Consideration of Whether a Climatic Regime Shift Has Prevented the Occurrence of a Cold Summer in Northeast Eurasia since 2010

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ABSTRACT: Does a warming world, where extremely hot summers are becoming more common, mean that cold summers will never again occur? It is crucial to know whether extremely cold summers are still possible, as such knowledge will significantly impact decisions regarding the further adaptation of crops to cold summers. Japan, which has suffered from many extremely cold summers, has managed past agricultural disruptions with emergency rice imports. In this paper, we show that a climate regime shift associated with the positive phase shift of the summer Arctic Oscillation occurred in 2010 in northeast Eurasia, making the occurrence of extremely cold summers highly unlikely as long as this new regime persists. In fact, Japan has not experienced a cold summer since 2010, while extremely hot summers have been frequent. Since 2010, a double-jet structure with subtropical and polar jets has strengthened, and the polar jet has meandered farther north of Japan, resulting in an upper-tropospheric anticyclone. This anticyclone, which extends downward and tilts southward, reaches southern Japan and prevents cold advection of oceanic air over the cold Oyashio. The Okhotsk high, known as the leading cause of cold summers, has occurred frequently in recent years; however, cold summers have not occurred due to the tilting anticyclone. The recent warming of the Oyashio weakens cold advection. The Pacific–Japan pattern, known as a remote tropical influence, has been weakened. A better understanding of the regime shift will help us understand the tilting anticyclone and the associated extreme summers in northeast Eurasia.

SIGNIFICANCE STATEMENT: Extremely cold summers are among the most destructive natural disasters, both socioeconomically and agriculturally. Historically, food shortages due to cold summers have triggered wars. This paper proposes that a hemispheric-scale climate regime shift occurred in or around 2010. This regime shift has included warmings in the North Pacific and East Eurasian land surface temperatures. The regime shift is accompanied by the positive shift of the Arctic Oscillation (AO), a jet meander, and an upper-tropospheric anticyclone, making eastern Eurasia extremely hot. Our results imply that extremely cold summers are unlikely to occur in eastern Eurasia so long as this regime persists. Moving forward, it is important that the link between this regime shift and global warming be explored.

KEYWORDS: Asia; Arctic Oscillation; Atmosphere-ocean interaction; Jets; Climate change
Northeastern Eurasia, including Japan, satisfies these peculiar atmospheric and oceanic conditions (Fig. 1a). Japan is located to the west of the cold Okhotsk Sea and the cold Oyashio Current (Kawasaki et al. 2021). In addition, a blocking high occasionally appears near Japan over the Okhotsk Sea or the North Pacific in summer (e.g., Tibaldi et al. 1994; Hwang et al. 2020; Lupo 2021). In fact, Japan has occasionally suffered from disastrously cold summers, such as in 1993 and 2003. In the cold summer of 1993, for example, average rice yields were approximately half of normal yields (Inoue 1993; Shimono et al. 2007). A blocking high over the Okhotsk Sea and its associated cold oceanic wind originating from the Okhotsk Sea were responsible for these extremely cold summers (e.g., Nakamura and Fukamachi 2004; Ogi et al. 2004a, 2005). The cold Okhotsk air mass is brought by a surface stationary anticyclone, referred to as an Okhotsk high, which accompanies an upper blocking high (Nakamura and Fukamachi 2004; Tachibana et al. 2004). Oceanic northeasterly cold wind associated with this high makes the Pacific side of northern Japan extremely cold (Ninomiya and Mizuno 1985a,b). This cold wind is commonly referred to as yamase in Japanese. In addition, the Pacific–Japan (PJ) pattern (Nitta 1987) also influences the summer climate of Japan. The PJ pattern is the remote response of pressure anomalies around Japan to convective activity in a western tropical Pacific region through Rossby wave propagation. When the negative PJ pattern occurs, high pressure anomalies form in the western tropical Pacific region and low pressure anomalies form around Japan. The low pressure anomalies signify weakening of the western Pacific subtropical high (WPSH), while the high pressure anomalies are associated with the westward expansion of the WPSH bringing a hot summer to Japan. The negative PJ thus makes Japan cool (e.g., Nitta 1990; Kubota et al. 2016; Xie et al. 2016).

Atmospheric wave trains along the polar jet stream originating in Europe through northeast Eurasia also induce extreme weather in East Asia along with Europe (e.g., Otomi et al. 2013; Kornhuber et al. 2019; Mitchell et al. 2019; Yasunari et al. 2021; Nakamichi et al. 2021; Nakamura and Sato 2022; Rouzi et al. 2022). Otomi et al. (2013) showed that a wave across Eurasia associated with a positive phase of the summer Arctic Oscillation (AO) causes the simultaneous occurrence of a heat wave in Europe and a heat wave in East Asia. Yasunari et al. (2021) pointed out that the circum-Arctic wave (CAW) pattern is responsible for summer heatwaves in many areas in the Northern Hemisphere. Nakamichi et al. (2021) showed that Siberian blocking highs associated with Eurasian wave trains are responsible for heavy rain in Japan along with hot summers in East Asia. Rouzi et al. (2022) showed that the double-jet structure (i.e., the coexistence of the subtropical jet and polar jet) influences the extreme weather in Europe. The double-jet structure tends to occur in the positive phase of summer AO (Tachibana et al. 2010). Thus, the summer AO is one of the most important factors for summer extreme weather.

Extremely cold summers such as those in 1993 and 2003 do not seem to have occurred in Japan in the last decade. On the contrary, extremely hot summers have been more frequent in recent years. The recent repeated occurrence of the hottest summer is attributed to the impact of global warming (e.g., Kamae et al. 2014; Imada et al. 2019). However, no previous studies have considered the question of why cold summers have not occurred. Depending on atmospheric circulation
patterns, cold summers may appear even in an era of global warming. Thus, it should not be concluded that cold summers will never again occur due to global warming without considering the tendencies of atmospheric circulation and ocean temperatures around Japan. Japanese rice cultivation has grown increasingly more tolerant of cold summers. The question now is, should we end efforts to improve cold tolerance and focus solely on improving tolerance to heat? Or should we continue to improve tolerance to cold? The choice is socioeconomically and agriculturally crucial for climate change adaptation. To move closer to an answer, it is important that we analyze the recent temperature trends in Japan and the shift of large-scale atmospheric circulation patterns.

To meet its objectives, this paper proceeds in three steps. In the first step, we show that cold summers have not occurred in recent years in northern Japan by establishing the air temperature tendency. In the second step, we show the regime shifts of large-scale atmospheric circulations and sea surface temperatures (SSTs) around northeast Eurasia and the North Pacific Ocean in association with the lack of cold summers. We further show that the regime shift of the summer AO is responsible for the absence of cold summers, while the influence of the tropics and the local Okhotsk high is irrelevant. In the final step, we examine the reasons why cold summers have not recently occurred. Based on the findings, the possibility of an extremely cold summer in the future is discussed.

The focus of this paper is on northern Japan, a main rice production region that has occasionally suffered from rice crop failures caused by extremely cold summers. This area is adjacent to the cold Oyashio and the cold Okhotsk Sea. The month of July was chosen because of its critical role in determining the rice crop yield for the year.

2. Data and methods

a. Analysis procedure and hypotheses

We then formulated the following three hypotheses regarding the reasons for the recent absence of cold summers based on previous studies: 1) The Okhotsk high has not developed in recent summers, 2) the negative PJ pattern has not occurred in recent summers, and 3) SSTs around Japan have become warmer. To test these hypotheses, we compared the monthly mean atmospheric and oceanic fields after 2009 with those before 2009 by composite analysis, paying particular attention to the Okhotsk high, the PJ pattern, and the SST. Based on the results of the composite analysis, several indices were defined to characterize cold summers and recent atmospheric and oceanic fields, and to organize the recent annual conditions. Finally, the results were synthesized in order to establish the reasons why cold summers have not occurred and assess the likelihood of unusually cold summers occurring in the future.

b. Data and methods

The study uses monthly mean air temperature from the JMA. Data from 40 stations in northern Japan for July over 65 years (1958–2022) were collected (Fig. 1b). We defined the climatological value as the 65-yr average for each station. Standardized monthly mean temperature anomalies from the climatological values in the individual years were prepared for each of the 40 stations. We then defined the 40-station-averaged temperature anomalies as northern Japan air temperature anomalies. The air temperature index in northern Japan is shown in Fig. 2. Any year in which the value was less than $-0.5\sigma$ is defined as a “cold summer.” The period extending from the last cold summer to 2022 is defined as “recent summers,” among which, by definition, there were no cold summers.

Composite analyses of atmospheric and oceanic fields were performed for the cold and recent summers. Monthly and daily atmospheric field values are from the Japanese 55-year Reanalysis (JRA-55) with a spatial resolution of 1.25° × 1.25° (Kobayashi et al. 2015; Harada et al. 2016). Monthly mean SST data are from the Hadley Centre Sea Ice and Sea Surface Temperature database (HadISST) with a spatial resolution of 1° × 1° (Rayner et al. 2003). To compare the atmospheric and oceanic fields for cold summers with those of other years, we used the mean field values for the noncold summers and applied Student’s t test to quantify the statistical significance of the deviations from the mean. Similarly, the mean field values for years other than recent summers were used to compare the recent summers with other years, with Student’s t test again being applied. If the significance level was less than 10%, the null hypothesis was rejected.

The results of the composite analysis were used to prepare six indices for regions where the deviations from the mean for years other than the selected years were large. The six indices include the following: 1) The Okhotsk high index (OH index), the standardized area-averaged monthly mean sea level pressure (SLP) of latitudes 48.75°–52.5°N and longitudes 145°–148.75°E, which covers the southern part of the Okhotsk Sea. The area showing
this index will be shown in the subsequent figures. When the value exceeds 0.25σ, we regard the year as an active Okhotsk high year. Negative values, that is, an inactive Okhotsk high, are expected in recent summers. 2) The index of the subtropical high around Japan (SuHJp index), a standardized area-averaged monthly mean SLP of latitudes 33.75°–36.25°N and longitudes 140°–150°E. This index represents the northwestward expansion of the WPSH. Positive values are expected in recent summers. This index also represents the northern portion of the PJ pattern. 3) The western tropical Pacific index (TrPa index), the standardized area-averaged monthly mean SLP of latitudes 22.5°–25°N and longitudes 52°–62°E. This index represents the southern portion of the PJ pattern. Whether the PJ pattern occurs is verified from both the SuHJp and the TrPa indices. We regard the conditions satisfying both the positive TrPa (more than 0.25σ) and negative SuHJp (under −0.25σ) as a typical negative PJ, which tends to make Japan cold. The negative TrPa index and the positive SuHJp index are expected in the recent summers because the conditions satisfying both the negative TrPa (under −0.25σ) and positive SuHJp (more than 0.25σ) are a typical positive PJ pattern accompanying hot summers. 4) The Oyashio SST index, the standardized area-averaged monthly mean SST off the coast of Japan, which coincided with a decadal-scale oscillation in temperature, highlights the differences between the former and recent summers. Before 2010, cold summers occasionally occurred. In addition to 1993 and 2003, low temperatures were frequently recorded in the 1980s (e.g., Ninomiya and Mizuno 1985b; Kanno 2004). In all, 15 years (1964, 1965, 1966, 1974, 1979, 1980, 1982, 1983, 1986, 1988, 1993, 2003, 2005, 2007, and 2009) were identified as cold summers in which the temperature anomalies were below −0.5σ. The average temperature in cold summers was 18.4°C, which is 1.8°C lower than the climatological value. In northern Japan, even slightly lower temperatures affect rice cultivation. The lower threshold temperature at which spikelet sterility begins to increase is about 20°C (e.g., Shimono et al. 2005, 2007). The average temperatures of the cold summers were below the lower threshold temperatures, indicating that we were able to identify the years in which rice cultivation was affected. The mean temperature anomaly in the recent summers is 0.94σ, as compared to −0.23σ before 2009. According to our t test result, the difference in means between the two periods is statistically significant at the 1% level.

b. Comparison of atmospheric and oceanic fields between cold summers and recent summers

A comparison of atmospheric and oceanic fields between cold summers and recent summers provides us with circumstantial conditions for the recent lack of cold summers and the frequent occurrence of abnormally hot summers. To begin, we show horizontal maps of air temperature at the 2 m level for the recent and cold summers. In recent summers, the temperature has been 1.5° to 1.8°C higher than the mean of the other summers, mainly in northern Japan (Fig. 3a). Temperatures on the northeast Eurasian continent are also increasing. In cold summers, the temperature was 1.8°C below the mean for the other summers (Fig. 3b). Specifically, in the past, the climatological value of the 20°C line (green contour) passed approximately 2°N farther south than in recent years (black contour).

SLP anomalies in recent summers show a statistically significant high area in the northwestern North Pacific (Fig. 4a). No significant features are seen in the Okhotsk Sea and the Philippine Sea, although the recent weakening of the Okhotsk high or strengthening of the positive PJ pattern was expected. In contrast, the composite map of cold summers shows that significant high anomalies are seen around the Okhotsk high and the negative PJ pattern (e.g., Tachibana et al. 2004; Kubota et al. 2016). The geopotential height at 250 hPa in recent summers shows that significant high anomalies cover most of the area in the map, where the anomalies are prominent over the Kamchatka

3. Results

a. Consecutive hot summers since 2010

We begin with the average air temperature index in northern Japan (Fig. 2). Based on our definition of a cold summer (i.e., a year below −0.5σ), the most recent cold summer occurred in 2009. For all subsequent years, the temperature anomalies are positive. Thus, warmer than normal summers have persisted for 13 years. Because 10 summers after 2009 exceeded +0.5σ, more than 75% of the recent summers were hot. The average temperature in recent summers was 21.4°C, which is 1.2°C higher than the climatological value of 20.2°C. Prior to 2009, there were no consecutive periods of hot summers comparable to those after 2010. Consequently, we can confirm that the period of recent summers (as defined in this paper) is characterized by an abnormal succession of consecutive hot summers. In addition, we can confirm that this recent high temperature is not a simple interdecadal variation. Focusing on the 11-yr running mean shown by the black line, the recent amplitude overwhelms the decadal variations. The continuous increase in temperature since 2010, which coincided with a decadal-scale oscillation in temperature, highlights the differences between the former and recent years.
Peninsula and the northeast North Pacific Ocean (Fig. 5a). Northward meandering of the westerlies is also seen over northeast Eurasia. In cold summers, large negative anomalies are centered in the northern part of Japan (Fig. 5b). The large negative anomalies signify that the southward meandering of the jet stream reaches Japan, over which the westerlies strengthen.

Next, we show latitude–height cross sections covering Japan and the Kamchatka Peninsula, where significant changes were observed in recent summers. Figure 6 displays the vertical structure of the geopotential height and westerly wind fields averaged over longitudes 135°–165°E. In recent summers, large positive anomalies, namely high pressure anomalies, have been seen over the northern Okhotsk and Kamchatka regions in the upper troposphere, the ridge of which extends downward to the middle troposphere. The positive ridge turns to the south in the lower troposphere, and finally touches ground level at about 30°–45°N, where Japan is located. Thus, the vertical structure has a baroclinic structure with a north–south tilt between the middle and lower troposphere. The positive SLP anomalies near Japan seen in Fig. 4 and positive anomalies centered over Kamchatka in the upper troposphere shown in Fig. 5 are thus identical. Two jet streams, that is, a double-jet structure, are clearly seen to the south and north from the location of large high anomalies in the upper troposphere. The subtropical jet stream is weaker than in the other summers because the center of the positive geopotential height anomalies is located north of the subtropical jet. The surface westerly wind speed is almost zero at about 40°N. Meanwhile, the vertical structure in cold summers is opposite to that in recent summers without a distinct polar jet. The signature of anticyclonic anomalies can be seen near the surface at 50°N and higher, corresponding to the surface Okhotsk high. In both the hot and cold summers, a north–south-tilted structure is observed in this region. The tilting structure is similar to the results of Kawasaki et al. (2021), which showed that a north–south-tilted structure is related to the cold influence of the Okhotsk Sea.

SSTs in recent summers show warm anomalies around Japan, especially over the region of the cold Oyashio (Fig. 7a), implying the recent weakening of this current (e.g., Miyama et al. 2021). Most areas in the Okhotsk Sea do not have significant features. In the cold summers, in contrast, significant cold anomalies surrounded Japan and the cold signature extended to the central North Pacific (Fig. 7b).
c. Year-to-year variations representing summer climatic characteristics

None of the maps produced from the composite analyses of recent summers showed signatures for the specific characteristics of a cold summer, namely the Okhotsk high, a negative PJ pattern, a southward meandering of the jet stream, and cold SSTs around Japan. Some were opposite to those for cold summers, notably the SSTs and the southward jet meandering. However, the composite analysis alone does not guarantee that the atmospheric and oceanic features characterizing cold summers have been absent in any recent summers. Here we examine the time series of the atmospheric and oceanic indices that represent a cold summer.

Figure 8a shows the year-to-year variation of the OH index. Eight summers after 2009 exceeded 10.25, indicating that, in many recent summers, the Okhotsk high was still active. Thus, we cannot conclude that the weakening of the Okhotsk high is the cause of the lack of cold summers in recent years. In contrast, in former years, extremely large positive values are seen in 1993 and 2003, which are famously known to have been disastrously cold summers (e.g., Tachibana et al. 2004).

The red curve in Fig. 8b shows the SuHJp index; the green bars show the TrPa index. In 2013 and 2022, a typical negative PJ pattern emerged, with negative SuHJp and positive TrPa exceeding 60.25. These years are marked in blue. The years of positive PJ, with positive values on the red curve and negative values indicated by the green bars, were 2011, 2014, 2015, 2018, 2019, and 2021. However, the values for 2011, 2014, and 2019 were quite small and did not exceed ±0.25σ in either index. Thus, typical positive PJ years occurred only three times (2015, 2018, and 2021; marked in red). Because the positive PJ pattern is caused by strong convective activity in the tropics, we counted the numbers of positive and negative TrPa index values (green bars) in recent summers and found that occurrences of the typical positive and negative values that exceeded ±0.25σ were almost the same in recent summers. In other words, the tropics have the potential to produce negative PJ patterns even in recent summers. Conversely, focusing on the SuHJp index (red curve), we can confirm that the value is positive in most recent summers. This suggests that the contribution of the PJ pattern, which is the north–south dipole pattern that appears as the midlatitude response to convective activity in the tropics, may have been smaller in recent summers.

We next discuss the Oyashio SST index. The index has shown positive anomalies for most recent years except for 2015 and 2018 (Fig. 8c). This indicates that the oceanic characteristics seen in cold summers have appeared very infrequently in recent summers. It is also interesting to note that since the 1990s, the frequency of years with positive anomalies has increased and the frequency of years with extremely negative anomalies has decreased.

Figure 8d shows the JetM index. This index has been positive in recent summers except for 2014 and 2020. Thus, the polar jet stream has not meandered southward in most recent summers.
summers. Rather, recent large positive signatures indicating northward jet meandering have occurred nearly every year. These results are summarized in Table 1. The absence of the Okhotsk high, or the positive PJ pattern, is not a primary factor in the recent consecutive anomalously hot summers. The northward jet meandering and the warm SSTs may have contributed to the lack of cold summers.

4. Discussion

a. Hypothesis testing

Here we examine the three hypotheses that were set forth in section 1. The first hypothesis was that SSTs around Japan have become warmer. This hypothesis is supported by the results shown in Figs. 7 and 8c. The SSTs for most recent summers have been positive except for 2015 and 2018. Higher SSTs are associated with a potential for larger latent and sensible heat flux transport to the atmosphere than normal, along with a large upward infrared radiation flux. This can result in the warming of the atmosphere over warm ocean waters. However, it cannot be simply concluded that the high SSTs are the cause of the lack of cold summers, as there is a possibility that the high SSTs are caused by an anomalously hot atmosphere. Because the change in atmospheric circulation is responsible for the temperature anomalies in northern Japan in both recent summers and cold summers, the ocean may not be the leading driver for the recent and cold summers. Perhaps the ocean may act as an amplifier in extreme weather. The oceanic role, which is an interesting issue, is left to future work.
The second hypothesis, that Okhotsk high has not developed in recent summers, is rejected. Except for 2011, 2014, 2015, and 2017, the OH index has remained positive since 2010 (Fig. 8a). Why has the recent active Okhotsk high not made Japan cold? One reason is that the Okhotsk high alone is insufficient to create a cold summer. The presence of the cold-air advection that accompanies the Okhotsk high is possibly needed for a cold summer. Northeasterly wind in northern Japan brings about cold advection since SSTs northeast of Japan are extremely cold compared with the land (see Fig. 1). Because the wind direction depends on an SLP pattern associated with ridges and troughs around the Okhotsk high, the existence of the Okhotsk high alone is not a necessary condition. To create a northeasterly anomaly wind, negative SLP anomalies are needed in the western North Pacific, as shown in Fig. 4b, where the direction of the geostrophic anomaly wind is northeast along the cold Oyashio. A pairing of a northern high and a southern low, as shown in Fig. 4b, is needed. Recent summers do not have the signature of the southern low (see Fig. 4a); instead, high SLP anomalies extend to the southern part of Japan. In addition, if the threshold value of OH index is set to 1.0, only in 2016, the Okhotsk high strongly developed in recent summers. The lack of an extremely strong Okhotsk high is another reason for the lack of a cold summer.

The third hypothesis was the lack of a negative PJ pattern. Except for 2013 and 2022, the results support this hypothesis (see Fig. 8b). Interestingly, the decrease in negative PJ is not due to the phase shift of the PJ pattern; that is, the number of typical positive PJ patterns has not increased in recent years. This signifies that the response of the midlatitude atmosphere to the tropics has modulated in recent summers. We emphasize that the recent frequent occurrence of anticyclonic anomalies over Japan, which is independent of the PJ pattern, prevents anomalously cold northeasterly wind, even when the Okhotsk high is present.

b. Recent climatic regime shift to explain the absence of cold summers

Explaining the reason why the anticyclonic anomalies tend to occur around Japan in recent summers suggests the cause of the lack of cold summers. One reason is the recent frequent occurrence of the north–south vertically tilting anticyclonic anomalies from Kamchatka in the upper troposphere to Japan in the lower troposphere (see Fig. 6a). We further examine whether atmospheric patterns in the hot summers of former years are similar to those of recent summers (Fig. 9). Since there is no significant signature over the Kamchatka Peninsula, as shown in Fig. 5, the northward jet meandering seen in Fig. 5 did not occur in the former hot summers. The time series of the standardized area-averaged geopotential height anomalies over the Kamchatka Peninsula, namely the KamB index, shows that only two of the hot summers in the former years (1961 and 2000) had significantly positive anomalies over Kamchatka. In contrast, most of the hot summers in the former years were accompanied by negative anomalies (Fig. 10a). The same analysis was performed for the period 1994–2003, which was a period of sustained warm summers in the former years, but no similar characteristics to those of recent summers were found (figures not shown). The value in the recent summers has tended to be positive and greater than +1.0σ. The KamB or the JetM index is positive in almost all years, at least for one of these indices (Table 1). The slight difference between the KamB and the JetM indices can

![Fig. 9. Composites of geopotential height (in meters) at 250 hPa for hot summers in earlier years. From Fig. 2, the hot summers before 2009 are 1961, 1977, 1978, 1984, 1994, 1995, 1997, 1999, 2000, and 2004, in which the index exceeds +0.5σ. Color shading indicates deviations from the climatology of values that are statistically significant at the 10% level (or less) according to the applied t test.](image-url)
be interpreted as a slight shift in the ridge of the polar jet because they are located close to each other. Thus, both indices can be interpreted as representing the northward meandering of the jet. There are no extreme negative years below $-1.0\sigma$ for either index. Therefore, upper atmospheric circulation patterns centered over the Kamchatka Peninsula have changed more anticyclonically in recent summers. This circulation shift is also seen in the summertime AO index defined by Ogi et al. (2004b) (Fig. 10b), where large positive anomalies are seen in recent summers. Moderate positive values are seen in 2010, 2018, and 2021, when record-breaking hot summers occurred in many areas in the midlatitudes in the Northern Hemisphere, including Japan (e.g., Otomi et al. 2013; Imada et al. 2019). Thus, the recent circulation shift seen over the Kamchatka region is hemispheric. Because the anticyclonic positive anomaly corresponds to the northward meandering of the polar jet stream, recent changes in polar jet behavior associated with the AO are responsible for the frequent occurrence of the recent hot summers. A large northward meandering of the polar jet can sometimes develop into a blocking high. Previous studies showed that the large meandering associated with the blocking high in the Okhotsk area is related to the positive phase of the summertime AO, which is characterized by polar jet stream meandering in the Northern Hemisphere (Tachibana et al. 2010; Otomi et al. 2013). A double-jet structure, such as that shown in Fig. 6a, is favorable for the blocking high because of the weakening of the northward potential vorticity gradient (Tachibana et al. 2010). As can be seen from many of the time series graphs shown here, a climate regime shift occurred in high latitudes in the Northern Hemisphere, which is responsible for the lack of the recent cold summers.

The north–south-tilted anticyclone can be interpreted as being formed by a thermal contrast between the warm northeast Eurasian continent and the cool northern North Pacific and the Okhotsk Sea. In summer, air temperatures over the continent are climatologically warmer than those over the ocean (see Fig. 1). The east–west sea–land heat contrast forms a north–south baroclinic structure. Because the west side is warmer than the east, an anticyclone with a baroclinic structure must tilt southward from the upper to the lower troposphere. This southward-tilting structure resembles a typical baroclinic structure with an eastward tilt of the anticyclonic axis associated with the warm south and cold north. Correspondingly, the thermal winds must be northerly, with stronger southerly winds in the lower troposphere and weaker meridional winds in the middle and upper troposphere. This may result in increased warm-air advection from the south in the surface air. This is confirmed by the map of horizontal temperature advection in recent summers (Fig. 11a). Anomalous warm advection is seen around Japan. In recent summers, the southerly winds have extended to about 50°N. It can be
confirmed from Fig. 4a, in which a northward shift of the WPSH is not clearly seen. If it were, positive anomalies in the area north of the WPSH would be seen. On the other hand, in the former years, strong southerly winds were seen in association with the WPSH, but they were limited to about 40°N at most (Fig. 11b). Thus, the recent enhancement of warm-air advection and southerly winds over northern Japan can be attributed to a north–south-tilting anticyclone rather than the strengthening of the WPSH. These two anticyclones probably overlap over northern Japan in the recent summers. Perhaps, recent anomalous warm SSTs in the Oyashio region (Fig. 7) strengthen the warm advection in comparison with previous summers.

c. Possibility of cold summers in the future

We have shown that cold summers have not occurred since 2010 in northern Japan, resulting in a warm summer streak of 13 years. A schematic of the reasons for the absence of cold summers is provided in Fig. 12. Based on the abovementioned recent climatic regime shifts, what is the possibility of an abnormally cold summer in the future?

The north–south-tilting anticyclone shown in Fig. 6a and illustrated in Fig. 12 tends to appear under the condition of the land–sea thermal contrast between a hot western continent and eastern cool oceans. In recent summers, the west–east land–sea thermal contrast has been increasing (Fig. 13), owing to the heat capacity difference between the continent and the seas. In addition, the Okhotsk Sea is covered by sea ice until June. The existence of sea ice further makes the sea colder than the surrounding continental areas (Kawasaki et al. 2021). The heat contrast has thus increased in recent summers, so

the north–south-tilting anticyclone has tended to occur in northeast Eurasia (Figs. 10a and 13). This large thermal contrast will continue even in the future.

The upper-tropospheric blocking high that occurs in northeast Eurasia is associated with a double-jet structure. A double-jet structure tends to occur in a period of the positive AO (Tachibana et al. 2010; Otomi et al. 2013). The atmosphere between the two jet streams tends to form blocking highs due to the weakening of the northward potential vorticity
gradient (Tachibana et al. 2010). Typical characteristics of the atmospheric fields when the positive and the negative AO are shown in Fig. 14. When the AO is positive, zonal-mean zonal winds have a double-jet structure, with low pressure anomalies in the Arctic and high pressure anomalies in the midlatitudes as was shown in Ogi et al. (2004b) (Figs. 14b,e). Conversely, when the AO is negative, a single jet structure is formed and the pressure deviations are opposite to those of the positive AO (Figs. 14c,f).

Recent global atmospheric patterns are similar to those with the positive AO (Figs. 14a,d). This is also confirmed in Europe (Rousi et al. 2022), where the double-jet structure amplifies recent extremely hot summers in Europe. Because the blocking high in northeast Eurasia tends to occur in the positive summer AO. Because the blocking high is an upper-tropospheric source of the north–south-tilting anticyclone, hot summers tend to occur in northeast Eurasia in recent years. Such AO-related extremes tend to occur not only in northeast Eurasia but also in other regions in the mid-latitudes. Because the change is on the scale of the Northern Hemisphere, it is reasonable to conclude that the climate regime shifts that affect the climate of the entire northeast Eurasia region have occurred.

The strength of the polar jet stream, which is a northern portion of the double jet, is associated with the degree of thermal contrast between the warm continents and cold Arctic (e.g., Serreze et al. 2001). A southern continental warming speed faster than that of Arctic Ocean warming strengthens the land–sea contrast due to the difference in heat capacity. This contrast strengthens the polar jet stream accompanying the double-jet structure that is favorable for blocking highs (e.g., Serreze et al. 2001). Because this strengthened thermal contrast probably continues in the future, we consider that the positive summer AO tendency also continues in the future. Thus, the increase in positive AO since 2010 could result from a climatic regime shift due to global warming, rather than a coincidence or decadal oscillation. It should be noted that this AO trend is more pronounced in July and August (figures not shown).

Since the north–south-tilting anticyclone occurring in northeast Eurasia is associated with the positive AO, the anticyclone is also expected to occur in the future. The strengthening west–east thermal contrast is also favorable for the north–south-tilting anticyclone. The local west–east thermal contrast between northeastern Eurasia and the Okhotsk Sea will also continue in the future (Toda et al. 2021). In addition, the warming of

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**Fig. 14.** Characteristics of atmospheric fields (a), (d) for recent summers, (b), (e) for positive AO, and (c) for negative AO. From the summer AO index (Fig. 10b), the positive AO summers are 1989, 1996, 2002, 2010, 2012, 2016, 2018, 2021, and 2022, in which the index exceeds $+1.0\sigma$, and the negative AO summers are 1958, 1960, 1965, 1968, 1976, 1977, 1978, 1985, 1987, 1995, 2009, and 2015, in which the index exceeds $-1.0\sigma$. Rows show (a)–(c) composites of geopotential height (in m) at 250 hPa and (d)–(f) composite latitude–height cross sections of zonal-mean zonal winds (unit: m s$^{-1}$) and geopotential height (unit: m). Contours indicate (a)–(c) the mean values for respective mean values and (d)–(f) zonal-mean zonal winds. In (a)–(f) color shading indicates that deviations from the mean for the years other than the selected years are statistically significant at the 10% level according to the applied t test.
the cold Oyashio will weaken cold-air advection even if northerly winds blow temporarily. For these reasons, it is highly unlikely that an extremely cold summer will occur again.

5. Conclusions

This study showed that cold summers have not occurred since 2010 in northern Japan, resulting in a warm summer streak of 13 years. The reasons for the absence of disastrously cold summers were discussed by using atmospheric data from the tropics to subarctic regions along with the SSTs around Japan. We conclude that the direct reason for this absence is the recent northward polar jet meandering over northeast Eurasia in the upper troposphere (Fig. 12). The north–south tilting of the anticyclone is accounted for by the east–west surface temperature contrast between the warm continent and the cold Oyashio region in the North Pacific. The anticyclonic anomaly in the upper troposphere corresponds to the weakening of the subtropical jet stream, resulting in a double-jet structure. This upper atmospheric circulation shift is accompanied by the recent tendency of the summer AO phase shift from negative to positive. A hemispherewide climate regime shift associated with the positive phase shift of the AO makes the occurrence of cold summers highly unlikely as long as this new regime persists. The positive phase shift is associated with strengthened thermal contrast between the warm continents and cold Arctic. Positive summer AO and the associated north–south-tilting anticyclone will tend to occur in the future because of the strengthening of the land–sea thermal contrast due to global warming. We can therefore conclude that it is highly unlikely that an extremely cold summer will occur again. Moving forward, it will be important to prove the link between this regime shift and global warming. The frequent occurrence of extreme weather events in other regions, such as Europe, and the prospects for their future occurrence may also be explained by the regime shift in the AO. The relationship of high-latitude atmospheric circulation and Arctic warming noted in many studies could be integrated with the present study (e.g., Coumou et al. 2015, 2018; Sato and Nakamura 2019; Nakamura and Sato 2022).

The possibility of the absence of the Okhotsk high was not supported since it appeared even in recent summers. The influence of the western tropical Pacific atmospheric convection was also not supported because both positive and negative PJ patterns have also appeared in recent summers. A probabilistic study of the nonoccurrence of cold summers by comparing the mechanisms presented in this study with random atmospheric internal variability and the tropical influence should be the next study.

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Data availability statement. The datasets used herein are publicly available. The monthly mean air temperature data at the stations are available from the JMA (https://www.data.jma.go.jp/obd/stats/data/en/smp/). The JRA-55 data are available from the NCAR Research Data Archive (https://rda.ucar.edu/datasets/ds628.1/). HadISST data are available from the Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadisst). The AO (SV NAM) index dataset is kept up to date and available from Mie University (https://atm.bio.mie-u.ac.jp/aoindex.htm).

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