funding acquisition; resources; supervision; writing-review & editing.

ORCID
Takumi Tsukijihara https://orcid.org/0000-0002-8100-0015
Ryuichi Kawamura https://orcid.org/0000-0002-6783-1496

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