NOTES AND CORRESPONDENCE

Changes in Hourly Heavy Precipitation at Tokyo from 1890 to 1999

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Abstract

Intensification of heavy precipitation foreseen in climate change studies has become a public concern, but it has not yet been examined well with observed data, particularly with data at short temporal scale like hourly data. On hourly heavy precipitation at Tokyo, previous studies investigated the data only from the 1970's due to the availability of digital data. In this research, we digitalized hourly precipitation since 1890 recorded at the Tokyo observatory in order to investigate historical changes in hourly heavy precipitation at Tokyo. The recent decade, the 1990's, was indeed a period with considerably strong and frequent hourly heavy precipitation, but another period with strong/frequent hourly heavy precipitation was found around the 1940's. Hourly heavy precipitation around the 1940's was even stronger/more frequent than in the 1990's. Thereby, it cannot be said that recent hourly heavy precipitation has become unprecedentedly strong or frequent. In addition, the numbers of hourly heavy precipitation events by tropical cyclone and by Baiu front were counted respectively, resulting in that the composition of the causes of hourly heavy precipitation events in the 1940's appears to be different from that in the 1990's.

1. Introduction

It is anticipated that the number and the intensity of heavy precipitation events would increase as a consequence of possible climate change (Meehl et al. 2000; Houghton et al.

2001). Model analysis has shown that precipitation with higher intensity and within narrower area would come out under the condition of global warming (e.g., Noda and Tokioka 1989). Urbanization seems to affect, probably increase, heavy precipitation as well. One may suspect whether such an increase has already appeared. Recent studies (e.g., Groisman et al. 1999; Easterling et al. 2000; Manton et al. 2001) analyzed the changes in observed heavy precipitation, based on daily precipitation, re-

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sulting in the detection of an increase in heavy precipitation at many parts of the world, with a decrease at some parts of the world. An upward trend in heavy precipitation over Japan was found in some studies (e.g., Iwashima and Yamamoto 1993; Manton et al. 2001) also based on daily precipitation. Due to the limitation of available digitalized records, as described above, daily precipitation has been the major material for analysis so far.

Typical temporal scales of precipitation phenomena may suggest us to analyze precipitation records of shorter resolution than a day. Considering the operationally observed items, it is possible to utilize hourly precipitation for analysis. Utilization of the hourly record is more valid in the investigation of precipitation over warm humid Asia where heavy precipitation in a short duration embarrasses the lives of the highly populated people mostly living in the cities on very narrow and fragile alluvial plains (Musiake 2002). Some previous studies (e.g., Fujibe 1998; Sato 2000) took the advantage of utilizing hourly precipitation for analysis of changes in precipitation in Tokyo, but the periods of the utilized data are generally limited to a few decades due to the availability of digital data. Recent progresses on decadal-scale variability of climate may point out to us the importance of studying the changes in hydrological cycle with a longer record.

In this study, we digitalized the hourly precipitation data from 1890 to 1999 recorded at the Tokyo observatory of the Central Meteorological Observatory (up to June 1956) and Japan Meteorological Agency (JMA) (after July 1956). Tokyo was arbitrarily selected from the limited numbers of stations where hourly precipitation has been recorded for more than 100 years, mainly because it is the capital with high population and we live there. Since such an observatory with a long record is mostly located in a city with urbanization through the last century, the mixture of the effects of large scale climate change and local urbanization is necessarily unavoidable.

2. Data

As mentioned above, hourly precipitation data observed at Tokyo was digitalized for the analyses of the present study. The data from 1976 was already digitalized by JMA and avail-

able on CD-ROM. The data from 1890 to 1975 was obtained from microfilms stored in JMA. We manually digitalized the data from 1890 to 1975 consuming a few months person-days.

Quality check was applied to the digitalized dataset such as calculating daily totals from the dataset and comparing them with another independent daily precipitation dataset (Kajiwar et al. 2002). When we found a difference in the comparison, we again went to JMA and checked the data. The above procedure was carried out for the prevention of mistype. Check of the quality of the original data itself was out of target, which is almost impossible. Hourly precipitation data in 1953, 54 and 55 is lacking probably due to an administrative change of the agency in those days. In 1953, 54 and 55, only the maximum hourly precipitation of each day is available. How the data of 1953–55 will be treated in the analyses/figures afterwards is described here. In Fig. 1, the information from 1953 to 1955 is lacking because this figure deals with total precipitation hours in each year. For Figs 2 and 4, only the maximum hourly precipitation of each year is needed. It is available for 1953–55. In Figs 3 and 5, we simply utilize the maximum hourly precipitation data of each day for these three years because many of hourly heavy precipitation events are considered to be included in it, but we should note that there probably remains some underestimation in the information for the 1950's. The lacks of measurement occurred as in Table 1. Since they occurred basically in winter, it is assumed that the impact of them on heavy precipitation analysis is minor.

In the past from 1890 to September 1965, precipitation was measured with a storage type rain gauge, which enabled the record on a 0.1 mm/hour basis. Then, the measurement became a 0.5 mm/hour basis, using a tipping bucket rain gauge from the middle of 1965. The

Table 1. The lacks of measurement.

Year	Month	Day	Local Time
1972	1	10	4–12
1974	1	21	22–24
1974	2	6	1–6
1988	7	30	3
1994	9	17	18–19
1998	1	8	16–21

data in CD-ROM since 1976 is available only on a 1 mm/hour basis.

Although these differences in the recording resolution do not affect our analyses much because this study mainly focuses on heavy precipitation, a tipping bucket simulation was applied to the digitalized dataset into a new dataset completely with 1 mm/hour resolution. The tipping bucket simulation assumes a 1 mm bucket in a computer program, which can keep and accumulate small precipitation amounts less than 1 mm to the next time step. Every 0.1 mm based data was hypothetically thrown into the bucket in the program to obtain a new 1 mm based dataset. Most analyses below are based on the new dataset after the tipping bucket simulation. The effect of the changes in rain gauge type is assumed to be negligible. The location of the rain gauge moved ($35^{\circ}41'N$, $139^{\circ}45'E$ until 1922, and $35^{\circ}41'N$, $139^{\circ}46'E$ from 1923), but it is assumed to be negligible as well.

Without the application of the tipping bucket simulation, there is an apparent decrease of total precipitation hours per year from 1890 to the present (Fig. 1), which may lead us to the misunderstanding that precipitation hours really would have decreased drastically. With the application of the tipping bucket simulation, almost stable rainfall hours in each year appear in Fig. 1, with a slight decrease from the

past to the current. Considering the changes in measurement, we should be careful about whether the decrease is actual or not. If we assumed the decrease in precipitation hours is in reality, mean precipitation rate would have increased. However, it is not sure. We leave this problem related to mean value and total hours here to go into the analysis of heavy precipitation.

3. Results

We tried to adopt several measures for heavy precipitation analysis, since there is not an only measure to clarify the changes in the time series of heavy precipitation. The first is the time series of annual maximum hourly precipitation (mm) in each year (Fig. 2). Secondary, the time series of the number of events above 20 mm/hour and 50 mm/hour in each decade are shown in Fig. 3. In the guideline of JMA for public, 20 mm/hour is the intensity of “strong” precipitation that may cause a flood in a stream and 50 mm/hour is “very torrential” precipitation with possibility of disasters. We also picked up the highest 110 events of hourly and daily precipitation since 1890 (here, 110 is just the number of total years), and plotted the number of the events in each decade (Fig. 3).

If looking at the time series only after 1976 or the 1970's in Figs 2 and 3, which correspond to the analyses based on the already available digital data on CD-ROM, upward trends can be seen (although the trend in Fig. 2 after 1976 is not statistically significant at 90% level). It can be said at least that many hourly heavy precipitation events (above 20 mm/hour) occurred in the 1990's compared with in the 1970's and the 1980's. The 1990's seems to be unprecedented in the history from the 1970's. However, if looking at the entire parts of Figs 2 and 3, we can find that very heavy hourly precipitation events (in terms of the maximum hourly precipitation of each year) and frequent hourly heavy precipitation (in terms of the number of hourly heavy precipitation events) occurred also around the 1940's. If we pick out the highest 10 events (Table 2), 9 events out of 10 occurred before 1960, mostly around the 1940's, and 1 event occurred in the 1990's. It can be stated that hourly heavy precipitation around the 1940's is even stronger/more frequent than in the 1990's. In the following, we will call these

Fig. 1. Total precipitation hours from 1890 to 1999. The triangles denote the total hours without the tipping bucket simulation. The squares denote the total hours with the tipping bucket simulation. The 11-year moving average of the total hours with the tipping bucket simulation is presented as well.

Fig. 2. Time series of annual maximum precipitation (mm/hour). Time series after 1976 based on already available digital data is shadowed. The arrow also indicates 1976. In addition, 11-year moving average is shown.

two periods (the 1940's and the 1990's) as "peaks", though the 1990's is not a peak mathematically because the 1990's is located at the edge of the time series. A "bottom" with smaller maximum hourly precipitation and less frequent hourly heavy precipitation can be seen in the 1970's. If one utilized the data only after the 1970's, he may conclude that recent heavy precipitation in the 1990's was unprecedentedly intense and frequent. However, this conclusion is first found to be wrong when viewed by the centennial scale data in the present study. This is simply a misunderstanding because the local frequency minimum in the longer time series is just located in the 1970's.

The peaks and bottom described above seem to form a multi-decadal variability. It may be possible that the peaks and bottom are linked with global or large scale variability of climate. For example, Kunkel (2003) mentioned that the spatial and temporal variations of SSTs on a global scale may be one direct and proximate cause of the recent observed upward trend in U.S. multi-day-duration extreme precipitation. Although his target of analysis is not based on hourly precipitation but on multi-day-duration precipitation, his study shows the possible impact of global or large scale climatic variability on regional extremes.

Zhu and Wang (2002) found 80-year scale variability in summer monsoon rainfall in China, which seems to be not much different from the time scale seen in Figs 2 and 3. Zhang

Fig. 3. The number of precipitation events more than 50 mm/hour and 20 mm/hour in each decade (bar graph). The number of the events in each decade which belong to the 110 highest hourly precipitation events through the 110-year history (line graph). That of the 110 highest daily is also presented.

Table 2. The heaviest 10 events of hourly precipitation from 1890 to 1999.

Year	Month	Day	Local Time	Precipitation (mm)
1911	8	10	1	70
1935	10	27	12	71
1939	7	31	21	88
1939	7	31	22	59
1947	8	28	7	64
1948	7	23	20	60
1949	8	24	20	65
1951	8	21	18	65
1958	9	26	18	69
1993	8	27	13	64

et al. (1997) found an ENSO-like interdecadal variability in sea surface temperature (SST) of the Pacific. A 50–70 year climatic oscillation over the North Pacific and North America was found by Minobe (1997). Other many studies in these days have referred to decadal or multi-decadal scale variability as well. However, such variability is mostly derived from the seasonally or annually averaged values of precipitation, SST and other climate items. Thus, variability in the time series of extremes in a short duration as analyzed in this study has been left for further analysis. The similarity between the time series of the highest hourly 110 events and that of daily (Fig. 3) may become a clue to the further analysis.

Fig. 4. Annual maximum precipitation (mm/hour) and the number of sunspots. Left vertical axis denotes mm/hour, and right denotes the number of sunspots.

It may also be possible, as shown in Fig. 4 that compares annual maximum precipitation with the number of sunspots, that the variability of heavy precipitation has a relationship with the variability of the activity of the sun. In particular from the middle of the 1930's, the timing of peaks and bottoms of annual maximum hourly precipitation and the number of sunspots are likely to correspond to each other. When X -year ($X = 1, 2, 3, \dots$) auto correlation coefficient (ACC) for the time series of annual maximum precipitation was calculated, the largest value of ACC was obtained when X equals 12. Spectral analysis also produces a peak in 12, but it is not statistically significant. This "12" seems to be similar to "11 years", the cycle of sunspots. However, we should note that the physical mechanism connecting heavy precipitation and the activity of the sun is very much uncertain. We also should note that the cycle obtained by ACC is 12-year which is not exactly the same as 11-year, the cycle of sunspots, and the good correspondence is not found before the 1930's. Further analysis is needed as well.

4. Heavy precipitation by tropical cyclones and Baiu

Classification of heavy precipitation events by their causes may help the understanding of the peaks and bottoms found in Figs 2 and 3. Heavy precipitation in Tokyo, which is located in warm humid East Asia, usually occurs with

four causes: tropical cyclone, extra-tropical depression, the Baiu front in June and July, and local strong convection triggered by land heating which usually can be seen in summer after the Baiu season. Heavy precipitation events by tropical cyclones and by Baiu front can be extracted, even though approximately, from the entire dataset as described below. On the other hand, it is very difficult to distinguish the others with limited information available from 1890.

The information of tropical cyclones was obtained from Global Tropical Cyclone Climatic Atlas maintained by Fleet Numerical Meteorology & Oceanography Detachment (<http://navy.ncdc.noaa.gov/products/gtcca/>) and weather charts of JMA. The data from 1932 was used due to the availability. If a heavy precipitation event more than 20 mm/hour was recorded when the center of a tropical cyclone was located within the area of 130° – 150° E and 30° – 40° N, the event was classified into the group of tropical cyclone-caused heavy precipitation. The area above is determined by considering the location of Tokyo ($139^{\circ}45'$ E, $35^{\circ}40'$ N), radius of cyclones and the fact that tropical cyclones tend to move faster when their direction is east rather than north.

JMA has determined the Baiu period of each year since 1951. Before 1950, we subjectively determined the Baiu period of each year. First, the period of 16 June to 5 July was automatically determined to be within Baiu because the JMA's Baiu periods in 1951–99 possess this period. Second, within the end of May to the beginning of August, 5-day moving average and daily precipitation amounts were examined to subjectively determine the Baiu period of each year. Periods with continuous and plenty of precipitation were simply determined as the Baiu periods. If the same method was applied to the data after 1951, the subjectively and blindly determined Baiu period of a year differs only by a few days from the JMA's Baiu period of the year. If a heavy precipitation event was recorded in the Baiu periods, the event was classified into the group of Baiu-caused heavy precipitation. If an event can be classified both into the group of Baiu-caused precipitation and the group of tropical cyclone-caused precipitation at the same time, both the two groups gain +1 each in counting the number.

Fig. 5. The number of tropical cyclone-caused, Baiu-caused and total precipitation events more than 20 mm/hour in each decade (vertical axis is on the left). The number of tropical cyclones passing through the area of 130°–150°E and 30°–40°N in each decade (vertical axis is on the right).

Since the above criteria are not perfect to classify the events into the group of tropical cyclone-caused precipitation or the group of Baiu-caused precipitation, some heavy precipitation events may be incorrectly contaminated into or excluded from each group. Suppose some very heavy precipitation events are incorrectly contaminated, extreme/maximum values may be affected much by the contaminated values. Also, mean values may be affected in such a case. If we deal with the number of events above (or below) a criterion, the effect of contamination becomes less. Thereby, we adopted the number of events above 20 mm/hour in each decade for the robustness of the analysis. The criterion (above 20 mm/hour) is arbitrarily determined because it is the intensity of “strong” precipitation of JMA as described already.

The result is shown in Fig. 5. In the following, we mainly investigate the two peaks and one bottom described in the previous section. The peak of the 1940’s was lead by many Baiu-caused heavy precipitation events. The mean period of the Baiu season averaged over the 1940’s was from 6 June to 17 July, which is not specifically longer than in other periods. The cause of the bottom of the 1970’s was a con-

siderably small number of heavy precipitation events caused by tropical cyclones. The 1990’s-peak was formed, to some extent, by the increase in heavy precipitation events caused by tropical cyclones, which is in contrast with the case of the 1940’s-peak. The contrast between the 1940’s and the 1990’s seems to become an interesting research topic, but further analysis may be not easy to carry out due to the less availability of many kinds of climatic data in the 1940’s. The number of heavy precipitation events caused by tropical cyclones in each decade has a close relation with the number of tropical cyclones passing the area (130°–150°E and 30°–40°N) in each decade. Therefore, abundant hourly heavy precipitation events in the 1990’s and less events in the 1970’s are considerably explained by the change in the number of tropical cyclones passing the area. The 1940’s is an exception, because it is dominated by Baiu-caused precipitation events.

A possible concern is supposed to be the extraction of the urbanization effect. Unfortunately, however, the classification of heavy precipitation events by their causes does not necessarily help to clarify the urbanization effect. We feel it difficult to extract the effect of urbanization only with the data at a location. It is expected that digitalized hourly precipitation data for a long period at multi-locations including both heavily and less urbanized locations will be of use to analyze the urbanization effect. If the effect of local urbanization is extracted somehow, at the same time, the effect of large scale climate variability and change on heavy precipitation may appear more clearly.

5. Summary

We digitalized and investigated the hourly precipitation record since 1890 measured at the Tokyo observatory. If only with the already available digital data from the 1970’s, the recent decade (1990’s) seemed to be the period with strong/frequent hourly heavy precipitation. However, the analyses based on the newly digitalized hourly precipitation record since 1890 show a different view. There was a period with very strong and frequent hourly heavy precipitation events around the 1940’s. The status of hourly heavy precipitation in the 1990’s is within the range of the variations for the 110 years. It is better not to mention, in

terms of hourly heavy precipitation, that an unprecedented status has already come out. Further studies are indispensable to solve several unclear issues particularly on the causes and mechanisms of variability and change.

This paper indicates the possibility that the change in heavy precipitation at a location is in correspondence with large scale climate variations. However, we should note that there also remains a possibility that the change in heavy precipitation at a location is not in correspondence with large scale climate variations. Local effects on the change in heavy precipitation, discrepancies among regions and statistical robustness should be further investigated. Thus, extended studies based on data at multi-locations are indispensable.

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