CLIMATE OF LITTLE ICE AGE IN JAPAN

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Abstract The climate during the period from 16th to 19th century in Japan was reconstructed by the historical weather records of the Feudal Clan Tsugaru. Fluctuations of monthly precipitation frequency, snowfall ratio and so on were examined, and deviations of temperature and precipitation were estimated. Further, "Little Ice Age" in Japan was divided into three cold phases and two interglacials. The cold phases are as follows: 1611–1650, 1691–1720 and 1821–1850.

1. Introduction

It is inferred from various kinds of documentary evidence that the colder climate than now had been predominant all over Europe for about 300 years from 16th to 19th century. Schove (1961) divided the European Little Ice Age into three phases of Little Ice Age, the first (1541–1680), the second (1741–1770) and the third (1801–1890), and two interglacials or lulls. Recently, Pfister (1980) concluded by means of historical phenological materials that in Central Europe three periods in which springs and summers were simultaneously cold: 1570–1600, the 1690s and the 1810s.

In Japan the existence of Little Ice Age has been pointed out by various kinds of fragmental document describing crop failure, unusual weather and so on. However, the detailed variation of the climate during these cold period of 300 years is not yet disclosed. The climate during the Little Ice Age was roughly reconstructed by some researchers in Japan. Yamasawa (1929) analyzed the tree rings of chestnuts (*Castanea crenata*) in Hida, mountainous region in Central Japan, indicating the minimum periods, from 1681 to 1690 and from 1731 to 1740, and maximum periods, from 1641 to 1650, from 1711 to 1720, from 1781 to 1790 and from 1861 to 1870.

After the illustration of the year-to-year variation of the tree ring growth for Japanese cypress (*Chamaechyparis obtusa*) prepared by Arakawa (1955) by the use of the data measured by Yamasawa (1936) in Central Japan, several marked minimum periods and maximum periods can be noticed: the former are the periods from 1580 to 1610, from 1810 to 1840 and from 1770 to 1790, and the latter are from 1500 to 1550 and from 1640 to 1710. Though the minimum periods, in general, may refer to the climatic deterioration during the summer half year, and the maximum periods to the optimum climate, close relationship between them can not be found.

Arakawa (1954) illustrated also the variation of rice production at Miide, a village near

Lake Suwa, Central Japan, from 1807 to 1871. From this figure, it is inferred that crop failures or cool summers occurred during the period from 1817–1828. The variation of crop index, which was devised by Suda (1976) by means of the tree ring data of Japanese cypress (*Chamaechyparis obtusa*) since 12th century prepared by Yamasawa (1936), showed that cool weathers during the growing seasons took place with the minimum years of 1590, 1723, and 1840, having the dominant periods of 249 and 125 years.

Outi (1964) investigated the tree rings of zelkova (*Zelkowa serrata*) in Yamagata, Northern Japan and concluded that their growth rates were greater as the westerlies were weak and the North Pacific high shifted westward; and they were smaller as the North Pacific high shifted eastward. Minimum values of the growth rate appeared in 1690, 1790 and 1890. From these facts, it was inferred that the North Pacific high shifted to the east and the westerlies were intensified during these periods.

Yamamoto (1970b) reconstructed the summer weathers for a half century from 17th century to 19th century by using the chronological data of disasters in Iwate Prefecture. The occurrence frequencies of the wet spell, flood, crop failure reached their maxima during the half century from 1751 to 1800.

Though not all the climatic fluctuations in summer mentioned above have some parallels to these disasters, it is probable that several colder periods existed in the recent historical climatic variation.

By using the well-known records of the freezing date in Lake Suwa, Yazawa (1976) inferred that cold winter period occurred from the middle of 15th century to the beginning of 18th century, and since then the climate became mild. By means of the chronology of natural disasters in Ishikawa Prefecture, Yamamoto (1970b) deduced that the extremity of cold and heavy snow was in the first half of 19th century after 17th century. These two results do not agree with each other.

In this paper we examined the historical weather records of the Feudal Clan Tsugaru and compared them with the results stated above. These historical records, owned by the City Library of Hirosaki, are one of the most valuable continual climatic documents during the recent historical times. The daily weather had been recorded both at Hirosaki and at Edo (old Tokyo). However, we used here the weather records at Hirosaki. These documents remain almost perfectly for about 200 years, from 1661 to 1868. So they are sufficient for estimating the climatic fluctuation for these years (Maejima et al., 1983).

In the diary weather phenomena were written as clear, fine, cloudy, heavy rain, rain, shower and snow. The duration of rain, wind direction, with its changing time and wind force were mostly supplemented. Maejima and Koike (1976) pointed out for the first time that the reconstruction of climate in historical time from the synoptic point of view can be made by using a series of daily weather distribution pattern of the country. After this method the reconstruction of summer weathers in Tempo period (1830s) was made in detail by Yaji and Misawa (1981). However, it takes a lot of time to reconstruct the daily weather pattern for long period. In this paper we examine mainly the climatic fluctuation for 200 years, two third of the period of the Little Ice Age, based on the year-to-year changes of precipitation frequency at Hirosaki.

2. The Reconstruction of Climate from the Documents of the Feudal Clan Tsugaru

Year-to-year fluctuation of precipitation frequency

The records of precipitation are expected to be more objective than those of other elements. The frequency is represented by percentage of number of days with heavy rain, shower and snow to the total number of days with weather description. First, the precipitation frequencies for each month were calculated, then the year-to-year variation curves were represented by means of eleven year running mean. The month with weather records less than 80 percent (22–24 days in a month) were excluded. Eleven year running mean was calculated only when precipitation frequency could be provided for more than 9 out of 11 years (Fig. 1).

Winter

In winter the year-to-year fluctuation of precipitation frequency is the highest, and remarkable maximum and minimum appear. The tendency of the each curve for winter months is similar. The markedly high precipitation frequencies appeared from 1690 to 1710 and from 1820 to 1840. The latter was extremely remarkable. The minima of frequency appeared from 1661 to 1680 (before 1661 weather records are not available, but the lowest frequency may be extended) and from 1710 to 1780. The latter includes three secondary maxima with rather high frequency, which result in two minima. The minimum around 1750 is pronounced.

Spring

The fluctuations of precipitation frequency for spring months are within a smaller ranges, though the maximum and minimum appear like in winter. In particular, the variation in March shows the same tendency as in winter months as stated above. In other words the wet periods in March appear around 1700 and 1830. In May the same tendency as from December to April is not noticed. However, it is the same as in winter that a weak maximum appears around 1830. In spring as a whole, maxima are found around 1700 and 1830, with a minimum from 1740 to 1790.

Summer

The variations of precipitation frequency for summer months have a little parallel with each other. For example, the period from 1820 to 1830 is a marked maximum in June, but a minimum in July. This reflects the fact that the summer season of Japan is divided into the Baiu, early summer rainy season, and the midsummer.

The precipitation frequency for July varies with the largest range among the summer months. It shows that the extreme weather situations, both maximum and minimum, occurred in July. The maxima existed from 1680 to 1720 and from 1790 to 1860 (since then unknown). Though the latter period is a maximum as a whole, several short period maxima can be noticed in about 1790, 1815, 1830 and 1860. During 200 years an extreme minimum appeared around 1770, abruptly switching over to the maximum around 1790. In the minimum period the precipitation frequencies are less than 30% even in eleven year running mean, which is only 60% of those in the maximum period.

Autumn

The year-to-year fluctuations for autumn months are similar to those for summer. Paral-

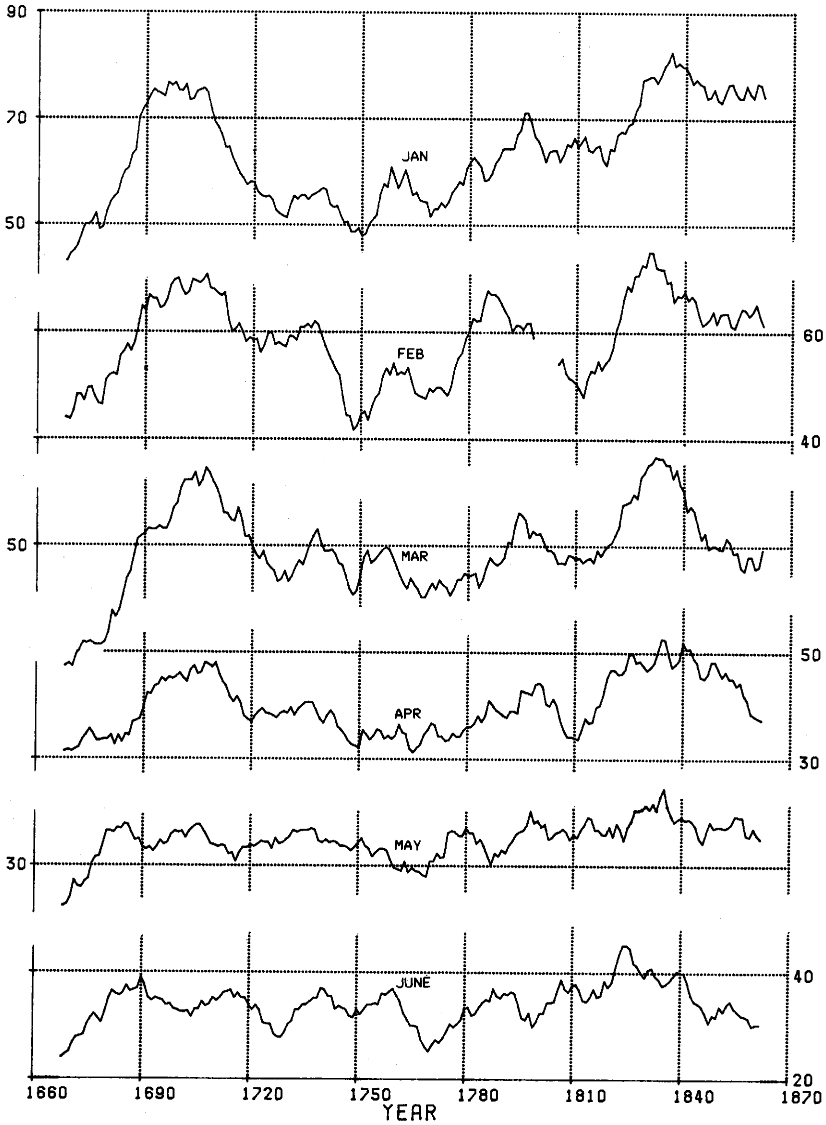

Fig. 1-a Year-to-year fluctuation of monthly precipitation frequency at Hirosaki for January to June (eleven year running mean)

lelism can be hardly found among them. In November the maxima appeared from 1690 to 1700 and from 1820 to 1840, being the same as in winter. The minima exist in about 1680, about 1710 and about 1860. The first and third minima are noted in October, too. In

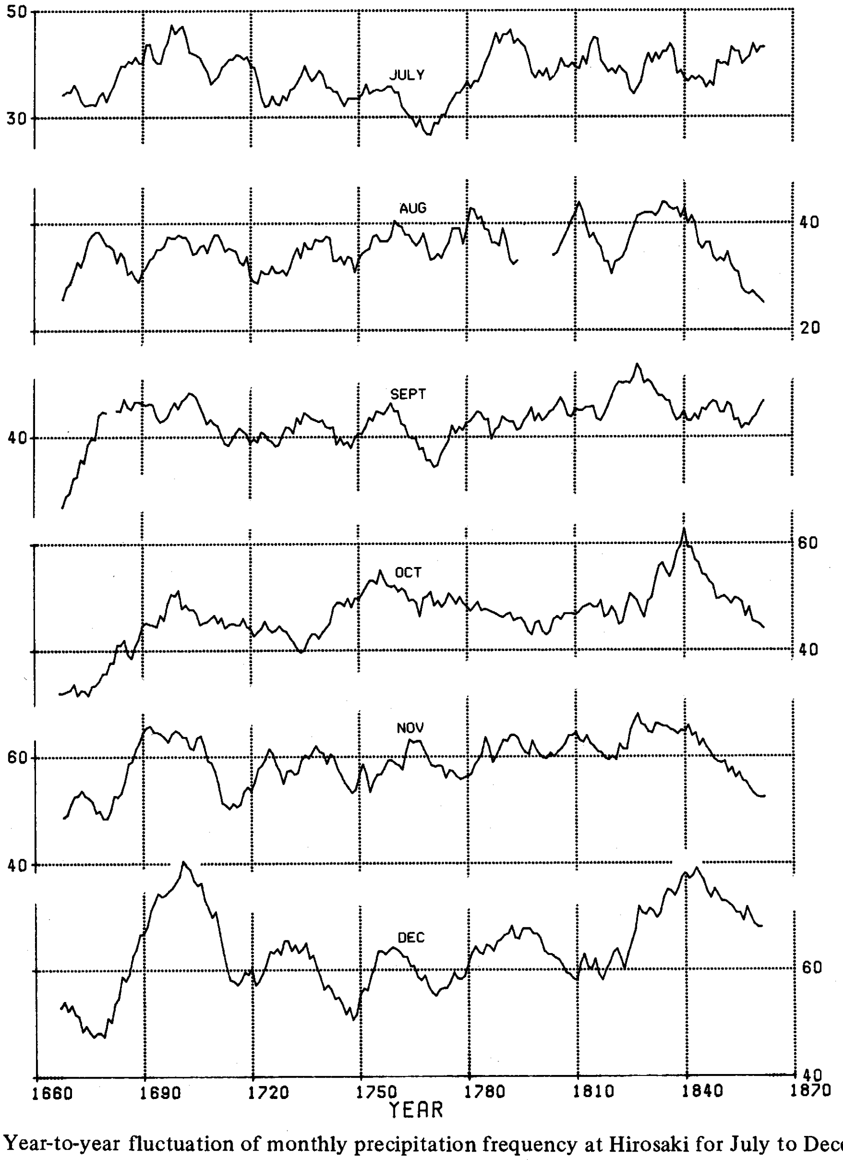

Fig. 1-b Year-to-year fluctuation of monthly precipitation frequency at Hirosaki for July to December (eleven year running mean)

September two marked maxima appeared in about 1690 and about 1830. These periods coincide with those in July and August. Roughly speaking, the maximum periods in autumn fairly well coincide with those in other seasons.

Year-to-year fluctuation in occurrence frequency of the various weather elements

Snowfall ratio

Snowfall ratio is defined as the percentage of the number of days with snowfall to that with precipitation. The snowfall ratio in Kyoto from November through March is a relevant indicator for the warmth and cold in winter (Yamamoto, 1970a). As the weather characteristics at Hirosaki in winter differs from those of Kyoto, the snowfall ratio at Hirosaki was calculated for each month.

The ranges of fluctuation in snowfall ratio is large in spring and autumn, especially in April (Fig. 2). In spring the maxima appeared in about 1710, 1760, 1790 and 1830, while the minima occurred around 1680, 1775 and 1815. The tendency of fluctuations in snowfall ratio coincides to that in winter as stated above. The minimum around 1815 is the most pronounced throughout the whole snowy season.

Strong wind

The strong wind occurs very frequently in winter. On the other hand, it was not registered in summer. Most records of strong wind are accompanied with those of snowfall. So the strong wind means snow storm in winter (Fig. 3). The year-to-year fluctuation reaches a maximum in January. The maxima appeared around 1700, 1730, 1760, 1790 and 1830. Among them the maximum around 1700 is the largest.

Cold

The record of cold very frequently appears in winter, especially in January and February and rarely in summer (Fig. 4). The record of cold is accompanied with that of snowfall or of clear weather.

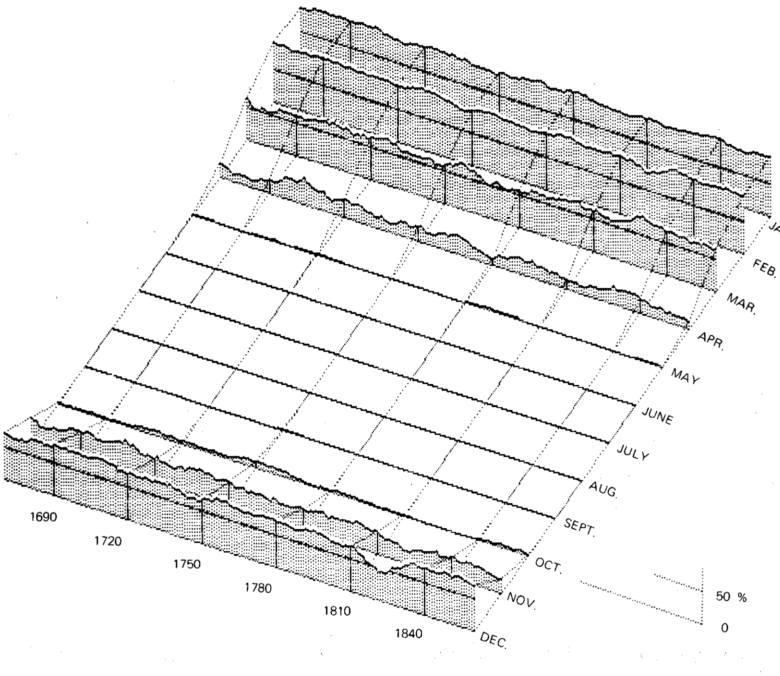

Fig. 2 Year-to-year fluctuation of monthly snow ratio (snow/precipitation) at Hirosaki

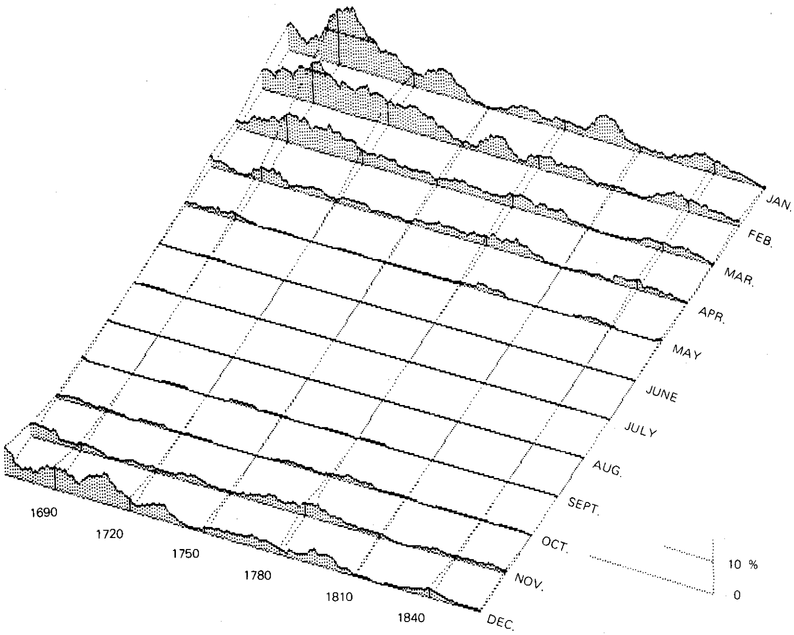

Fig. 3 Year-to-year fluctuation of monthly strong wind frequency at Hirosaki

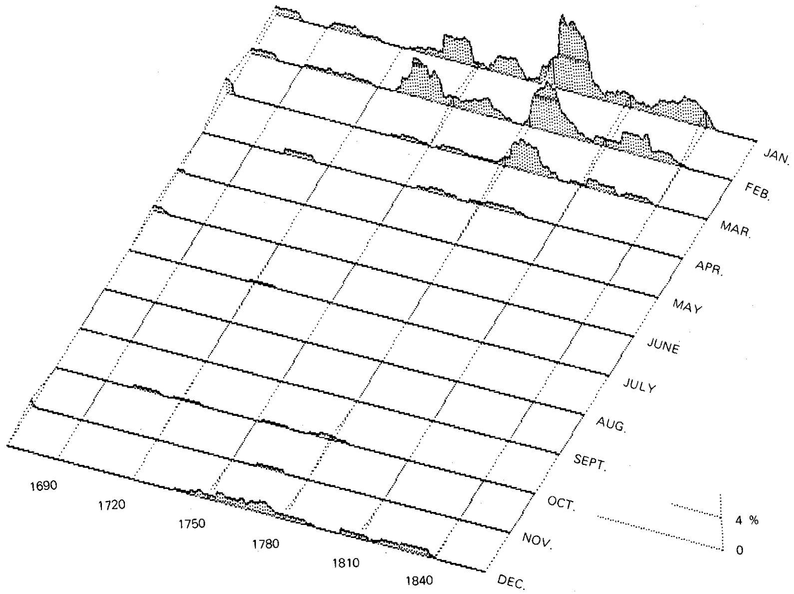

Fig. 4 Year-to-year fluctuation of monthly "cold" frequency at Hirosaki

From this, it is supposed that the winter cold in those days were caused by the intensification of the northwest monsoon or the radiation cooling under the calm weather. The maxima appear around 1740, 1760, 1790 and 1830, which coincide well with those of strong wind. An absolute maximum appears around 1790, while a peak is not found around 1700, which is the common maximum revealed by other weather elements.

Frost

Frost occurs in spring and autumn, particularly in April, October and November. The frost was recorded with the description of clear weather. Thus the fluctuation in frost occurrence is reversed to that for precipitation. Maxima appear around 1680, around 1740, around 1760, around 1780 and around 1800 (Fig. 5). The occurrence frequency of frost should be noticed, because the killing frost has powerful effect on crops.

Light rain

Light rain occurs more frequently in summer, especially in July, August and September and lesser in winter. In these months the frequency fluctuates from year to year in the same way as that of precipitation occurrence stated above. It shows that long wet spells consist of light rain. Thus the year-to-year fluctuation in occurrence frequency of light rain indicates that of cool and wet weather in summer. Maxima appear around 1690, around 1750, around 1790 and around 1840 (Fig. 6). These are intervened by the minima around 1720, around 1770 and around 1800.

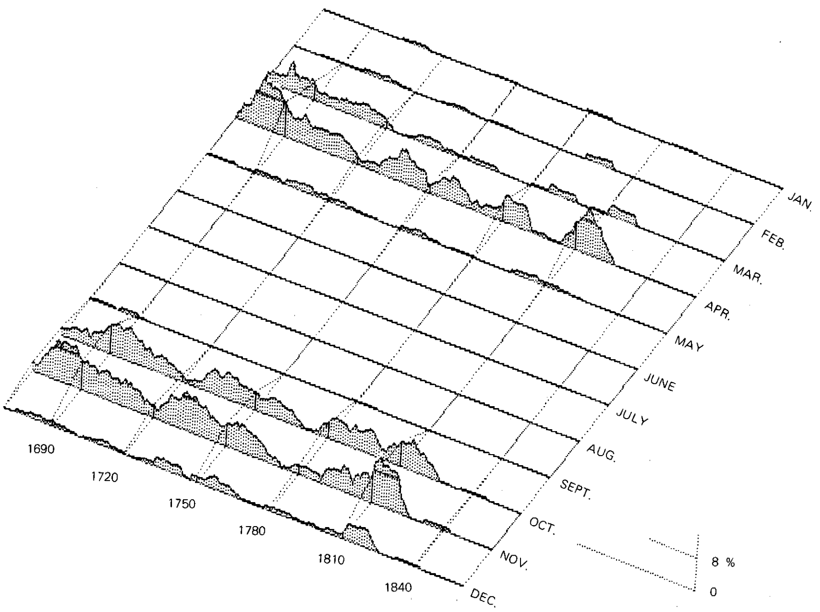

Fig. 5 Year-to-year fluctuation of monthly frost frequency at Hirosaki

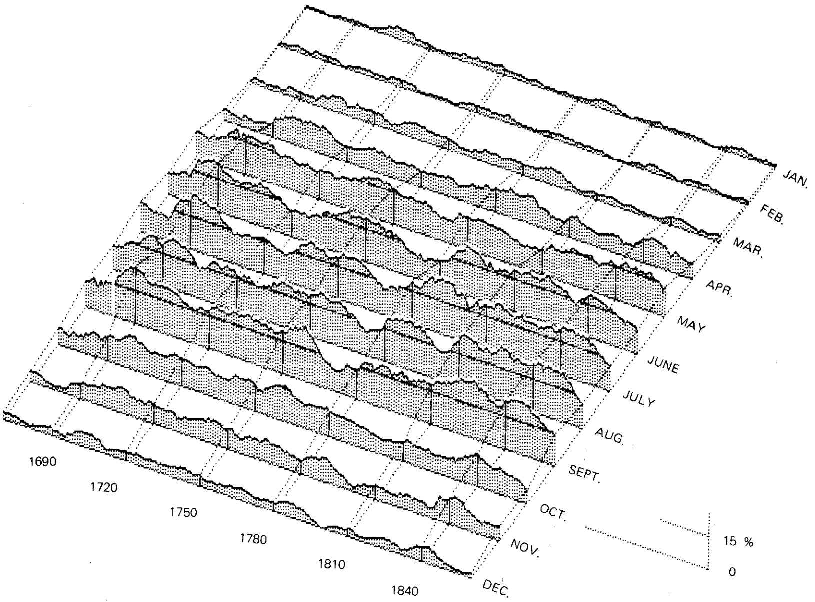

Fig. 6 Year-to-year fluctuation of monthly light rain frequency at Hirosaki

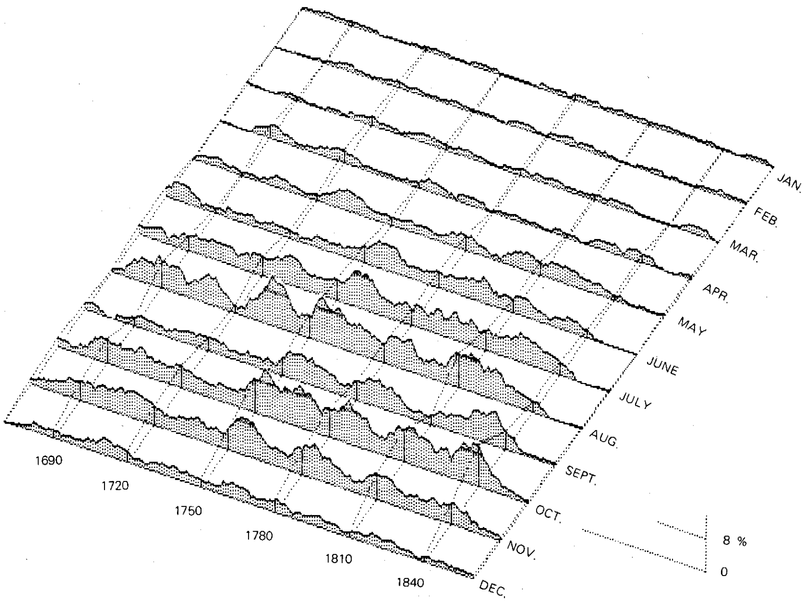

Fig. 7 Year-to-year fluctuation of monthly thunder storm frequency at Hirosaki

Thunder

Thunder frequently occurs in summer and autumn, particularly in August and October. In August most thunders were accompanied with shower and also with clear weather. On the other hand, they were mostly accompanied with the records of rainy weather in October. The year-to-year fluctuation is marked in each month (Fig. 7). In August the maxima appear around 1730, 1750 and 1810. In October they appear around 1750, 1760, 1780, 1810 and 1840. In August the fluctuation in thunder occurrence coincides with those in occurrence frequency of precipitation or shower. However it is quite different from those of frequencies of precipitation and of thunder.

3. Fluctuation of Cold and Wetness during the Little Ice Age

Relation between historical weather record and modern climatic data

It is a pity that the period in which the diary of the Feudal Clan Tsugaru had been written does not overlap the modern instrumental observation period. So it is impossible to calculate directly the climatic values from the weather records in the diary. First, the relations between the temperatures and the number of days with precipitation or snowfall, or the amount of precipitation are examined. Next, the temperature characteristics in the Little Ice Age are estimated from the precipitation records of the diary.

As modern instrumental data, Monthly Agricultural Meteorological Report of Aomori Prefecture (1953–1981) and Annual Precipitation Report 7–11 (1941–1970), were used. The climatic means are monthly mean daily maximum temperature, monthly mean daily minimum temperature, monthly number of days with precipitation more than 1 mm, monthly number of snowy days and monthly amount of precipitation.

These climatic means are shown in Table 1. At Hirosaki the annual range of temperature is great. Both daily maximum temperature and daily minimum temperature reach their minima in January and their maxima in August. The number of days with precipitation is largest in winter, especially in January. During summer months it is small, though a little higher in June and July. The number of days with snowfall is registered from November to April. In October it occurred nine days for 21 years. There are two maxima in the annual variation of monthly precipitation, the largest in September, the second largest in January. These average values reveal the characteristics of climate at Hirosaki. First, the snowy climate in winter which is typical in the Japan Sea Side is observed. Second, both precipitation and number of days with precipitation for June similar to those for July. This indicates the precipitation characteristics of delayed rainy season typical in Northern Japan. Third, daily maximum temperature is low in June because of the predominance of "Yamase", cool northeasterly wind.

The correlation coefficients between monthly temperatures or precipitation and monthly number of days with precipitation or snowfall were calculated. Here, the ratio of number of days with snowfall to total number of days with precipitation was used instead of the number of days with snowfall (Table 2). The correlation coefficients between number of days with precipitation and precipitation amount range from 0.43 in March to 0.77 in July. From this, the increase or decrease in number of days with rainfall indicates the increase

Table 1 Monthly means of climatic element and weather at Hirosaki
*: precipitation amount is over 1mm, **: any amount of snowfall

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
daily max temp(°C)	1.8	2.7	6.1	14.6	20.5	23.2	27.4	28.4	24.1	18.0	10.7	4.5
daily min temp(°C)	-5.5	-5.4	-2.5	3.1	8.2	13.4	17.8	18.7	13.9	7.3	2.0	-2.4
rainy days *	23.1	17.7	16.1	10.2	9.4	10.1	10.1	9.9	11.8	12.5	17.2	20.7
snowy days **	28.0	24.6	19.8	3.5	0.0	0.0	0.0	0.0	0.0	0.4	10.0	22.7
precipitation(mm)	136.9	105.0	87.7	71.2	60.4	90.6	100.8	118.3	152.0	92.8	105.4	130.1

Table 2 Correlation coefficient between climatic element and weather frequency at Hirosaki (with modern data)

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
precipit - rainy days	0.69	0.58	0.43	0.53	0.59	0.62	0.77	0.60	0.48	0.52	0.75	0.54
max temp - rainy days	-0.10	-0.66	-0.47	-0.19	-0.53	-0.21	-0.43	-0.36	-0.24	-0.35	-0.36	-0.67
min temp - rainy days	-0.07	-0.44	-0.35	0.43	-0.18	0.01	-0.03	-0.15	0.03	0.13	-0.11	-0.54
max temp - snow ratio	-0.59	0.19	-0.39	-0.73	0.00	0.00	0.00	0.00	0.00	-0.30	-0.63	-0.41
min temp - snow ratio	-0.46	0.02	-0.23	-0.71	0.00	0.00	0.00	0.00	0.00	-0.09	-0.59	-0.44

Table 3 Regression coefficient between climatic element and weather frequency at Hirosaki (with modern data)

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
precipit - rainy days	9.59	4.43	4.74	8.70	5.97	9.18	13.79	12.84	10.07	6.72	5.93	4.02
max temp - rainy days	-0.04	-0.31	-0.21	-0.10	-0.30	-0.08	-0.22	-0.20	-0.10	-0.11	-0.12	-0.20
max temp - snow ratio	-0.04	0.02	-0.02	-0.04	0.00	0.00	0.00	0.00	0.00	-0.03	-0.05	-0.03

or decrease their precipitation. Monthly mean daily maximum temperature has negative correlation with number of days with precipitation for each month. In particular, in December and February the correlation coefficients amount to –0.66. On the other hand, the monthly mean daily minimum temperature has, in general, negative correlation with number of days with precipitation, with some exceptions in spring and autumn. So the increase or decrease in number of days with precipitation may represent the decline or rise in temperature. Especially in winter half year, it serves as a most reliable index of daily maximum temperature. Moreover, the daily maximum temperature has negative correlation with the snowfall ratio stated above.

Snowfall ratio has also large negative correlation coefficient with daily minimum temperature. Thus the temperatures in spring and autumn can be estimated by the snowfall ratio.

The regression coefficients were obtained for five relations stated above which had high correlation between number of days with precipitation or snowfall and temperature or precipitation amount (Tab. 3). If number of days with precipitation and precipitation are set as independent variable and dependent variable respectively, the smallest regression coefficient 4.02 appears in December, and the largest value 13.79 in July. One day increase in number of days with precipitation means 10 mm increase in monthly precipitation. On the other hand, the regression coefficients of daily maximum temperature to number of days with precipitation are –0.04 in January and –0.31 in February which are the largest and the smallest, respectively. One day increase in number of days with precipitation means 0.2°C decrease in monthly mean daily maximum temperature. The regression coefficient of daily maximum temperature to snowfall ratio is, on an average, around –0.04. 10%

increase in snowfall ratio means 0.4°C decrease in monthly mean daily maximum temperature.

Periodicity in the fluctuation of precipitation frequency

In the year-to-year fluctuation of precipitation frequency at Hirosaki, a periodic changes is noted (Fig. 1). The precipitation frequencies from 1665 to 1864 were used to detect the period. By means of maximum entropy method spectrum analysis was applied here. As shown in Figure 8, one or two marked periods more than several years appear. The dominant periods of about ten years from January to December are as follows; 12.7, 9.5, 12.3, 13.4, 13.0, 11.1, 9.5, 14.5, 13.3, 10.8, 9.5, 9.5. The arithmetic mean of these peaks around ten years is 11.6 years, which corresponds to that of sunspot number. On the other hand, the longer periods are from 50 to 80 years. These facts indicate that the climate does not vary with longer definite periods, excluding sun spot number cycle. Thus it is not appropriate to apply a definite period (for example 30 years) to divide the history of climatic variation.

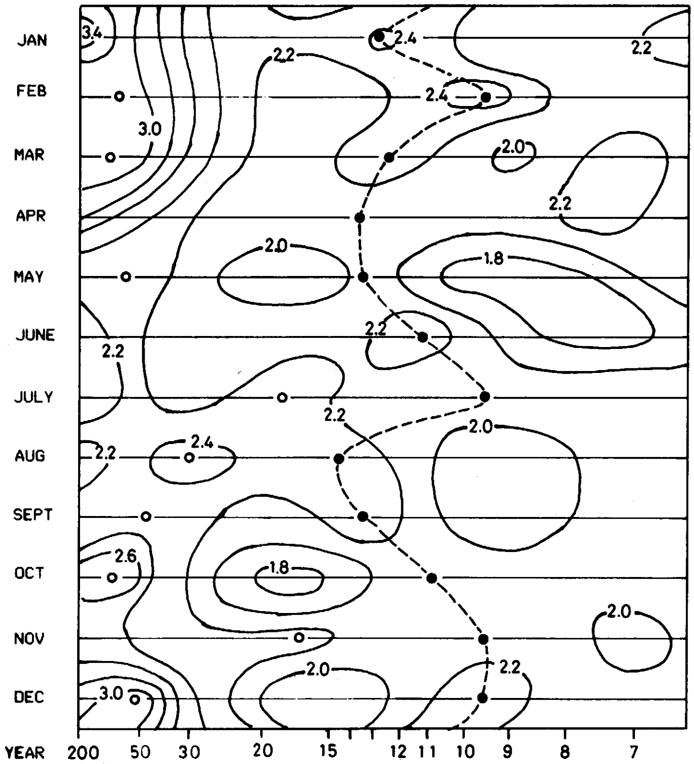

Fig. 8 Distribution of power spectrum of monthly precipitation frequency (Numerals are shown by logarithm of power; broken line denotes each power peak around 10 year)

Division of the Little Ice Age

As stated above, the distinct fluctuation can be noticed on the curve of the moving average of precipitation frequency. It suggests that the Little Ice Age in Japan can be subdivided. By applying the student's t-test the significant periods can be separated. In other words, the boundary can be determined where the variable of probability has the largest or the smallest value. The procedures for discriminating significant 30 year period are as follows:

1. Set up the hypothesis that population means of precipitation frequency for two periods are the same.
2. Calculate the variable of probability (t) and degree of freedom (ν) when both variances of population are unknown.
3. For the case of the significant level of two-sided test 5% and 1%, critical value of hypothesis with degrees of freedom (ν) is calculated from student's t-distribution.
4. When absolute value of probability variable (t) is larger than the absolute value of critical value, the hypothesis is rejected, and the significant difference between two periods is to be supposed.

Table 4 Values of probability variable of the difference between the 30 year means of precipitation frequency
**: significant level 1%, *: significant level 5%

	1661-1690 1691-1720	1671-1700 1701-1730	1681-1710 1711-1740	1691-1720 1721-1750	1701-1730 1731-1760	1711-1740 1741-1770	1721-1750 1751-1780	1731-1760 1761-1790	1741-1770 1771-1800	1751-1780 1781-1810	1761-1790 1791-1820	1771-1800 1801-1830	1781-1810 1811-1840	1791-1820 1821-1850	1801-1830 1831-1860	1811-1840 1841-1870
JAN.	-3.9**	0.3	5.3**	6.3**	2.5*	0.3	-1.2	-0.7	-2.2*	-2.3*	-2.9**	-0.8	-2.3*	-3.2**	-4.2**	-0.9
FEB.	-3.5**	-1.5	0.9	2.9**	3.1**	4.2**	1.7	-1.0	-4.0**	-3.6**	0.0	0.2	-0.9	-3.0**	-1.3	0.3
MAR.	-6.5**	-3.0**	1.3	3.7**	2.1*	1.8	1.0	1.5	-0.9	-2.0*	-2.6*	-1.2	-2.5*	-2.7**	-1.5	2.2*
APR.	-4.8**	-1.2	0.9	2.5*	1.8	2.6*	1.9	0.8	-2.0	-2.4*	-1.6	-0.9	-2.0*	-3.0**	-1.6	1.1
MAY	-1.3	-0.1	1.2	-0.1	-0.0	1.2	1.1	1.0	-1.6	-1.1	-2.0*	-0.8	-1.7	-0.3	-0.6	1.5
JUNE	-1.5	0.5	0.9	1.0	-0.3	0.3	0.7	1.0	-0.2	-2.3*	-2.2*	-2.8**	-1.2	-0.9	2.0*	2.4*
JULY	-2.2*	-0.4	0.9	2.5*	1.0	2.3*	1.0	0.7	-2.2*	-2.7**	-2.5*	-0.1	-0.0	1.2	-0.6	0.3
AUG.	-1.2	0.7	0.0	0.8	-0.5	-0.4	-1.3	-0.7	-0.5	0.4	0.6	0.0	-1.2	-1.1	0.2	2.8**
SEPT.	-2.1*	-0.4	1.5	1.2	-0.1	0.3	-0.1	0.8	-0.5	-1.3	-1.8	-2.0	-1.3	-1.1	0.9	1.2
OCT.	-2.6*	-0.8	0.6	0.5	-1.4	-2.7*	-2.3*	-0.3	1.2	1.7	0.8	-0.5	-1.5	-1.9	-1.4	0.3
NOV.	-2.0	-0.3	1.1	0.4	0.7	-0.1	0.1	-1.2	-0.5	-1.0	-0.1	-1.2	-0.8	-1.2	0.6	1.6
DEC.	-4.0**	-1.2	2.5*	2.8**	1.7	1.1	-0.1	-0.2	-1.6	-1.3	-0.9	0.0	-1.1	-2.7**	-3.4**	-1.4

Applying t-test to the monthly precipitation frequencies between the preceding 30 years and the following 30 years of a given year, the probability variable of the difference is often over significant levels (Tab. 4). The years, 1690, 1720, 1740, 1780 and 1820, serve as the boundaries between the statistically different periods. Thus the Little Ice Age in Japan can be divided into climatic phases.

Estimation of deviation of air temperature and precipitation for each phase

Tab. 5 indicates the monthly precipitation frequencies for the periods obtained in the preceding section. Two periods between 1691 and 1720, 1821 and 1850 have high frequency both in summer and in winter. On the other hand, the periods between 1661 and 1690, 1741 and 1780 have low frequency both in summer and winter. The periods from 1721 to 1740, from 1781 to 1820 and from 1851 to 1870 are transitional in character.

As stated in the first chapter, an increase in number of days with rainfall means a rise in precipitation and a fall in air temperature. If the precipitation frequency at that time can be compared with that of today, the amount of precipitation and air temperature in the Little Ice Age will be reconstructed. Actually, the precipitation frequencies at Hirosaki during the recent historical period are similar to those in the modern times (Tab. 6).

The difference between the frequencies in these two periods amounts to only less than

Table 5 Mean precipitation frequency for each climatic phase
upper - - - frequency of precipitation (%)
under - - - number of years with data arailable

	1661-1690	1691-1720	1721-1740	1741-1780	1781-1820	1821-1850	1851-1870
JAN.	55.5 23	70.5 29	54.2 20	54.9 39	64.7 39	76.2 29	74.9 15
FEB.	51.5 25	65.3 30	60.4 20	48.7 39	59.3 37	66.4 29	64.9 15
MAR.	35.5 22	57.2 30	47.3 20	44.2 40	49.4 38	58.9 30	49.4 13
APR.	33.0 23	44.0 29	39.5 20	33.9 40	39.6 39	48.8 30	40.3 14
MAY	30.9 22	34.4 29	35.2 20	32.6 40	35.8 39	37.8 29	36.0 14
JUNE	31.0 25	34.9 30	32.1 19	31.8 40	35.9 37	39.0 30	31.5 14
JULY	35.1 25	41.8 30	36.1 20	32.4 40	41.5 38	38.1 30	40.9 15
AUG.	31.9 23	35.3 30	33.6 20	35.8 40	36.4 36	39.1 30	27.9 15
SEPT.	36.4 20	43.5 30	41.7 20	40.3 40	44.3 37	47.8 29	43.8 15
OCT.	37.3 19	45.5 29	42.5 20	50.4 40	46.3 39	52.8 28	47.1 15
NOV.	53.3 23	59.7 26	60.4 20	57.5 40	61.1 39	64.1 29	55.2 15
DEC.	54.4 25	69.4 29	63.8 20	57.8 40	63.3 39	72.1 29	70.0 14

Table 6 Precipitation frequencies by historical record and modern observation

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
historical record	63.9	58.7	49.2	39.7	34.6	34.1	37.8	35.0	42.7	46.7	59.1	63.8
modern observation	74.5	62.7	51.9	34.0	30.3	33.7	32.6	31.9	39.3	40.3	57.3	66.8

Table 7 Estimated value of precipitation deviation for each climatic phase

	1661-1690	1691-1720	1721-1740	1741-1780	1781-1820	1821-1850	1851-1870
JAN.	-25	20	-29	-27	2	37	33
FEB.	-9	8	2	-12	1	10	8
MAR.	-20	12	-3	-7	0	14	0
APR.	-18	11	-1	-15	-0	24	1
MAY	-7	-0	1	-4	2	6	3
JUNE	-8	2	-6	-6	5	14	-7
JULY	-12	17	-7	-23	16	1	13
AUG.	-13	1	-6	3	5	16	-28
SEPT.	-19	2	-3	-7	5	15	3
OCT.	-20	-3	-9	8	-1	13	1
NOV.	-10	1	2	-3	3	9	-7
DEC.	-12	7	-0	-7	-1	10	8

Table 8 Estimated value of temperature deviation for each climatic phase

	1661-1690	1691-1720	1721-1740	1741-1780	1781-1820	1821-1850	1851-1870
JAN.	0.1	-0.1	0.1	0.1	-0.0	-0.2	-0.1
FEB.	0.6	-0.6	-0.1	0.9	-0.0	-0.7	-0.5
MAR.	0.9	-0.5	0.1	0.3	-0.0	-0.6	-0.0
APR.	0.2	-0.1	0.0	0.2	0.0	-0.3	-0.0
MAY	0.3	0.0	-0.1	0.2	-0.1	-0.3	-0.1
JUNE	0.1	-0.0	0.0	0.1	-0.0	-0.1	0.1
JULY	0.2	-0.3	0.1	0.4	-0.3	-0.0	-0.2
AUG.	0.2	-0.0	0.1	-0.0	-0.1	-0.3	0.4
SEPT.	0.2	-0.0	0.0	0.1	-0.0	-0.2	-0.0
OCT.	0.3	0.0	0.1	-0.1	0.0	-0.2	-0.0
NOV.	0.2	-0.0	-0.0	0.1	-0.1	-0.2	0.1
DEC.	0.8	-0.5	0.0	0.5	0.0	-0.7	-0.5

2% on annual average. Thus the precipitation and air temperature in historical times can be estimated, by using the regression equations between number of days with precipitation and precipitation or air temperature which were obtained above. The precipitation frequencies for winter in the historical period are smaller than those in the modern period, while they are larger in summer than those of today. These differences are less than 15%

even in January and July. This may result from the fact that the number of days with precipitation of today does not contain the days with daily precipitation less than 1 mm. In summer at that time it seems that light rains would be registered. Therefore, it may be difficult to estimate strictly the correct amounts of precipitation and mean air temperature during the Little Ice Age. In this paper, we will explain not the actual amount of precipitation and air temperature in each climatic phase, but their standard deviations.

From the precipitation frequencies during the historical times, the standard deviation of precipitation for each phase is obtained by using the regression equation between number of days with precipitation and precipitation (Tab. 7). The climatic characteristics for each phase are as follows.

1661 – 1690: a little rain throughout the year
1691 – 1720: much rain throughout the year
1721 – 1740: rather less rain throughout the year
1741 – 1780: little rain throughout the year
1781 – 1820: much rain in summer
1821 – 1850: much rain throughout the year
1851 – 1870: much rain in winter

From the above-stated facts, standard deviations are probably over-estimated in summer. The largest estimate of monthly average precipitation appears in April from 1821 to 1850, being 34% more than today.

The deviations of air temperature for each climatic phase are calculated by using the regression coefficient between mean number of days with precipitation and monthly mean daily maximum temperature (Tab. 8). The climatic characteristics are as follows.

1661 – 1690: warm throughout the year
1691 – 1720: cold in winter
1721 – 1740: moderate throughout the year
1741 – 1780: warm throughout the year
1781 – 1820: cool in summer
1821 – 1850: cool and cold throughout the year
1851 – 1870: cold in winter

The deviations for summer may be a little overestimated as in the case of precipitation. Temperature differences between warm and cold periods reach to 1.6°C in February, and 0.7°C in July.

4. Unusual Weather and Climatic Fluctuation

In Japan many historical documents with the records of natural disasters remain for many years. In particular, most disasters resulted from unusual weathers were described in every detail. For example, there were long lasting crop failures all over Japan from 1782 to 1787. Serious famines caused the decline in population. It reached to 1,119,159 and it is called "Famine in Tenmei Era" (Nakajima, 1981). In the Tohoku District, the northern part of Honshu, fatal crop failures happened. In 1783, a long spell of rain and cool weather in June, northerly wind even in midsummer caused the damage to the growth of crops. In addition, the killing frost in September made the situation the worst (Kusakabe, 1981).

These records of unusual weather does not cover any whole period. Whether they are appropriate to estimate correctly climatic conditions at that time, must be examined. From this purpose, the records of unusual weathers were compared with the climate reconstructed from consecutive daily weather records in the old diary. The records about the "Famine in Tempo Era" show that it was cool and cold in summer and extremely cold in winter. On the other hand, the weathers reconstructed from the diary records of the Feudal Clan Tsugaru are as follows: precipitation frequencies in July and August are large, and frequencies of fine and cloudy weather are small (Fig. 1). Occurrence frequencies of heavy rain and rain are not large, whereas that of light rain is large (Fig. 6). This indicates that the light rains result from the northeasterly wind from the Okhotsk High, which caused the cool and cold summer. Occurrence frequency of thunder is also high (Fig. 7). On the other hand in winter the occurrence frequencies of snow, strong wind (Fig. 3) and cold are large, too (Fig. 4). From the fact stated above, it is assumed that frequent snow storm resulted from the outburst of the Siberian High. In April the frequencies of both frost (Fig. 5) and snowfall (Fig. 2) are large. It is supposed that low temperature was predominant in spring. The climate reconstructed from the diary of the Feudal Clan Tsugaru is characterized by low temperature, especially cool summer. This coincides well to the weather estimated from the records of crop failure and other disasters. From these facts, the records of unusual weathers serve as fundamental data to reconstruct the past climate.

The records of noted natural disasters which caused a considerable damage in two or more provinces before 19th century, were elaborately collected (Kusakabe, 1981). As unusual weather long spell of rain, cool summer, heavy snow, severe winter, warm winter and drought were described in some detail. As stated above, they are important proxy data for reconstructing climatic fluctuation. The ratio of occurrence of unusual weather can be regarded as an indicator of the climatic fluctuation.

Figure 9 shows 30 year running mean of ten year average occurrence frequency for each unusual weather since 15th century. Long spell of rain and cool summer show low temperature in summer, and heavy snow and cold winter refer to low temperature in winter. On the other hand, drought indicates high temperature in summer. During the perod from 1616 to 1868 in which the diary of the Feudal Clan Tsugaru was recorded, we can discriminate three low temperature periods centered in 1705, 1785 and 1835, by examining the proxy data of unusual weathers and natural disasters. These situations coincide with the estimated low temperature periods from 1691 to 1720, from 1781 to 1820 and from 1821 to 1850 stated in preceding chapter. After 1868, when the diary ended, unusual weathers with low temperature often occurred from 1880 onwards. Before 1660 unusual weathers with low temperature often occurred during the period from 1610 to 1650. Before that the climate is uncertain because of shortage of documents. However, two periods with low temperature around 1430 and 1510 were discerned.

The records of the noted disasters were also collected for the other parts of Japan (Kusakabe, 1959 etc.). Calculating occurrence ratio of unusual weathers in other provinces for the above-stated climatic phases several similar situations are pointed out (Fig. 10). In other provinces the climatic fluctuation appeared in the same way as in northern Honshu or Tohoku. The frequencies of unusual weathers with the low temperature (long spell of rain,

cool summer, heavy snow and severe winter) are summarized for each climatic phase:
1661 – 1690: small (except Hokkaido)
1691 – 1720: a little larger (except Chugoku and Shikoku)
1721 – 1740: intermediate
1741 – 1780: a little small
1781 – 1820: intermediate (except Kinki)
1821 – 1850: large (except Chubu and Kinki)
1851 – 1870: a little larger (except Tohoku and Kyushu).

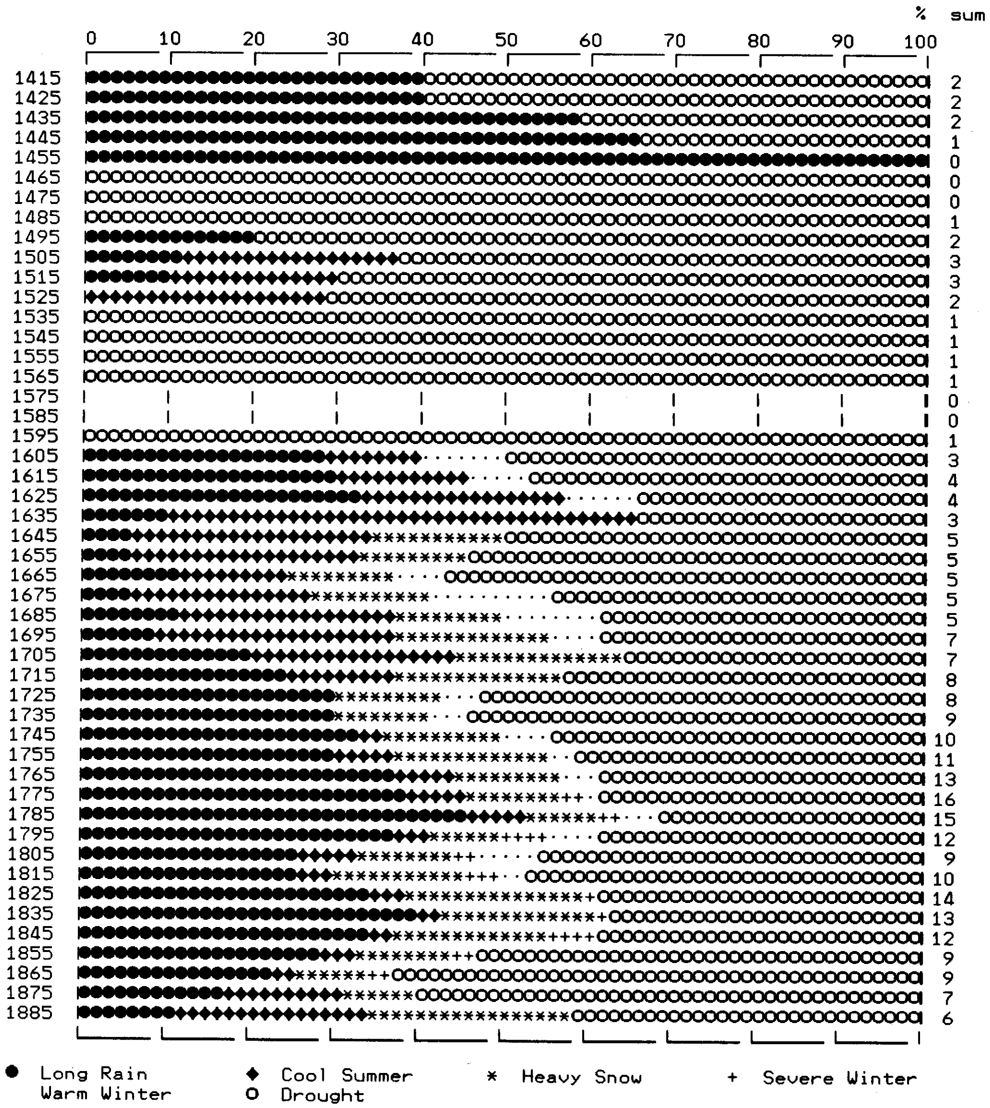

Fig. 9 Variation of unusual weather frequency in Tohoku District (changed into the occurrence ratio of each unusual weather to the total of them)

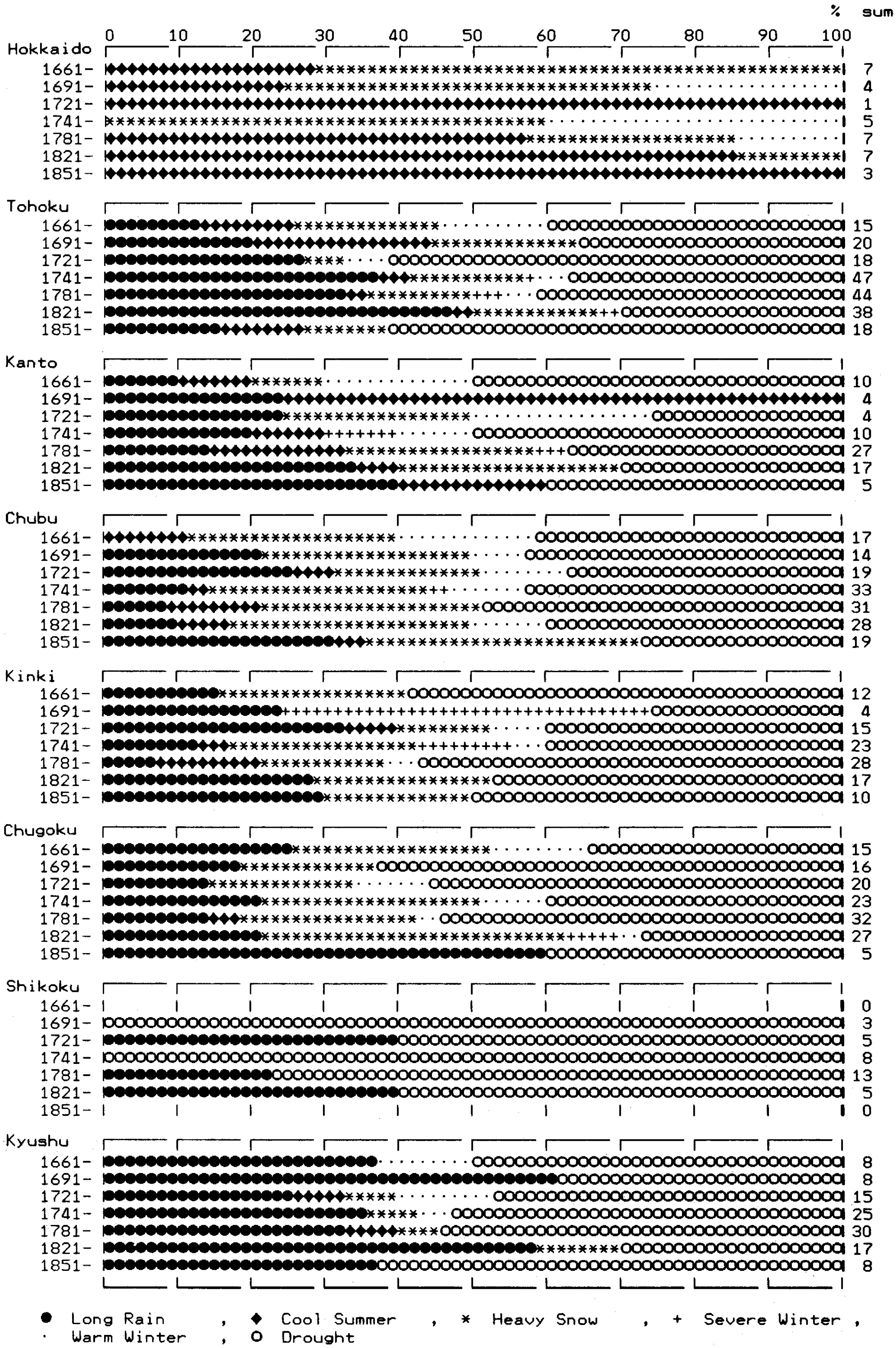

Fig. 10 Variation of unusual weather frequency in each district of Japan (changed into the occurrence ratio of each unusual weather to the total of them)

As stated above, despite few discrepancy the general tendency of climatic fluctuation coincides with the temperature trend reconstructed from the weather records at Hirosaki. From these facts, it can be confirmed that the climate fluctuated in the same way all over Japan during the recent historical times, the Little Ice Age.

5. Conclusion

According to the reconstruction of the climate by using daily weather records in the diary of the Feudal Clan Tsugaru (Maejima, I. et al., 1983), the divisions of the recent historical climatic phases can be established (Tab. 9). In this study, the periods extremely cold in winter and cool in summer are called the phase I, II and III of the Little Ice Age. These phases of Little Ice Age occurred all over Japanese Islands.

Table 9 Pattern of the Little Ice Age in Japan

period	climate type		winters	summers
1611-1650	very cold	- Little Ice Age, Phase I	very cold, heavy snow ?	very cool, rainy ?
1651-1690	mild	- Interglacial I	mild, light snow	hot in the first half
1691-1720	very cold	Little Ice Age, Phase II	very cold, heavy snow	very cool, rainy
1721-1740	cold		cold	cool
1741-1780	mild	- Interglacial II	two mild, light snow terms	hot in the second half
1781-1820	cold	Little Ice Age, Phase III	cold	very cool, rainy
1821-1850	very cold		very cold, heavy snow	very cool, rainy
1851-1880	cold		very cold, heavy snow	warm

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