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Strongly Negative Correlation between Monthly Mean Temperatures in April and August since 1998 in Northern Japan

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Abstract

Monthly mean temperatures for April and August have been strongly and negatively correlated from 1998 to 2011 in northern Japan. When monthly mean temperatures in April were either significantly below or significantly above normal, the temperatures in the following August had the opposite anomalies. We attribute this seasonal behavior of temperatures to a displacement of the core of upper-level westerly winds. When monthly mean temperature was higher than normal in August, the subtropical jet stream had been strengthened in April and a continental polar air mass affected northern Japan in April. In August of that year, if a jet located north of Japan moved further north, Japan was covered by a maritime tropical air mass, and a maritime polar air mass rarely affected summer weather in northern Japan. In the opposite case, when temperatures were cool in August and warm in April, we inferred that the jet had been weak and the continental polar air mass did not move south and affect northern Japan in April; thus, in August the jet shifted southward and the maritime polar air mass could affect summer weather. An empirical orthogonal function analysis of the 200-hPa height field revealed that two principal component modes were associated with the anomalous temperatures in these two months. On the basis of these results, we identify these modes as the cause of upper level westerly wind variations on the northern hemispheric scale. Based on a singular value decomposition analysis of the 200-hPa height field and the sea surface temperature, the year 1998 marked one of the several pronounced climatic shifts of the last century.

Keywords northern Japan; climatic shift; temperature; ENSO; AO

1. Introduction

In Hokkaido and Tohoku, northern Japan (Fig. 1), agriculture is the main economic activity and climate variations in the warm season greatly impact the local economy. During normal summers, a frontal zone remains north of Hokkaido, and a maritime tropical (mT) air mass brings hot, humid weather. Rice grows well and yields a good quality crop in northern Japan's summer season climate—large diurnal temperature variations under normal summer conditions are especially good for the quality of rice. Occasionally, though, the Bai-u front settles over central Japan in summer, a maritime polar (mP) air mass and the cold northeasterly *Yamase* wind create cool summer conditions over northern Japan (Kudoh 1984; Ninomiya and Mizuno 1985), and rice suffers damage from cool weather. In recent years, mean summer temperatures in northern Japan have exhibited cyclical variations (Kurihara 2003; Kanno 2004) following a global-scale climatic regime shift that occurred in the late 1970s (Nitta and Yamada 1989; Kawasaki 2010). Since then, summer weather has oscillated between cool and hot; a good example is the cool summer in 1993 and the following hot summer in 1994 (Kawamura et al. 1998), when extremely hot weather frequently damaged the rice crop. The seasonal weather in 2010 was unusual; the spring was very cold, which led farmers to fear that a continuously cool summer would follow, but in fact the summer was quite hot, and much of the rice crop was damaged by

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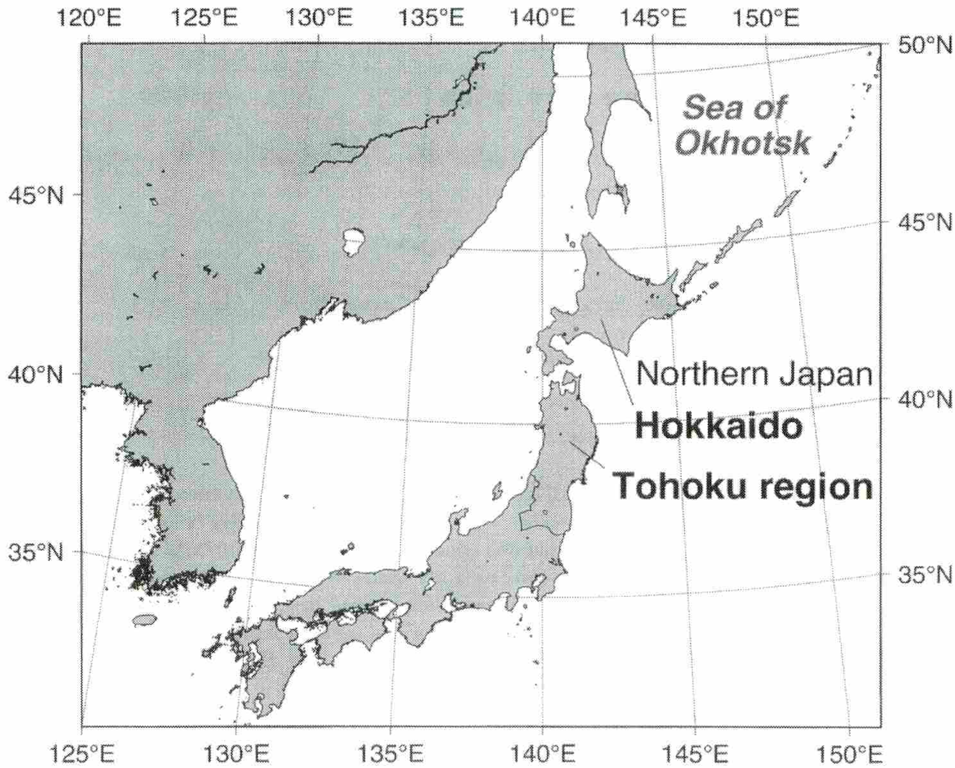

Fig. 1. Map of northern Japan, which is composed of the island of Hokkaido plus the Tohoku region.

extreme heat.

In previous studies, summer weather in Japan was explained by reference to the global atmospheric circulation. Various authors proposed hemispheric teleconnections that influence summer weather in Japan. Wakabayashi and Kawamura (2004) and Ogasawara and Kawamura (2007; 2008) reported that cool summers in northern Japan are influenced by components of both Pacific–Japan (PJ) and Europe–Japan (EJ) teleconnection patterns, and indicated that summer weather in northern Japan is primarily affected by large-scale dynamics such as Rossby wave propagation and air–mass migration from the north and the south. The relationships between anomalies in two distinct seasons, as in 2010, deserve to be understood in order to fully explain the recent frequent occurrences of anomalous weather. Spring weather is important for crops because planting and flowering typically occur in that season, and of course the summer is fruiting season, and so the covariation of weather conditions in spring and summer of the same year is an important research topic in agriculture as well as in climatology.

To advance research on the seasonal climatology of northern Japan and on the stabilization of agricultural production in the region, in this study, we examined the relationships between anomalies in different seasons of the same year, and whether statistical relationships exist between such anomalies and larger-scale atmospheric fields. We selected northern Japan for our investigation because crop yields in this region are more sensitive than they are in southern Japan to seasonal and annual climatic anomalies, and because northern Japan is in the climatic location of the frontal zone between mT and mP air masses, and is affected by the different characteristics of these two air masses.

2. Data and methods

For surface air temperature, we used monthly mean values from 39 manned meteorological observation stations having long-term records of the Japan Meteorological Agency (JMA) in Hokkaido and Tohoku. For the climatological temperatures in northern Japan, we used the 30-year means from 1981

Table 1. Correlation coefficients between each possible pair of monthly mean surface temperatures in the last 13 years, from 1999 to 2011, in northern Japan. Shaded boxes indicate statistical significance at the 5% level or better.

	Jan										
Feb	0.51	Feb									
Mar	0.14	0.44	Mar								
Apr	−0.11	0.01	0.53	Apr							
May	0.28	0.20	0.27	0.22	May						
Jun	0.41	0.08	−0.59	−0.51	−0.27	Jun					
Jul	−0.06	−0.06	−0.12	−0.19	−0.07	0.17	Jul				
Aug	0.21	−0.01	−0.51	−0.83	−0.41	0.56	0.42	Aug			
Sep	0.21	0.14	−0.34	−0.57	−0.45	0.62	0.46	0.84	Sep		
Oct	0.02	−0.10	0.13	−0.12	−0.69	0.25	0.29	0.33	0.39	Oct	
Nov	−0.25	−0.02	−0.43	−0.44	−0.05	0.45	−0.03	0.19	0.13	0.01	Nov
Dec	0.16	0.17	0.17	−0.33	0.15	0.20	−0.16	0.11	0.19	0.00	0.45

to 2010. For the upper-air standard pressure level analyses, we used the Japan 25-year Reanalysis (JRA-25) data (Onogi et al. 2007). However, in the JRA-25 data, the climatological normal temperatures are assumed to be the 26-year means from 1979 to 2004. The SST data used in this study were the Extended Reconstructed Sea Surface Temperature (ERSST.v3b) by NOAA (Xue et al. 2003; Smith et al. 2008). The Interactive Tool for Analysis of the Climate System (ITACS)-version 4 from JMA was used for the Singular Value Decomposition (SVD) analysis.

First, we calculated 13-year running correlations between monthly mean temperatures in northern Japan for each pair of months from 1950 to 2011. We recognize that 13 years might be too short to establish statistical significance, but it is an adequate period for finding decadal scale variations. Furthermore, by limiting our study to this short period we hoped that important relationships between seasons that have emerged only in recent years might be more apparent. We selected target periods after examining the correlations found for each pair of months over the whole period. Then we performed an empirical orthogonal function (EOF) analysis for geopotential height data at 200-hPa, and the principal component (PC) fields were correlated with surface temperatures and regressed on upper-level wind. In addition, we did a SVD analysis of 200-hPa height and SST to investigate possible reasons for the strong correlations that we found.

3. Results

3.1 Air temperature relationships between months in northern Japan

For the 13 year period from 1999 to 2011 (Table 1), we obtained the strongest correlation coefficient (r = 0.84) for the August–September pair. Since the weather and atmospheric circulation patterns may be similar in these two months and they are part of the same sub-season (late summer), we do not discuss this correlation in this paper. The next strongest correlation coefficient (in absolute value; $r = -0.83$) was between April and August. This correlation was very strong even though these months are in different seasons. Other statistically significant correlations were between March and June, April and September, May and October, June and August, and June and September, but that between April and August was the strongest among the interseasonal correlations.

The time series of the 13-year running correlation coefficients between April and August shows that the coefficients were positive from the 1970s to the 1990s, but they were not significant at the 5% level (Fig. 2). However, shortly after 2000, the coefficients became negative at a statistically significant level, and since 1998 the April and August temperature anomalies have been opposite in variation. Since the temperature correlation for the most recent 13-year period was strongly negative, we focus on the 14-year period from 1998 to 2011 in the following analysis. From 1998 to 2011, except in 2004, whenever April temperatures

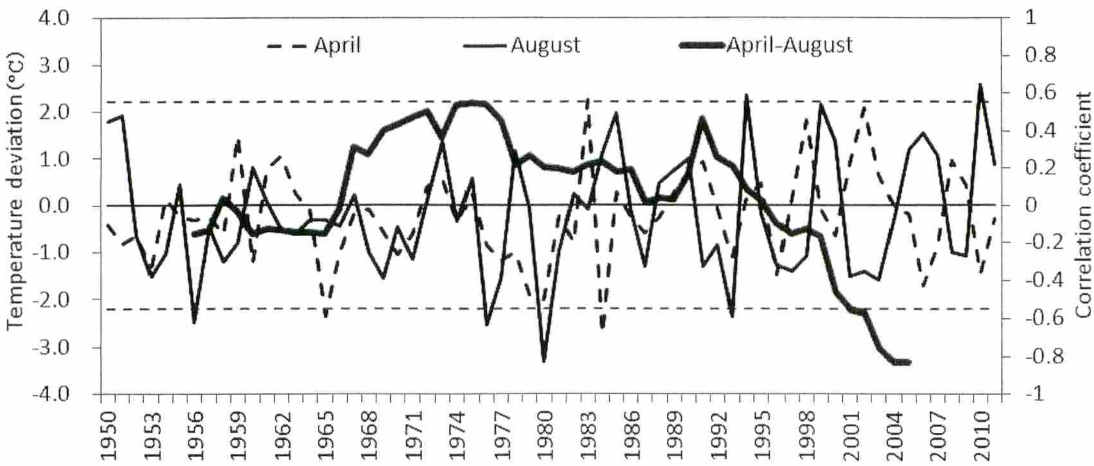

Fig. 2. Time series of the separate monthly mean temperature deviations (left axis) in April and August in northern Japan, and the 13-year running correlation coefficients between these two months (right axis) during 1950–2011. Only those few correlation coefficients greater than 0.55 or less than −0.55 (horizontal dashed lines) were significant at the 5% level.

were significantly cooler than normal, then temperatures in the following August tended to be warmer than normal, and vice versa (Fig. 3). Next, we examined the temperature anomalies in these two months in relation to the larger scale atmospheric circulation.

3.2 *Variations in the wind and temperature fields around Japan*

We examined the upper level wind field variations in relation to surface temperature anomalies in northern Japan from 1998 to 2011. On the 200-hPa *u*-component wind field in August, an area of distinctly positive correlation was located north of Hokkaido, and an area of negative correlation extended from northeastern China to the east of the Japanese islands (Fig. 4). This suggests that, when high temperatures prevail in August, the subtropical jet stream (STJ), which is normally positioned over northern Japan, had moved northward, which allows an mT air mass to cover the Japanese islands, and does not allow an mP air mass to affect summer weather. In contrast, low temperatures in August may indicate that the STJ has moved southward so that the surface frontal zone linked to it remains over Japan and allows an mP air mass to produce the typical cool summer weather pattern. The August 850-hPa temperature field is positively correlated with northern Japan surface temperatures in August (Fig. 5) over an area between the zones of negative and positive correlation of the

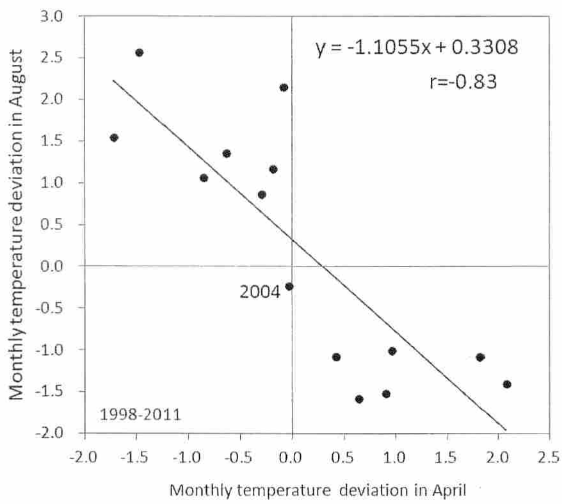

Fig. 3. Scatterplot of the relationship between April and August monthly temperatures in northern Japan from 1998 to 2011.

200-hPa *u*-wind field (see Fig. 4), which supports the preceding supposition.

On the 200-hPa *u*-component wind field in April, the correlation of August surface temperature with the April wind field at 200-hPa (Fig. 6) had a spatial pattern of correlations opposite to the corresponding

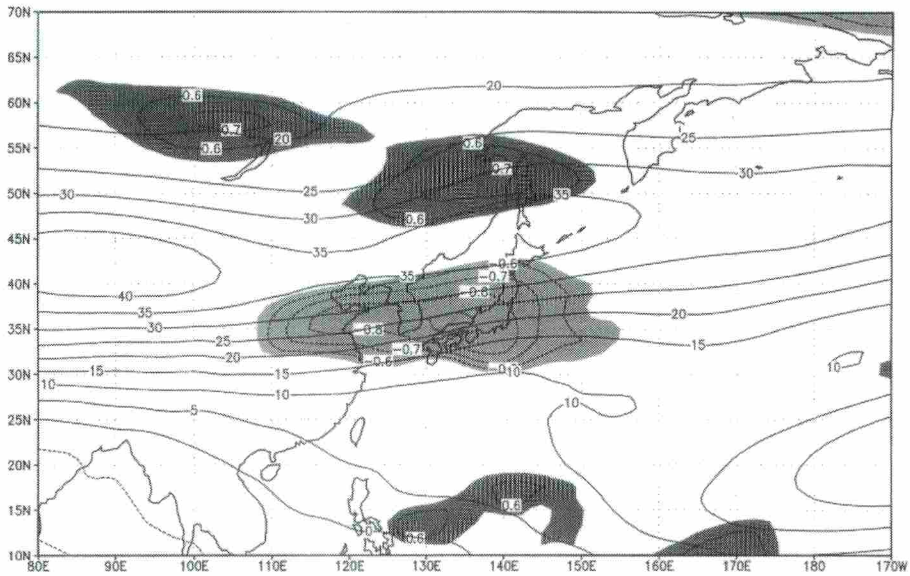

Fig. 4. Correlation (shaded regions) between northern Japan's surface temperature deviations in August and the 200-hPa u-component of wind in the same August from 1998 to 2011, and the normal u-component of wind in August (thin solid contours, m s^{-1}). Positive correlations significant at the 5% level are shaded dark gray; negative correlations, light gray.

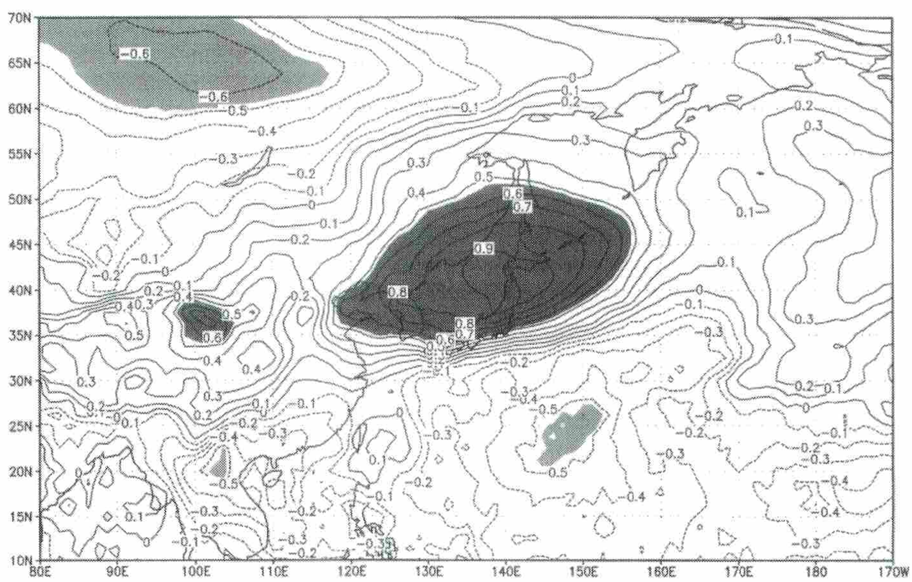

Fig. 5. Correlation between northern Japan surface temperature deviation in August and the 850-hPa air temperature in the same August from 1998 to 2011. Positive correlations significant at the 5% level are shaded dark gray; significant negative correlations, light gray.

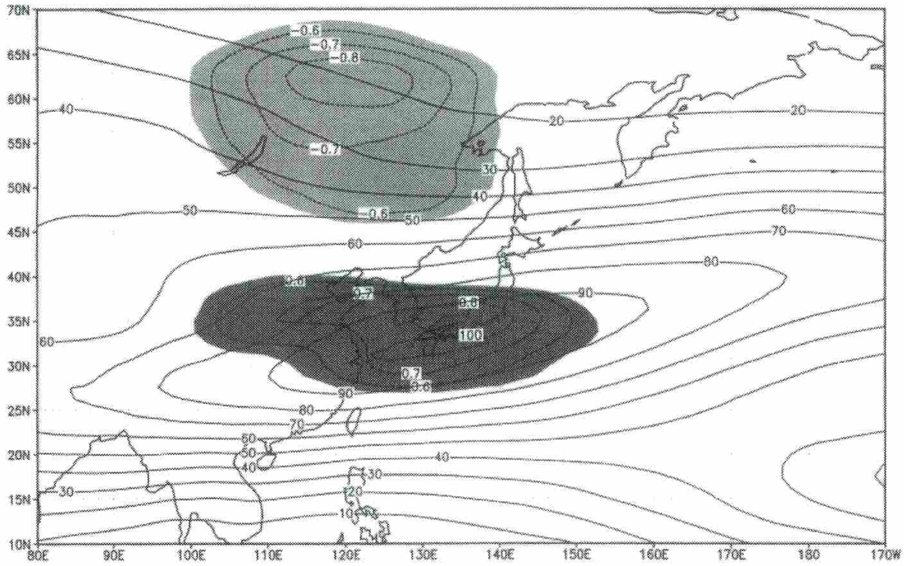

Fig. 6. As in Fig. 4 for northern Japan surface temperature deviation in August, but for the 200-hPa u-component of wind in the preceding April, from 1998 to 2011.

spatial pattern for the August wind field (Fig. 4): an area of distinctly positive correlation with August surface temperatures in northern Japan extended from eastern China to east of Japan, and corresponded to the axis of the STJ in April. High temperatures in August may thus be associated with a strong STJ in April. This pattern may be due to the reinforcement of the westerly winds by thermal winds, which together with an increase in the meridional temperature gradient, allows a southward movement of a continental polar (cP) air mass from higher latitudes in northern Japan. The area of negative correlation around eastern Siberia may also reflect the southward displacement of strong upper level westerly winds. A region of negative correlation between the 850-hPa air temperature in April with surface temperature anomalies the following August was widespread around Japan and northeastern China (Fig. 7), which supports the relationship between upper level westerly winds and a cP air-mass movement. Consequently, the weather in the April preceding a hot August in northern Japan tends to be cold as a result of a strong STJ and the associated southward intrusion of a cold air mass near the surface. The opposite case, cool temperatures in August preceded by warm temperatures in April, might result from a weakened STJ in April and consequently less frequent southward displacements of a cold air mass.

We examined the above relationships on a large scale: the correlations between surface temperature deviations in August in northern Japan and the 200-hPa geopotential height in the preceding April were statistically significant in some areas, despite the four month separation (Fig. 8). Around eastern China and the Korean Peninsula, there was a large area of negative correlation, but the correlation was distinctly positive in north-central Siberia and the Arctic coast. We also observed negative correlations around the Aleutian Peninsula, and positive correlations around southern Europe. The widespread distributions of these significant correlations in the northern hemisphere possibly indicate that the correlation between April and August temperatures in northern Japan is not a local scale but a hemispheric scale phenomenon. For example, it might be affected by the large-scale variations of upper-level westerly wind and Rossby wave propagations. Thus, in the following section we also consider the upper level height and wind fields over a wide area.

3.3 *EOF analysis of upper air fields in April and August*

We applied an empirical orthogonal function (EOF) analysis to the April and August monthly mean height fields at 200 hPa from 1979 to 2011. The EOF analyses were performed in the area from 20°N to 70°N latitude and from 0° eastward to 140°W longitude (boxed

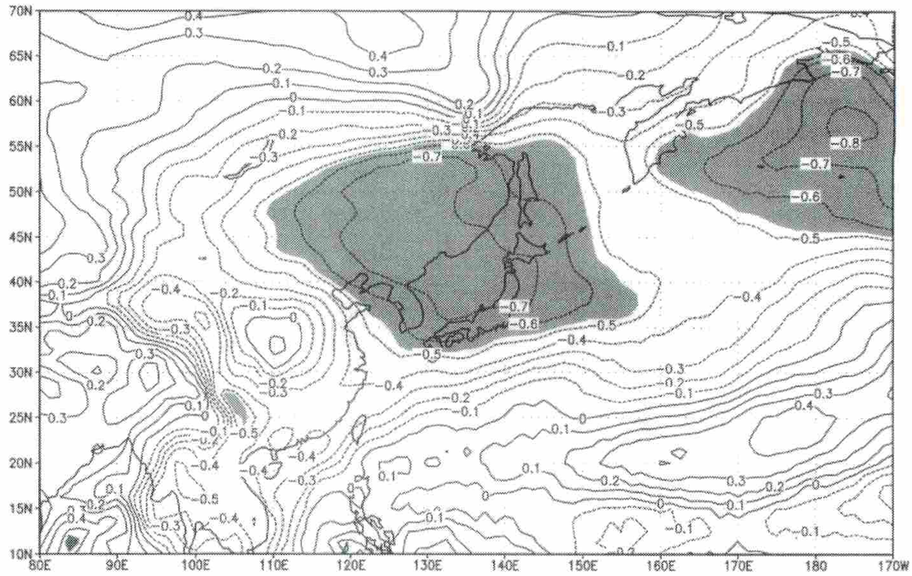

Fig. 7. As in Fig. 5 for northern Japan surface temperature deviation in August, but for the 850-hPa air temperature in the preceding April.

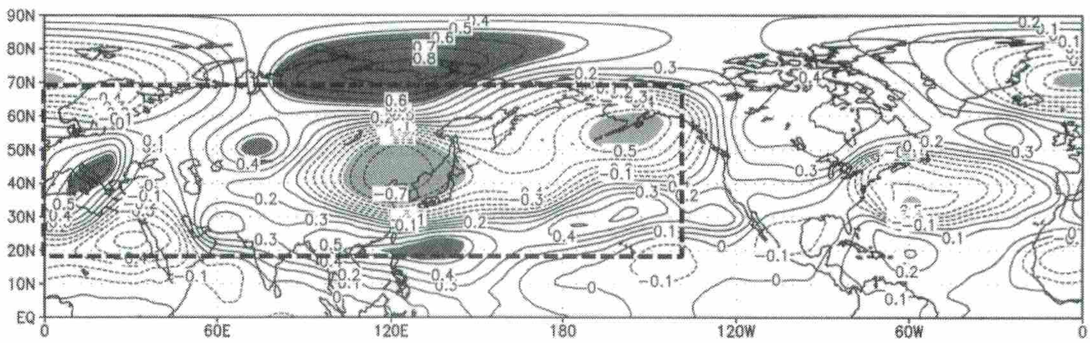

Fig. 8. Correlation between the surface air temperature deviation in August in northern Japan and the northern hemisphere 200-hPa geopotential height in the preceding April, from 1998 to 2011. Positive correlations significant at the 5% level are shaded dark gray; significant negative correlations, light gray. Dashed lines indicate the EOF analyzed area from 20° N to 70°N latitude and from 0° eastward as far as 140°W longitude.

rectangle in Fig. 8) because this area contains the large-scale atmospheric conditions that affect the Japanese summer climate, such as the jet stream variations and their teleconnections. The first five modes explained 68% of the variation in April and 61% in August. First, we calculated the correlations between each PC mode in April and each PC mode in August from 1999 to 2011 (Table 2). The highest correlation in absolute value ($r = -0.78$) was found between principal component 2 (PC2) in April (accounting for 13.9% of the variation) and PC3 in August (13.5%). However, in April PC1, PC3, and PC4 have no statistically significant correlations with August PCs. Only PC5 in April has a significant correlation ($r = 0.60$) with PC4 in August, but because they explain a lower percentage of variation, we did not select the latter pair for further analysis.

On the other hand, some correlation coefficients between the same PCs and monthly mean temperatures also exhibited significantly high values: $r = -0.65$

Table 2. Correlation coefficients between each of the first five principal components (PC) of the EOF analysis of the 200-hPa height field in April (rows) and in August (columns) in the last 13 years, from 1999 to 2011. Numerals in parentheses indicate the percentage (%) of variance explained by each PC. Shaded boxes indicate statistical significance at the 5% level or better.

		August				
		PC1 (15.3)	PC2 (14.6)	PC3 (13.5)	PC4 (9.7)	PC5 (8.5)
April	PC1 (25.2)	0.13	−0.03	0.49	−0.24	−0.11
	PC2 (13.9)	0.21	−0.33	−0.78	−0.08	0.48
	PC3 (11.2)	−0.11	0.53	−0.22	0.42	−0.09
	PC4 (10.8)	0.15	0.43	−0.47	0.23	−0.17
	PC5 (7.0)	−0.12	0.42	0.12	0.60	−0.20

Table 3. Correlation coefficients between each of the first five PCs of the EOF analysis of the height field at 200 hPa, and northern Japan surface temperatures, in April and August in the last 13 years (1999 to 2011). Numerals in parentheses indicate the percentage (%) of variance explained by each principal component. Shaded boxes indicate statistical significance of the correlation was at the 5% level or better.

April		August	
PC ranking	Correlation coef.	PC ranking	Correlation coef.
PC1 (25.2)	−0.65	PC1 (15.3)	0.32
PC2 (13.9)	0.63	PC2 (14.6)	−0.08
PC3 (11.2)	0.14	PC3 (13.5)	0.69
PC4 (10.8)	0.32	PC4 (9.7)	0.33
PC5 (7.0)	−0.01	PC5 (8.5)	−0.49

between PC1 in April and temperatures in April, r = 0.63 between PC2 in April and temperatures in April, and r = 0.69 between PC3 in August and temperatures in August in northern Japan (Table 3). Since the correlation coefficient between PCs in April and northern Japan surface temperatures in April was high, we compared the time series of 13-year running means of the correlations between PCs, and April temperatures (Fig. 9). The time evolution of the correlations between April and August temperatures closely paralleled that of the PC2-temperature correlations in April, although the final value (in 2005) of the PC1-temperature correlations had a higher absolute value than any of the PC2-temperature correlation values did, the correlation between April temperatures and PC1 had consistently high absolute values. However, the time evolution of the correlations did not correspond well with that of the correlation between April and August temperatures (unlike the case of PC2 and April temperature). As a result, we chose PC2 in April and PC3 in August as the two explanatory modes for analyzing possible causes of the negative correlation of April and August temperatures in northern Japan.

Since 2000, fluctuations of PC2 in April and PC3 in August for the 200-hPa height field had opposite signs (Fig. 10). The 13-year running mean of the correlation between PC2 in April and PC3 in August varied in a manner that was similar to the correlation between monthly temperatures in April and August, but the temperature correlation became significant sooner than the correlation of PC2 with PC3 did.

Next, we examined these two important PC modes of the 200-hPa height field in April and August. In April, PC2 exhibited a dipole-like negative-positive pattern in western Russia and eastern China (Fig. 11a).

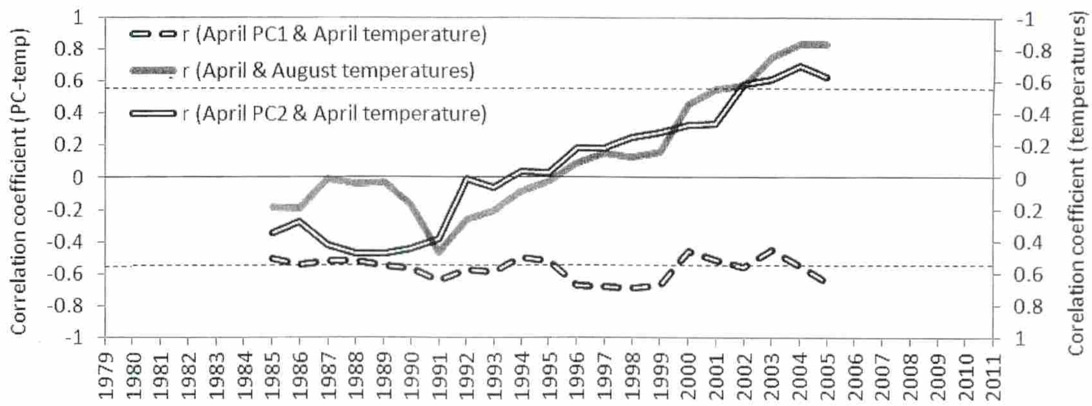

Fig. 9. Time series of three correlations: between PC1 in April and April temperature, PC2 in April and April temperature, and between April and August temperatures. The dashed white line indicates the 13-year running correlation coefficient between PC1 and temperature in April, and the solid white line indicates the 13-year running correlation coefficient between PC2 and temperature in the same month (left axis). The thick gray line is the correlation coefficient between April and August temperatures (right axis; note that the scale is reversed on the right).

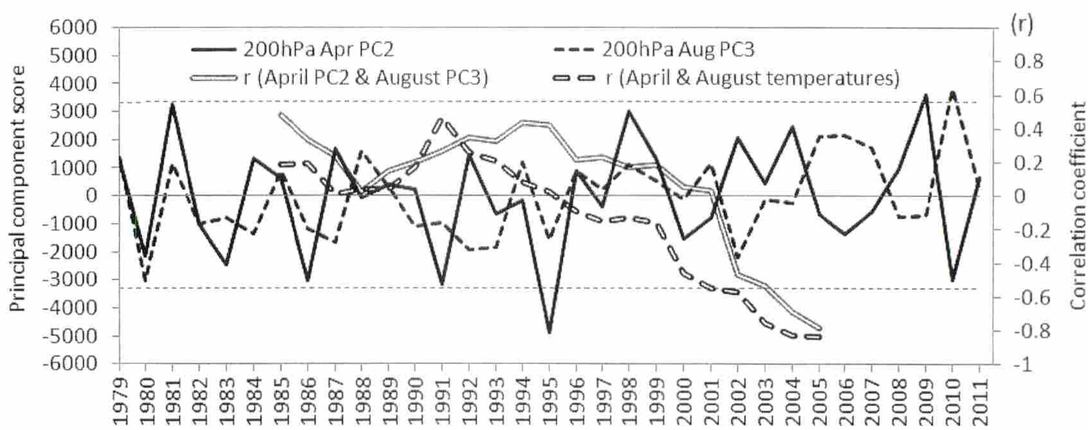

Fig. 10. Time series of PC2 in April (solid black) and PC3 in August (dashed black) at the 200-hPa level (left axis). The solid white line indicates the 13-year running correlation coefficient between PC2 in April and PC3 in August, and the dashed white line indicates the 13-year running correlation coefficient between surface temperatures in April and in August in northern Japan (right axis).

If one includes the positive region located over the Norwegian Sea, the positive–negative–positive pattern resembled a wave train. According to previous investigations by Ogi et al. (2003a, b; 2004), the winter North Atlantic Oscillation (NAO) indeed teleconnects with summer high pressure over the Sea of Okhotsk. Moreover, in the years of solar maximum, spring is still characterized by a seesaw pattern. Therefore, if the positive region over the Norwegian Sea is a trace of the NAO from the prior winter, it is possible that the NAO plays an important role in summer weather in northern Japan.

In August, the PC3 pattern was more complicated, with several positive areas that were widespread (Fig. 11b). Strongly positive regions were located around western Russia, and from the Tibetan plateau across Japan to the north central Pacific. Interestingly, since PC2 in April and PC3 in August have a negative correlation (Table 2), around western Russia the height variations were strong while the signs were the same

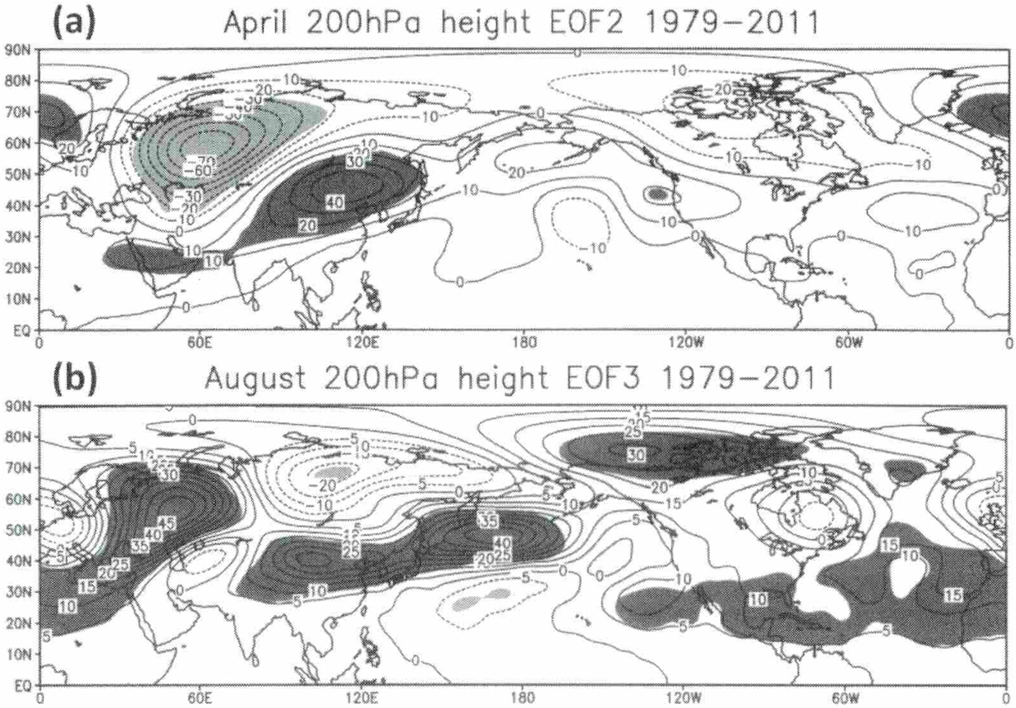

Fig. 11. The two most important principal component (PC) analyses of the 200-hPa height field from 1979 to 2011 in the northern hemisphere: (a) PC2 in April and (b) PC3 in August. The units are m. Positive correlations significant at the 5% level are shaded dark gray; significant negative correlations, light gray.

between PC2 in April and PC3 in August, whereas around Japan the signs were reversed in the same year. The Ogasawara high pressure cell strongly affects summer weather in Japan (e.g. Enomoto et al. 2003). When this cell is linked to the Tibetan high pressure cell, then Japan will have a hot summer, according to Enomoto et al. (2003), Enomoto (2004), Yasunaka and Hanawa (2006), and Nagano et al. (2009). The clear positive signal in August PC3 extending from the Tibetan plateau across northern Japan to the North Pacific Ocean (Fig. 11b) does seem to imply that there was a close relationship between the Tibetan and the Ogasawara high pressure cells. Enomoto et al. (2003) analyzed an Ogasawara high pressure cell around 40°N on the 200-hPa surface, while the positive area on PC3 in August was located northeast of that region, but since these areas partially overlapped, then that positive area might be related to the Ogasawara high pressure cell. Indeed, PC3 may be the mode that best correlated with August mean temperatures in Japan.

Next, we regressed the same two PC modes against the u-component of the wind at the 200-hPa level. In April, a wave-train-like pattern can be followed southeast from the Kara Sea (negative), through central Eurasia (positive), to eastern China and Japan (negative) (Fig. 12a). Each of the three parts of this negative–positive–negative wave pattern extended from southwest to northeast, and at least in the area of Japan, the negative correlation area near Japan overlapped the core of the climatological STJ. So, this prominent wave-like pattern was tied to the variations of the STJ around Japan, which suggests that the temperature anomalies in April in northern Japan might be produced by continental-scale dynamical variations like Rossby wave propagation and its corresponding teleconnections.

In August, the negative belt extended from the southern Tibetan Plateau across Japan to the Pacific Ocean (Fig. 12b); this deviation in the u-component apparently reflected fluctuations of the STJ around Japan and should have affected temperature variations there. Such a pattern would be consistent with a weaker jet from southern Tibet across Japan to the Pacific Ocean. In addition, there is a north–south

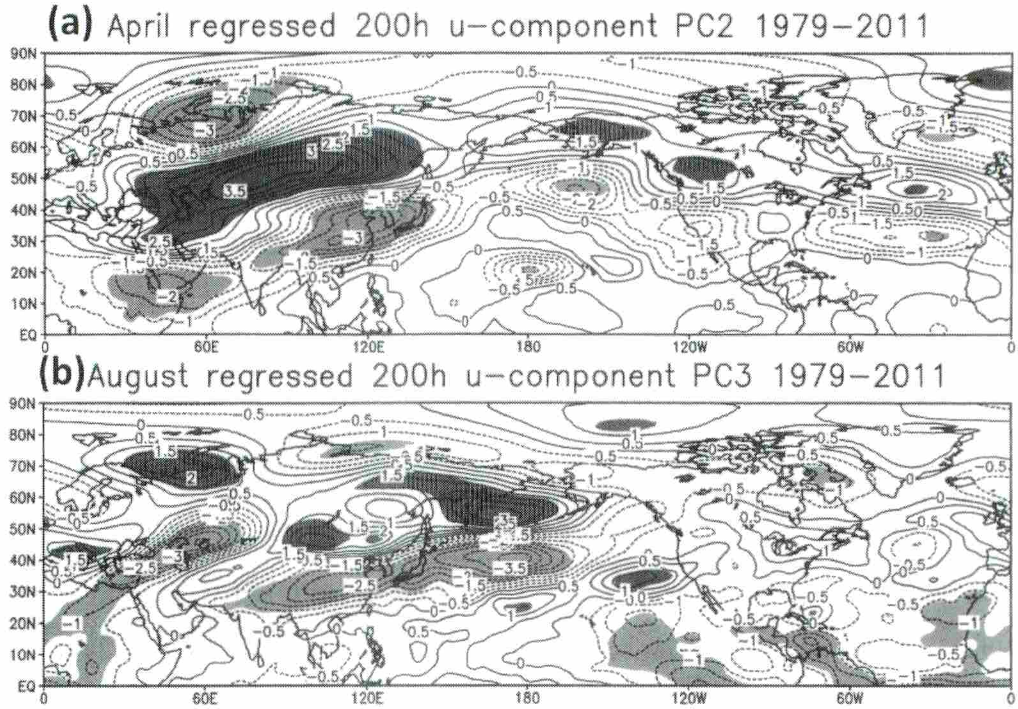

Fig. 12. Regression of (a) the PC2 time series of the 200-hPa height field in April, and (b) the PC3 time series of the 200-hPa height field in August, against the 200-hPa *u*-component wind field in the same month. Contour unit is m s^{-1}. Positive correlations significant at the 5% level are shaded dark gray; negative correlations, light gray.

dipole pattern in the northern Pacific (Fig. 12b). Because the border between the positive and negative areas is near the normal position of the STJ, the PC3 pattern may reflect the north–south fluctuation of the axis of the STJ over the northern Pacific. Wakabayashi and Kawamura (2004) refer to the wave train from the Black Sea to the Gulf of Alaska as the WJ teleconnection pattern. There was an apparent correspondence between the WJ pattern and the August PC3 pattern from the Black Sea to Lake Baikal; however, from Japan to the Pacific Ocean, the WJ pattern appeared to be disturbed by other strong circulation patterns, and was unlike the PC3 pattern.

In conclusion, the combination of PC2 in April and PC3 in August explained rather well the negative correlation between monthly mean temperatures in April and August in northern Japan. In April, the wave-like pattern in PC2 was possibly related to the westerly jet fluctuations around Japan. In August, the PC3 pattern linked northern Japan summer temperatures to STJ fluctuations from the Tibetan high through Japan to the far northern Pacific Ocean.

3.4 SVD analysis of upper air fields and SST in two periods

Why did a strong negative correlation between April and August temperatures emerge since 1998? The Pacific Decadal Oscillation changed during the twentieth century (Biondi et al. 2001), and recently two other famous climate shifts occurred: one in the mid-1970s (Nitta and Yamada 1989; Trenberth 1990; Tanimoto et al. 1993; Mantua et al. 1997; Zhang et al. 1997; Minobe 1999; Yasunaka and Hanawa 2002) and the other in the late 1990s (Chikamoto et al. 2012). The following studies documented the stepwise climatic shift of the late 1990s with diverse lines of evidence. Tu et al. (2009) reported that the frequency of typhoons abruptly increased near Taiwan in the late 1990s; Kim et al. (2011) demonstrated a regime shift for the interseasonal fluctuations of summer precipitation over the Korean Peninsula during the mid-1990s; and Minobe (2002) reported that SST and upper ocean heat content in the Central North Pacific Ocean rapidly increased, while the Eastern North Pacific rapidly cooled during the late 1990s. Chikamoto et al. (2012)

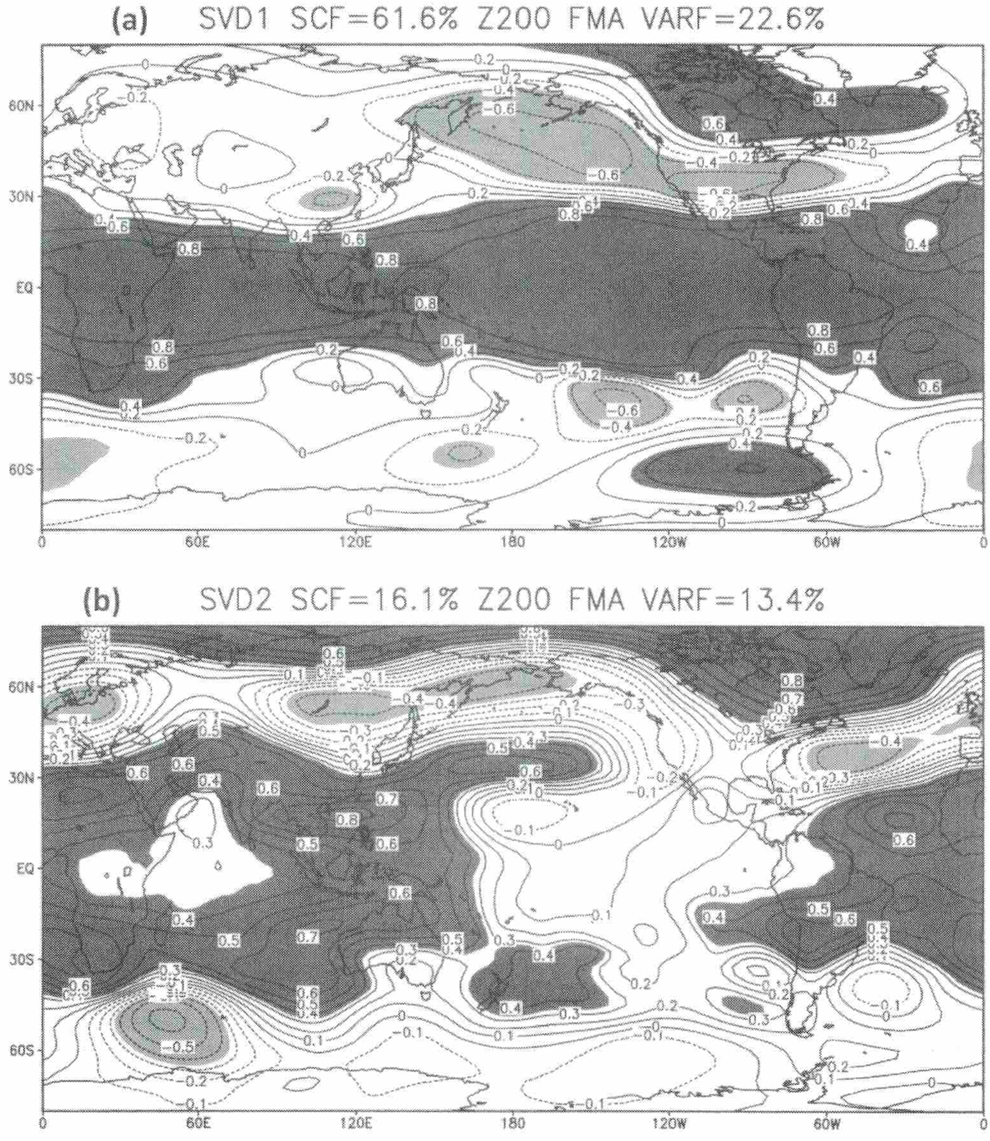

Fig. 13. Global map of the first and second SVD modes of the February–March–April (FMA) height field at 200 hPa and the SST field for 1979–2011.
(a, b) Heterogeneous correlation map for the 200-hPa height in (a) mode 1, and (b) mode 2.
(c, d) Heterogeneous correlation map for SST in (c) mode 1, and (d) mode 2. Positive correlations significant at the 5% level are shaded dark gray; significant negative correlations, light gray.

observed a horse-shoe-like pattern of increasing surface air temperatures in the western tropical Pacific Ocean in the 1991–1995 and 2000–2004 periods, and discussed the physical processes in atmospheric and oceanic variability during the late 1990s. In addition, Yeo et al. (2012) reported that the connection between the SST anomaly in the tropical Pacific associated with ENSO and large-scale atmospheric anomalies in the extra-tropical regions changed significantly since 1999.

Focusing on the most recent stepwise climate shift, we performed an SVD analysis with SST and 200-hPa height fields in two seasons: February, March, and April (FMA), and June, July and August (JJA); these

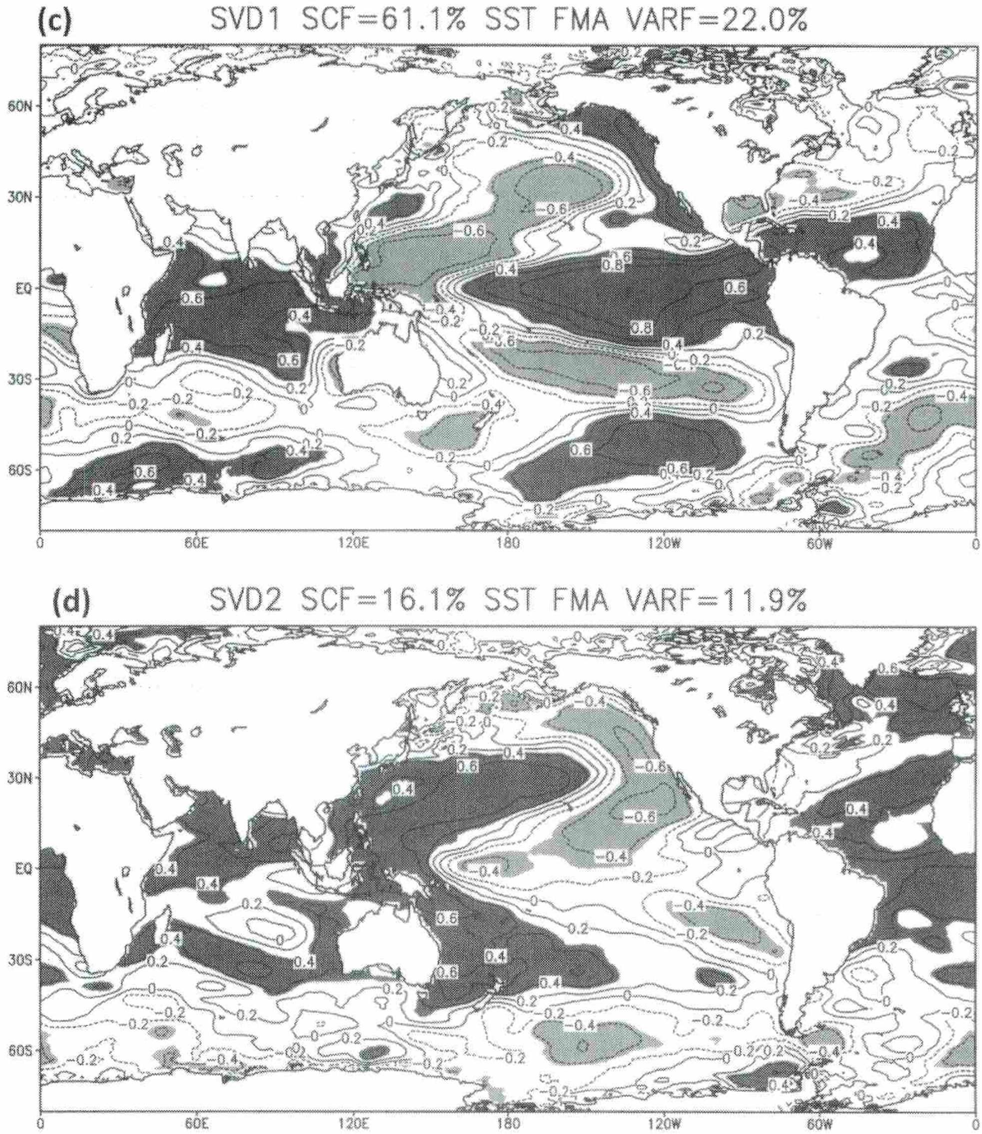

Fig. 13. continued

two periods were chosen as focused seasons that included April and August. In the first SVD mode for FMA in 1979–2011 (Fig. 13), the area of high correlations at the 200-hPa level was spread broadly over the tropics (Fig. 13a). This SVD mode of 200-hPa height yielded a pattern that seems to resemble an El Niño–Southern Oscillation (ENSO) pattern in SST (Fig. 13c). Thus, we consider mode 1 to be the typical El Niño pattern. In mode 2, an east–west contrast was apparent in the 200-hPa height field (Fig. 13b) and there was no strong correlation over the eastern Pacific; this differed from the PC2 pattern in April. The SST pattern (Fig. 13d) was not similar to an ENSO pattern, but may be similar to the horse-shoe pattern in the south Pacific shown by Chikamoto et al. (2012). In addition, another three-part pattern—positive areas in the tropics and high latitudes, and a negative area in the mid-latitudes (Tanimoto and Xie, 2002)—was seen in the North Atlantic Ocean, in both the 200-hPa height and the SST fields, except for a mid-latitude negative-

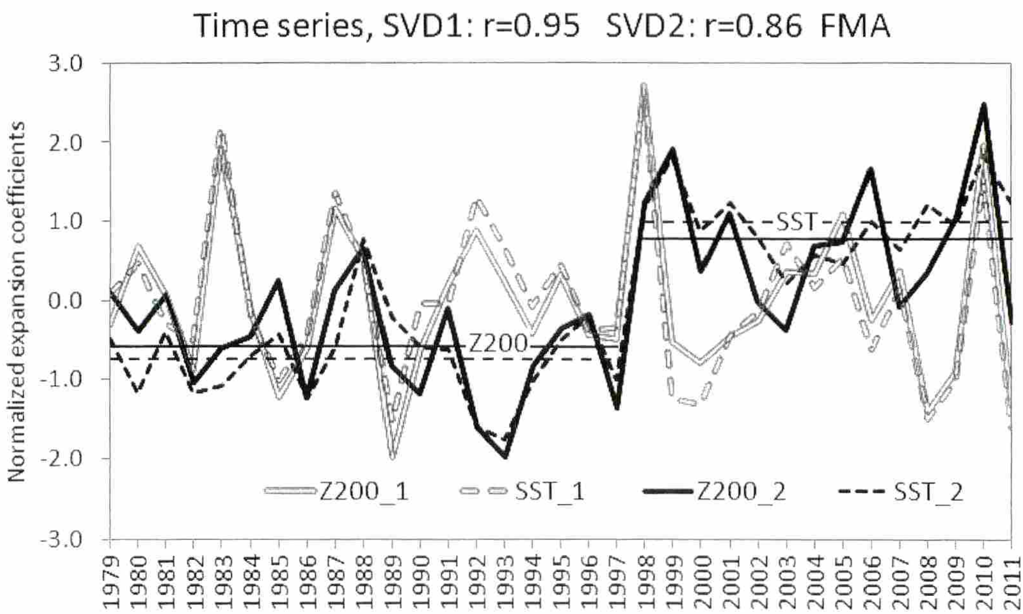

Fig. 14. Time series of the normalized expansion coefficients for the 200-hPa height (white solid line, mode 1; black solid line, mode 2) and the SST field (white dashed line, mode 1; black dashed line, mode 2). Straight horizontal lines indicate long-term averages for mode 2 only from 1979 to 1997, then a shift, then new averages from 1998 to 2011, of height (solid) and SST (dashed). Correlation coefficients are r = 0.95 for mode 1; r = 0.86 for mode 2.

area in SST (Fig. 13c, d). In the time series of normalized expansion coefficient curves (Fig. 14), there were large variations from year to year in both modes, but in mode 2, there was a discontinuous change in 1998: after that year, the coefficients remained larger than they were before.

In JJA, mode 1 of the 200-hPa height field (Fig. 15a) yielded no correlations over the tropical Pacific, unlike mode 2 (Fig. 15b), but did yield positive correlations around the northern hemisphere mid-latitudes, and was not similar to the PC3 pattern in August. However, the SST pattern (Fig. 15c) did look similar to mode 2 in FMA except that the central tropical Pacific area had negative values and was similar to the ENSO mode pattern (Fig. 15c). Although mode 1 of the 200-hPa height had no correlations over the tropical Pacific (Fig. 15a), mode 1 of the tropical SST indicated a typical ENSO pattern (Fig. 15c); therefore, mode 1 in JJA is regarded as an ENSO mode in this paper. Otherwise, the ENSO-like pattern in FMA was also apparent in mode 2 in JJA (Fig. 15b, d). Just as in FMA, the JJA time series of the normalized expansion coefficients of mode 1 (Fig. 16) had a discontinuous change in 1998, after which values remained larger than before the shift. Therefore, the global scale oceanic SST and atmospheric fields changed in 1998 to a mode that was different from the typical ENSO mode, except with a similar SST pattern. Although these more recent and important modes cannot be described yet by well-known patterns, the year 1998 might be an important climatic boundary, not just for monthly temperatures in northern Japan, but also for global atmospheric fields and the SST in the oceans. The features that we consider the most important for separating climatic regimes into two periods (before 1998 and since 1998) are (a) the areas of positive correlation on the mode-2 SVD analysis of SST for FMA (Fig. 13d); and (b) similar positive areas on the mode-1 SVD analysis of SST for JJA (Fig. 15c). Since the SST pattern in JJA seems to connect the ENSO, the ENSO pattern of SST might be changed around 1998 and possibly affect the climate shift.

4. Discussion

Otomi et al. (2012) proposed that the extremely hot summer weather in 2010 was caused by the negative phase of the Arctic Oscillation (AO) in the previous winter, and that the three-part SST pattern that formed in the North Atlantic Ocean continued into the summer. They suggested that the warm summertime

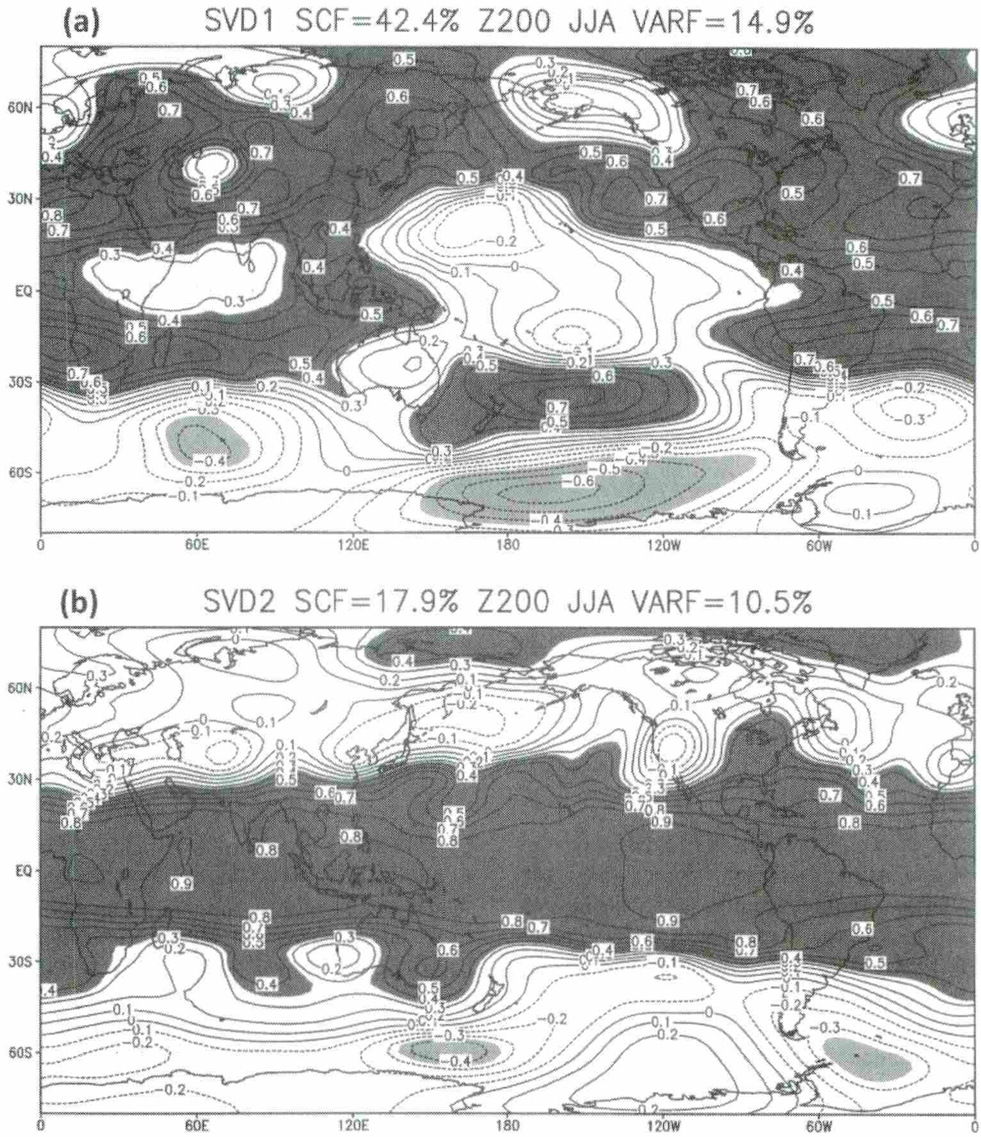

Fig. 15. As in Fig. 13, but for the June–July–August (JJA) period.

North Atlantic SST anomalies, which were related to the AO, caused remote blocking highs to form over Europe. Furthermore, there was an inter-seasonal linkage of the AO in which the oceanic memory of a wintertime negative phase of the AO induced a positive phase in the following summer. This hypothesis of Otomi et al. (2012) may aid us in interpreting our research, especially as 2010 was a typical year in Japan with a cold April and a hot August. For example, the fact that a three-part pattern appeared in our SST fields might be related to such an influence of the AO. We wonder why the importance of the AO for summer weather in northern Japan has increased since 1998—this is an inference that needs to be analyzed.

Next, why has there been a high negative correlation between April and August surface temperatures in northern Japan during 1998–2011, but May, June and July temperatures were not strongly correlated with those in April? The previous explanation in this paper

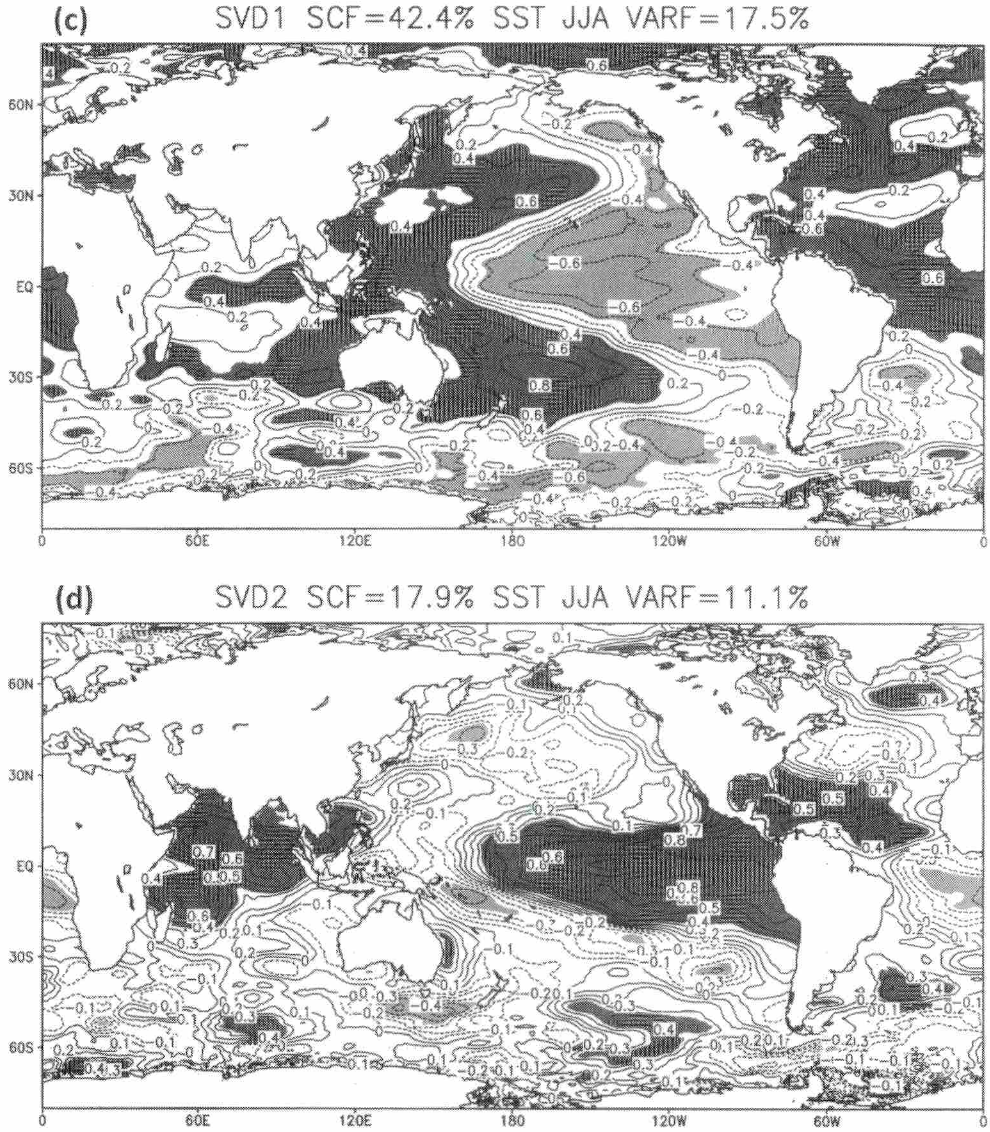

Fig. 15. continued

based on the location and behavior of the STJ does not work for the period between April and August. The axis of the seasonal variation of the STJ along 140°E in the 14-year analysis period was located around 33°N in April (Fig. 17), but with a large standard variation of wind speed. This does not contradict the result in section 3.2, that in April a strong STJ was aligned along the south coast of Japan but with a large year-to-year variation of wind speed. However in May, the axis of the STJ began to move northward. Since another area of high variability was located around 43°N, it seems that in May the STJ meandered more, or the polar-front jet stream frequently affected the analysis. In June the axis of the STJ was around 40°N with low variability. Then in July the location of the axis became unclear. The variability became large again around 40–45°N in July and August, and then finally the jet stream axis distinctly re-appeared at 45°N in August. Therefore, we can explain the strong correlation of the temperatures in April with those in

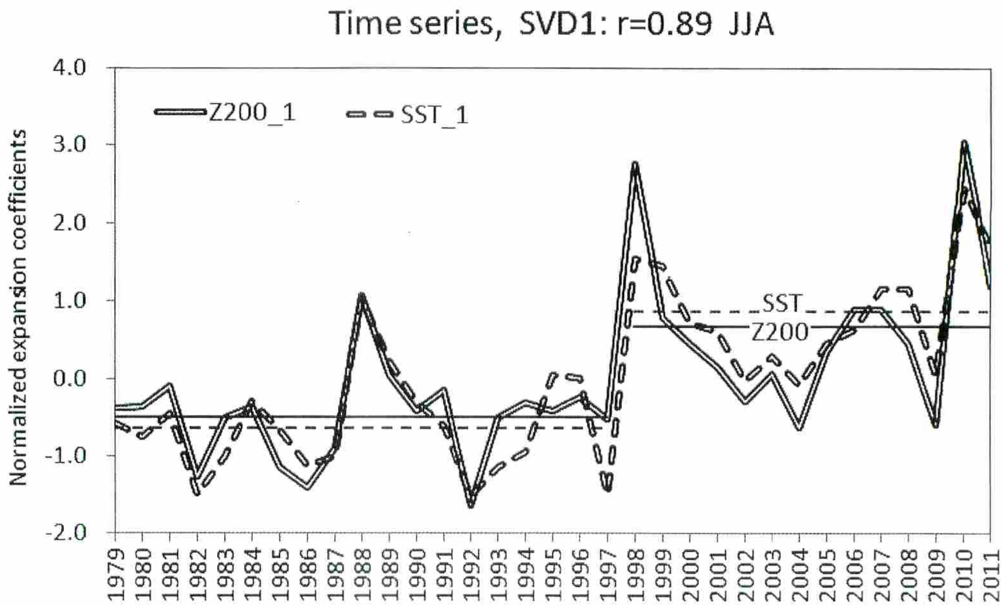

Fig. 16. As in Fig. 14, but for the June–July–August (JJA) period of mode 1 only. The correlation coefficient was r = 0.89. Mode 2 was omitted in this figure.

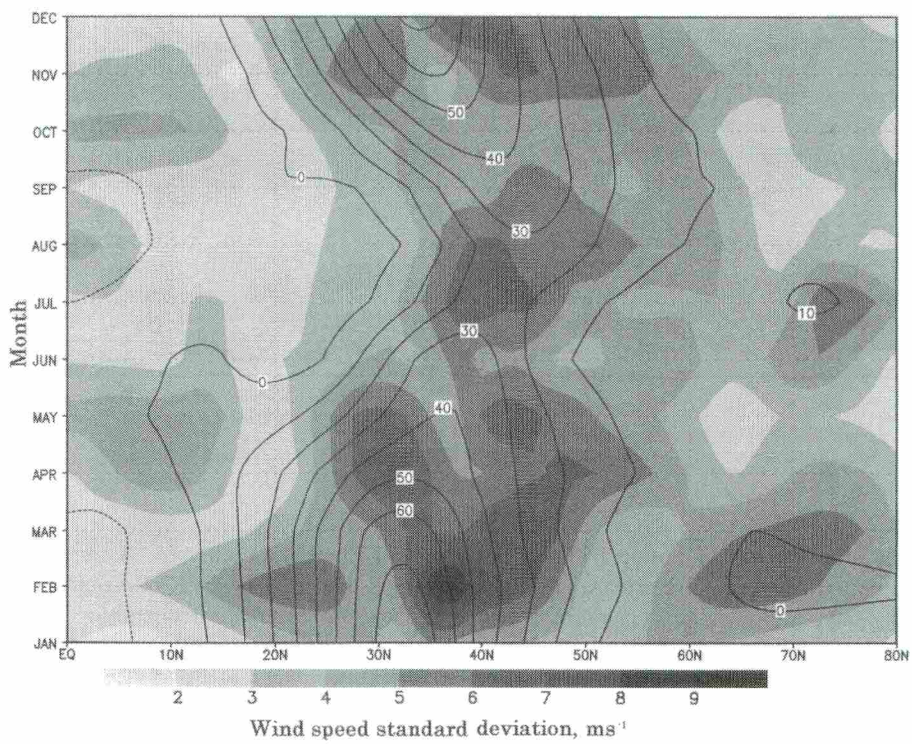

Fig. 17. Time-latitude cross section along 140°E for monthly mean 200-hPa u-component wind for the period 1998–2011. Contours indicate wind speed (m s^{-1}) and shading indicates standard deviation (m s^{-1}, gray-scale legend at bottom).

August and the weak correlations of May, June, and July with August, as follows: the STJ gradually moved north from May to July in a seasonal march, but because its location was relatively variable in May, it had no clear effect on surface temperatures in northern Japan in that month, unlike the setup in April. In June, its position was stable and then did not produce a large temperature variation. In July, wind speeds in the jet were weak; also an mP air mass frequently affects weather in northern Japan because of displacements of the Bai-u front, which causes peculiarly large temperature variations in northern Japan. In these circumstances, fluctuations of both the location and the strength of the upper-level jet are not related to conditions in the preceding spring. However, by August, the location of the axis of the STJ became distinct once again, and differences between April and August became clear.

5. Conclusion

Monthly surface temperatures in April and August have been strongly and negatively correlated since 1998 in northern Japan. The cause seems to be the displacement and intensification of the upper-level westerly winds in the STJ: that is, southward movement of a deep cold air mass in April is associated with strengthening and southward movement of the jet while temperatures are unusually cold in northern Japan. The events in the spring seem to be linked to northward movement of the jet in the following August, which leads to unusually high temperatures in northern Japan. According to Otomi et al. (2012), the warm summertime North Atlantic SST anomalies, which were related to the AO, caused remote blocking highs to form over Europe. They pointed out that there was an inter-seasonal linkage of the AO in which the oceanic memory of a wintertime negative phase of the AO induced a positive phase in the following summer. This hypothesis may aid us in interpreting the results of our research in terms of the negative correlation of temperatures between different seasons; however, more analyses will be needed.

The August temperatures in northern Japan are significantly correlated with PC3 of the 200-hPa height field in August. In April, the monthly mean temperatures are well corresponded with PC2 in April during 1998 to 2011. In addition, values of PC2 in April were negatively correlated with values of PC3 in August from 1998 to 2011. It is similar to the relation between the surface temperature anomalies in April and August. Moreover, the regression patterns of the 200-hPa u-component wind field in April against the PCs indicate the displacement of the STJ which positions are consistent with the temperature in northern Japan. Therefore, the spatial patterns and correlations of these two PC modes since 1998 may partly explain the strong negative correlation between temperatures in April and August.

After assessing our SVD analysis for the 200-hPa height field and the surface SST field, we conclude that a robust climate shift occurred in 1998, not only for temperatures in northern Japan, but also for the global climate. Although Yeo et al. (2012) defined the year of change as 1999, the one year difference seems unimportant. The important conclusion is that the climate shifted around the year 1998.

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