Analysis of Precipitation Data at Yokohama, Japan, from 1863 to 1869 Observed by J.C. Hepburn

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Abstract
This study analyzed precipitation data during the 1860s in Yokohama, Japan, using observations made by an American Christian missionary, J.C. Hepburn. Hepburn’s meteorological data included monthly maximum, mean, and minimum temperatures, monthly precipitation, and the number of rain days in each month. The climate during the late 1860s was characterized by large inter-annual precipitation variability during summer. We detected unusually heavy rainfall during the summer of 1868, whereas the summer of 1867 was characterized by extremely low precipitation. These trends are in accordance with precipitation patterns reconstructed from historical weather documents. Furthermore, we investigated the spatial distribution of extreme climate events in 1867 and 1868 throughout Japan. The results suggest that the unusual dryness in 1867 and wetness in 1868 were related to synoptic-scale climate in Japan, rather than local-scale patterns in Yokohama. The results from this study could be used to understand the nature of summer climate variations in Japan in the 1860s.

Key words: early meteorological data, Yokohama, precipitation, 1860s, J.C. Hepburn

I. Introduction

Historical meteorological data is important not only for investigating past climate, but also for evaluating present and future climate changes. However, there is a lack of reliable meteorological data outside Europe before the mid-19th century (Lamb, 1995). Recently, data rescue studies have collected and digitized early meteorological data from around the world (Burnet and Jones, 2011; Dunn et al., 2015; Edinburgh and Day, 2016).

In Japan, official meteorological observations by the Japan Meteorological Agency (JMA) started in the early 1870s, offering a much shorter meteorological observation record compared to Europe. The Japanese government imposed a national isolation policy from the 17th century to the mid-19th century; thus, it was difficult to introduce modern meteorological instruments into Japan before the mid-19th century. However, Dutch settlers were allowed to conduct meteorological observations in a small settlement in Nagasaki, western Japan (Können et al., 2003).

On the basis of these early meteorological records, Können et al. (2003) recovered pressure and temperature data for Nagasaki from as far back as 1819. Zaiki et al. (2006) recovered pressure and temperature data from Edo...
(Tokyo) and Osaka dating back to the 1820s. Early meteorological observations in these areas were taken by Japanese scientists as part of the so-called “Dutch Study” associated with astronomical research (Zaiki et al., 2006). Furthermore, Zaiki et al. (2009) reconstructed sea level pressure patterns around Japan back to the 1820s based on instrumental temperature and pressure series from Tokyo and Nagasaki.

Compared to pressure and temperature data, precipitation data are rare prior to the 1870s. Due to a lack of a reliable precipitation data series, our knowledge of precipitation variability for the pre-JMA period is limited. Although analyses of early temperature series have detected warm summers in the 1850s (Zaiki et al., 2006; Mikami et al., 2013), precipitation variations during the mid- to late-19th century have not yet been clarified.

Recently, a consecutive precipitation series observed from 1863 to 1869 by an American Christian missionary, James Curtis Hepburn, has been found for Yokohama, Japan (Fig. 1). In this study, we investigate this series to clarify the nature of climate variations during the 1860s. Based on a preliminary investigation, the precipitation series indicates unusually high rainfall in the summer of 1868, and extremely low precipitation in the summer of 1867. Therefore, we focus our investigation on the summer climate conditions in 1867 and 1868. We also compared Hepburn’s meteorological records to historical daily weather documents to check the reliability of his observations. Finally, we investigated the spatial patterns of dryness and wetness in 1867 and 1868, respectively, throughout Japan based on historical climate event records available for various locations.

II. Data source and description

A table of the meteorological data observed by Hepburn is presented in a bulletin of the Asiatic Society of Japan, entitled “Transactions of the Asiatic Society of Japan from 22nd October 1873 to 15th July, 1874” (Hepburn, 1874). This meteorological table contains monthly maximum, mean, and minimum temperatures, monthly precipitation, and the number of rainy days in each month. This newly found series recorded by Hepburn is archived in the Meiji Gakuin Historical Museum in Tokyo.

Monthly mean temperature values of Hepburn’s observations have been digitized and are available on the Japan–Asia Climate Data Program (JCDP) website (Mikami et al., 2013). However, precipitation data from these observations have not yet been analyzed, which represents a gap in our knowledge of early meteorological series in Japan.

The monthly precipitation values are record-
ed in inches (25.4 mm); therefore, we converted the data from inches into millimeters. The converted values of monthly precipitation and number of rain days for each month are shown in Tables 1 and 2, respectively.

III. Inter-annual variation in precipitation during the late 19th century in Yokohama

Next, we investigated the inter-annual variation in precipitation during the late 19th century based on Hepburn’s data. To check the reliability of Hepburn’s observations, we compared Hepburn’s precipitation records with reconstructed climate data from historical daily weather documents for the 1860s.

1) Inter-annual variation in precipitation during the 1860s

Figures 2a–d show the variations in precipitation for each season from 1863 to 1869. Precipitation variations in summer (i.e., June, July, and August) (Fig. 2c) showed a prominent peak in 1868. The precipitation level in 1868 was above 1400 mm, whereas that in 1867 was less than 400 mm. Because such heavy precipitation was not observed in other seasons, the unusually wet summer in 1868 appears to be a unique phenomenon. Therefore, we investigated the detailed variations in monthly precipitation for June, July, and August, and the heavy precipitation in 1868 was observed during all summer months (Figs. 2e–g).

In contrast, the amount of precipitation in July (Fig. 2f) and August (Fig. 2g) of 1867 was extremely low. The difference in precipitation between 1867 and 1868 suggests that the summer climate in the late 1860s was characterized by large inter-annual variability.

Figure 3 shows a comparison of Hepburn’s summer precipitation data in the 1860s and precipitation at the JMA Yokohama station after 1897. Precipitation in 1868 was the high-

| Year | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1863 | 92.7| 57.2| 149.9| 135.6| 143.3| 35.6| 69.9| 197.1| 181.9| 104.1| 87.4| 29.7|
| 1864 | 21.1| 48.8| 51.1| 238.0| 104.1| 231.4| 113.8| 145.0| 452.9| 100.8| 113.5| 194.1|
| 1865 | 33.0| 167.4| 62.7| 179.6| 113.5| 159.8| 241.8| 79.0| 135.1| 170.4| 50.0| 149.9|
| 1866 | 46.0| 89.7| 113.0| 156.5| 94.7| 195.3| 148.3| 198.4| 256.0| 80.0| 119.1| 158.0|
| 1867 | 59.7| 46.0| 55.4| 165.9| 111.8| 216.4| 33.3| 8.6| 190.5| 58.2| 50.8| 86.1|
| 1868 | 114.8| 66.5| 169.9| 122.4| 260.1| 456.2| 610.6| 433.1| 489.5| 295.1| 56.1| 41.4|
| 1869 | 50.3| 58.9| 296.9| 175.3| 205.7| 161.3| 243.3| 131.3| 106.4| 422.7| 137.4| 21.3|

unit: mm.

| Year | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1863 | 5   | 5   | 10  | 11  | 10  | 7   | 8   | 12  | 13  | 8   | 9   | 4   |
| 1864 | 5   | 8   | 8   | 12  | 9   | 11  | 6   | 9   | 15  | 5   | 5   | 7   |
| 1865 | 1   | 9   | 8   | 11  | 8   | 16  | 18  | 7   | 14  | 6   | 8   | 4   |
| 1866 | 3   | 7   | 11  | 11  | 12  | 12  | 11  | 9   | 12  | 1   | 5   | 3   |
| 1867 | 8   | 3   | 4   | 11  | 9   | 10  | 8   | 2   | 11  | 4   | 4   | 4   |
| 1868 | 4   | 6   | 11  | 9   | 7   | 18  | 12  | 16  | 9   | 13  | 4   | 5   |
| 1869 | 5   | 5   | 7   | 3   | 4   | 5   | 7   | 10  | 9   | 12  | 11  | 3   |

unit: day.
est level on record since the 1860s. Based on these results, the summer climate of the 1860s was characterized by a marked contrast between dryness and wetness from 1867 to 1868.

2) **Comparison of Hepburn’s precipitation data with historical weather documents**

Hepburn’s daily precipitation data have not yet been found. In addition, Hepburn’s paper (Hepburn, 1874) does not contain metadata for the observations, and instrumental precipitation data located near Yokohama are not available for the 1860s. Therefore, it was difficult to assess the quality of Hepburn’s precipitation data.

However, daily historical weather documents from old Japanese diaries have been collected and digitized (Yoshimura, 1993, 2013; Mikami, 1996, 2008; Mikami et al., 2013), which document weather in many locations throughout Japan during the Edo period of Japanese history (i.e., 17th to mid-19th century). Therefore, we verified the reliability of Hepburn’s observations by comparing them with reconstructed cli-

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Fig. 2 Interannual variation of seasonal and monthly precipitation at Yokohama for the period 1863–1869.
mate data from historical weather documents.

Although it is difficult to reconstruct monthly and seasonal precipitation from historical weather documents, we can count the number of “heavy rain” days from these diaries. Daily weather documents from the Ishikawa Diary series (Hachioji History Museum, 1991) have been documented in Hachioji, a western suburb of Tokyo (Fig. 1). As Hachioji is close to Yokohama, this series enables a comparison between Hepburn’s precipitation data and historical weather records.

Figure 4 shows the number of heavy rainfall days during summer documented in the Ishikawa Diary series. A prominent peak was observed in 1868. Frequent heavy rainfall in 1868 appears to agree with the heavy summer rainfall in Yokohama. Therefore, we conclude that Hepburn’s records indicating heavy rainfall in 1868 are highly reliable.

IV. Spatial patterns of precipitation in 1867 and 1868

Hepburn’s meteorological data showed an unusually dry summer in 1867 and a wet summer in 1868. To clarify whether these unusual summer climates were related to synoptic-scale climate, we analyzed the spatial patterns of summer precipitation in 1867 and 1868 using historical weather documents and climate event records available for various locations throughout Japan.

1) Spatial patterns of anomalous rainfall frequency

We investigated the spatial patterns of anomalous rainfall frequency for 1867 and 1868. We used historical daily weather documents stored in the Historical Weather Database (Yoshimura, 1993, 2013) for this analysis. In addition to this database, we used historical weather records of “Murakami-Kajou Dairy” in Hiroshima, which is not included in Historical Weather Database. Using historical weather documents for 16 locations in Japan, we computed the rainfall frequency during summer (i.e., JJA rainfall frequency) for 1860–1869. Then, we computed anomaly of rainfall frequencies for 1867 and 1868 relative to average values during the 1860s (Fig. 5). The summer of 1867 (Fig. 5a) was characterized by a negative anomaly over central Japan. Conversely, 1868 (Fig. 5b) was characterized by a positive anomaly over the same area. These features are consistent with the extremely dry summer of 1867 and the rainy summer of 1868 in Yokohama, as observed by Hepburn.

2) Spatial patterns of climate events in 1867 and 1868

Next, we investigated the spatial patterns of
summer climate events in 1867 and 1868 using the chronology of natural disasters (Kusakabe, 1959, 1968, 1973, 1975, 1977, 1978, 1981).

This chronology contains climate disasters, such as drought and long-term persistent rain, heavy rainfall, and storms/violent winds. In general, drought occurrence can be easily detected using descriptions of “drought” or “days without rainfall”. Therefore, we categorized disasters such as “drought” and “continuous days without rain” into a “drought type disaster” category. We categorized disasters related to extremely wet conditions, such as “long-term persistent rainfall”, “heavy rainfall”, and “storms/violent winds” into a “wet type disaster” category. Then, we created spatial maps of disaster types for the summers of 1867 and 1868 (Fig. 6).

Climate events in 1867 (Fig. 6a) were characterized by frequent “drought type disasters” over a large area of Japan, but there were no records of “wet type disasters” in 1867. Table 3 represents each “drought type disaster” that occurred in 1867. We can confirm that severe dry conditions were frequently recorded from June to August in many areas of Japan. In particular, descriptions imply that extremely dry weather without rainfall continued through July and August. For example, “sunny days continued without rainfall from July 24 to August 29” in Gifu, central Japan.

In contrast, 1868 (Fig. 6b) was characterized by the occurrence of “wet type disasters” over a large area of Japan. However, we should note that frequent “wet type disasters” does not always guarantee a high amount of rainfall. For example, the amount of rainfall is not always proportional to the length of rainy days. To confirm whether the summer of 1868 was indeed extremely wet, we investigated each “wet type disaster” event in detail. Then, the documents representing “wet type disasters” in 1868 are shown in Table 4.

As shown in Table 4, long-term persistent rainfall occurred over a large area of Japan, which involved frequent heavy rainfall. In Northern Japan, “heavy rainfall continued through night and day from July 13 to July 23 in Miyagi Prefecture, which was very unusual weather.” (Kusakabe, 1981). In Tokyo, Chiba,
and Kanagawa, “cloudy and rainy days have continued since June 18, and flooding occurred”. “Strong storm/heavy rainfall occurred in in June 27” (Kusakabe, 1973). In addition, a disaster chronology of “Buko Nenpyo” in Tokyo (Imai, 2003) reported that “rainy days continued in Tokyo from June to July, heavy rainfall frequently occurred, and fine days have been rare in recent days”. These documents indicate that the summer climate of 1868 was characterized by long-term persistent rainfall, which accompanied frequent heavy rainfall events.

Climate disaster records for 1867 and 1868 are in good agreement with the spatial patterns and rainfall frequency anomalies in both years (Fig. 5). Moreover, they are consistent with observed precipitation data for Yokohama. Therefore, we suggest that the unusually dry summer in 1867 and heavy rainfall in 1868 were related to synoptic-scale climate rather than local-scale patterns around Yokohama.

V. Discussion and conclusions

In this study, we analyzed newly found precipitation data from the 1860s observed by J.C. Hepburn in Yokohama, Japan. The results show that the climate in the late 1860s was characterized by large inter-annual variabili-
ty of summer precipitation. In contrast to the well-known famine in the 1780s (Mikami, 1983) and 1830s (Yaji and Misawa, 1981), few studies have investigated climate in the 1860s. This study reveals that climate in the 1860s was characterized by large inter-annual variability of summer precipitation.

We detected an unusually dry summer in 1867 and a wet summer in 1868, which were confirmed by historical daily weather documents and climate event records at various locations throughout Japan. Therefore, these unusual patterns were likely related to largescale atmospheric circulation patterns around Japan. In 1867, drought events were recorded over a large area of the Japanese Islands. We assume that the dry climate in 1867 was influenced by a strong North Pacific Subtropical High (NPSH), which suppressed cloud cover over Japan.

Climate in 1868 was characterized by frequent “wet-type disasters”. Extreme wet conditions are often caused by multiple factors, such as typhoons and activity of the Baiu frontal zone. Therefore, it is difficult to determine the cause of the extremely wet summer of 1868 using historical data within Japan.

To understand meteorological cause of extremely wet summer of 1868, a reconstruction of dryness and wetness patterns throughout East Asia is required. The Baiu frontal zone influences rainfall not only in Japan but over middle and south China (Yoshino, 1991). Yearly charts of dryness and wetness over China for the previous 500-year period were reconstructed using many historical documents (Chinese Academy of Meteorological Science, 1981). Using historical data from both Japan and China is valuable for reconstructing dryness and wetness patterns over East Asia. These efforts can determine whether the Baiu front is related to the extremely wet summer.

With respect to typhoons, Grossman and Zaiki (2013) reconstructed annual numbers of typhoons affecting Japan during the late 19th century using historical weather data in Japan and early weather observations from outside of Japan. According to their study, two typhoons affected Japan in 1868, which is less than the average for the late 19th century. However,
the influence of remote typhoon activities on heavy rainfall was not clarified in their study. Even typhoons located far from land can influence frontal activities and cause heavy rainfall (Wang et al., 2009; Yoshida and Itoh, 2012). Thus, additional studies are required to clarify typhoon activities in the northwest Pacific. Specifically, using ship logbooks (García-Herrera et al., 2004; Mock et al., 2010) is a potentially useful methodology for reconstructing typhoon activities over ocean areas.

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ヘボンの気象観測記録からみた
横浜における1863-1869年の降水量変動

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本研究では、米国人宣教師ヘボン（J.C. Hepburn）によって1860年代に行われた気象観測資料をもとに、1863-1869年における横浜の降水量変動の特徴を明らかにした。横浜におけるヘボンの気象観測資料には、月最高気温、平均気温、最低気温、月別降水日数、および月別降水量が記録されている。これまで、日本では公式気象観測開始（1870年代）以前の降水量観測記録はほとんど知られていない。今回、新たに発見されたヘボンの降水量観測記録は、1860年代の降水量変動の特徴を解明する上で貴重な資料である。月別および季節別に降水量変動を分析した結果、1868年の夏季（6-8月）は他の年に比べて著しく多雨であり、また1867年は降水量がきわめて少なく、乾燥傾向の強かったことが明らかとなった。これらの現象の空間特性を検証するために、日本各地に残された古日記天候記録において1867年と1868年の降水出現率を算出し、それらの空間分布との関連を比較した。その結果、1867年の夏季は全国的に降水出現率が少なく、また1868年は全国的に降水出現率が高かったことが明らかになった。さらに、気候災害記録との比較を行った結果、1867年は日本各地で干ばつや少雨が記録されているのに対して、1868年の夏は各地で大雨や長雨に伴う水害が頻発していたことが明らかになった。これらの結果は、1867年夏の少雨と1868年夏の多雨が広域的な現象であったことを示している。

キーワード：古気象観測記録、横浜、降水量、1860年代、ヘボン

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