Long-term Changes in Japanese Extreme Precipitation Analyzed with APHRO_JP_EX

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Abstract

The authors constructed a dataset of historical extreme precipitation indices in Japan named APHRO_JP_EX. This dataset contains more than 40 annual indices derived from daily precipitation. Although the spatial coverage is limited to the land of Japan, the uniqueness of these data with their long period (1900-2009) and high resolution (0.05 x 0.05 degrees) is useful not only for climate research but also for application to studies such as risk assessment of hydrological disasters. Using this dataset, we analyzed trends and annual variations of these indices to quantify the effects of global warming on local extreme precipitation in Japan.

The number of wet days has significantly decreased all over Japan, especially in the northeastern part, where about 20 wet days per year have been lost during the past century. The annual mean precipitation has slightly decreased in most regions. Looking at the regional average of all of Japan, increased heavy precipitation intensity is distinct. The local changes in heavy precipitation are larger in the western part; however, they are not significant in many areas due to large annual variations. When the former and the latter halves of the 20th century are compared, increases in the annual variations of heavy precipitation indices are remarkable in the latter period. While indices of wet spells and dry spells show clear regionality in their trends, wet-spell indices have been decreasing on the Japan Sea side and dry-spell indices have been increasing on the Pacific Ocean side, though both results indicate a progression of meteorological dryness.

After the beginning of the 20th century, in which surface temperatures were rising, precipitation in Japan has become more extreme overall; however, we found regional differences in these signals.

Key words: climate model, extreme precipitation, global warming, IPCC, water resources

1. Introduction

As referred to in the Fourth Assessment Report of the IPCC (Solomon *et al*., 2007), many regions around the world are projected to see increased extremes in precipitation such as heavy rain or severe droughts in the future due to global warming. The relationship between global warming and precipitation changes has been investigated in theoretical studies, as well as empirical research which uses model simulations and observation data.

As temperatures rise, the total amount of water in the atmosphere is indicated to increase at a rate of 7%/K by both climate models and satellite observations, consistent with the theoretical expectations of the Clausius-Clapeyron equation (*e.g*., Wentz & Schabel, 2000; Trenberth *et al*., 2005; Santer *et al*., 2007). However, the changes in global precipitation are much slower, at a rate of 1 to 3%/K, according to many climate model experiments (Allen & Ingram, 2002; Wentz *et al*., 2007). Weakening of atmospheric circulation is considered a reason for this inconsistency between the rates of change of atmospheric water vapor and precipitation amounts. Held and Soden (2006) examined some aspects of the changes in the hydrological cycle using CMIP3 (phase 3 of the Coupled Model Intercomparison Project) Global Circulation Models (GCMs), whose results indicated a decrease in convective mass fluxes, an increase in horizontal moisture transport, an associated enhancement of the pattern of evaporation minus precipitation and its temporal variance, and a decrease in the horizontal sensible heat transport in the extratropics. Other studies support the result that global warming weakens global circulation such as Walker circulation and Hadley circulation (Tanaka *et al*., 2005; Vecchi *et al*., 2006). As for extreme precipitation studies, Allan and Soden (2008) confirmed that observations reveal a distinct link between rainfall extremes and temperature, with heavy rain events increasing during warm periods and decreasing during cold periods. Furthermore, the observed amplification of rainfall extremes is found to be larger than that predicted by models, implying that projections of future changes in extreme precipitation in response to anthropogenic global warming may be underestimated.

Historical and future changes in Japanese precipitation have also been investigated. A detailed analysis of historical daily precipitation changes was done by Fujibe *et al*. (2006) using 51 rain-gauge data from 1901 to 2004, and they found heavy precipitation increases and wet day decreases during the period. Mizuta *et al*. (2005) projected future changes in extreme precipitation indices under the IPCC SRES A1B emission scenario (Nakicenovic & Swart, 2000), using a 20-km-mesh atmospheric general circulation model (AGCM). The results indicated that annual precipitation would significantly increase in the western part of Japan and increases of heavy precipitation would also be seen in almost the same region.

Although, the study of precipitation changes has been progressed as referred to above, the effect of global warming on precipitation, especially on local extreme precipitation, is not sufficiently understood, because of the insufficiency of both observation and model data with high spatial resolution over a long term. A better understanding of that is crucial not only for scientific concerns but also for application such as in water management policy, agriculture plans, economic policy, and so on. Consequently, this study investigated historical changes in Japanese extreme precipitation spanning more than a century, utilizing the new high-resolution daily precipitation data of APHRO_JP (Kamiguchi *et al*., 2010) to quantify the global warming effect. "Extremeness" should be measured from a multilateral viewpoint, not only by magnitude but also by frequency or duration, so this study used "extremes indices" which are used widely in extreme precipitation analysis.

2. Data and Analysis Method

As a first step, we constructed APHRO_JP_EX (JP_EX), a suite dataset of extreme precipitation indices in Japan. JP_EX comprises more than 40 indices of extreme precipitation, which are almost the same as those proposed by STARDEX (STAtistical and Regional dynamical Downscaling of EXtremes for the European region; STARDEX, 2005). The advantage of using this index is that it makes it easy to compare results with those of other similar studies, because it is widely used in extreme precipitation analysis (*e.g*., Alexander *et al*., 2006; Kamiguchi *et al*., 2006; Endo *et al*., 2009). The details of 17 indices used in this study are explained in Table 1. Each index is categorized into four groups as elaborated by Schmidli and Frei (2005). "Basic" indices diagnose mean states such as annual mean precipitation amounts and the numbers of wet days, *i.e*., days with precipitation of at least 1 mm/day, while "heavy precipitation" indices are used for analysis of the frequency or intensity of heavy precipitation. Both "wet-spell" and "dry-spell" indices analyze the frequency or persistence of meteorological conditions for wetness and dryness, respectively. All indices were calculated each year using daily precipitation data provided by APHRO_JP (Kamiguchi *et al*., 2010). APHRO_JP is a historical (1900-2009) and high-resolution (0.05 x 0.05 degree) terrestrial daily precipitation data, created using rain gauge observations and elaborate interpolation techniques, considering local topographical features and statistical characteristics of precipitation. Thereby the estimation bias of grid values remained relatively small even in early years of the 20th century, in which rain gauges were few in number. The number of rain gauges used in APHRO_JP was less than 100 until the 1940s, but after the late 1970s, it increased to more than 1,300 due to the installation of AMeDAS (Automated Meteorological Data Acquisition System). AMeDAS is a high-density surface observation network system developed by the Japan Meteorological Agency (JMA) which consists of automatic observation equipment and a telecommunications system. The temporal changes in spatial rain gauge density may cause an artificial trend in the long-term analysis of extreme precipitation, as suggested by Kamiguchi *et al*. (2010). For such purposes, APHRO_JP provides optional data produced by these identical rain gauges constantly available throughout the period. Using

Table 1 Definitions of 17 extremes indices used in the analysis.

index	definition	unit	kind
PAV	Annual mean of daily precipitation	mm/day	basic
R1	Number of wet_days (>=1mm/day)	day	basic
SDII	Simple daily intensity. Mean precipitation intensity on wet_days	mm/day	basic
PQ90	Daily precipitation intensity at 90th percentile	mm/day	heavy precipitation
PQ95	Daily precipitation intensity at 95th percentile	mm/day	heavy precipitation
R10	Number of days with heavy precipitation (>=10mm/day)	day	heavy precipitation
PF95	Fraction of total precipitation above 95th percentile of wet_day amount		heavy precipitation
R1D	Annual maximum daily precipitation totals	mm	heavy precipitation
R3D	Annual maximum of 3-day precipitation totals	mm	heavy precipitation
R5D	Annual maximum of 5-day precipitation totals	mm	heavy precipitation
R10D	Annual maximum of 10-day precipitation totals	mm	heavy precipitation
PWW	Mean wet_day (>=1mm/day) persistence		wet spells
CWD	Annual maximum of consecutive wet days (>=1mm/day)	day	wet spells
MWS	Mean wet spell length	day	wet spells
PDD	Mean dry_day (>=1mm/day) persistence		dry spells
CDD	Annual maximum of consecutive wet days (>=1mm/day)	day	dry spells
MDS	Annual maximum of consecutive dry days (<1mm/day)	day	dry spells

this data, we also constructed APHRO_JP_EX_CSTN (EX_CSTN). Long-term changes in precipitation were analyzed mainly using EX_CSTN. The specifications of JP_EX and EX_CSTN are almost the same as that of APHRO_JP. The spatial coverage includes the whole land of Japan (123°E-146°E, 24°N-46°N) with an approximately 5-km (0.05 x 0.05 degree) grid, and the temporal coverage is the 110 years from 1900 to 2009.

JP_EX was produced with an eye on HadEX (Alexander *et al*., 2006), which is also a suite of climate change indices derived from daily temperature and precipitation with a primary focus on extreme events. HadEX includes seasonal and annual extreme indices for the period of 1951-2003, with 16 and 11 extreme indices for temperature and precipitation. Although HadEX covers almost all global land areas, it is not suitable for regional analysis because of its coarse horizontal resolution (2.5 x 3.75 degrees). Both JP_EX and EX_CSTN are freely available from the web site <http://www.chikyu.ac.jp/precip/> for academic research purposes. The analysis covered the entire land of Japan, with the exception of some surrounding territories (Fig. 1).

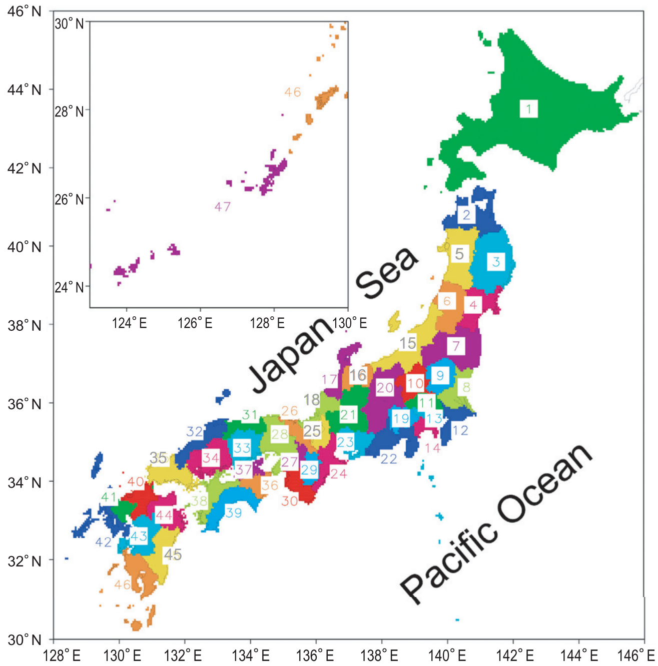

Fig. 1 The study area and locations of the 47 prefectures of Japan. The digits in the figure indicate the prefectural number. (see Table 2)

3. Results

Figure 2 shows the geographical distribution of the climatology of eight extreme precipitation indices. Here

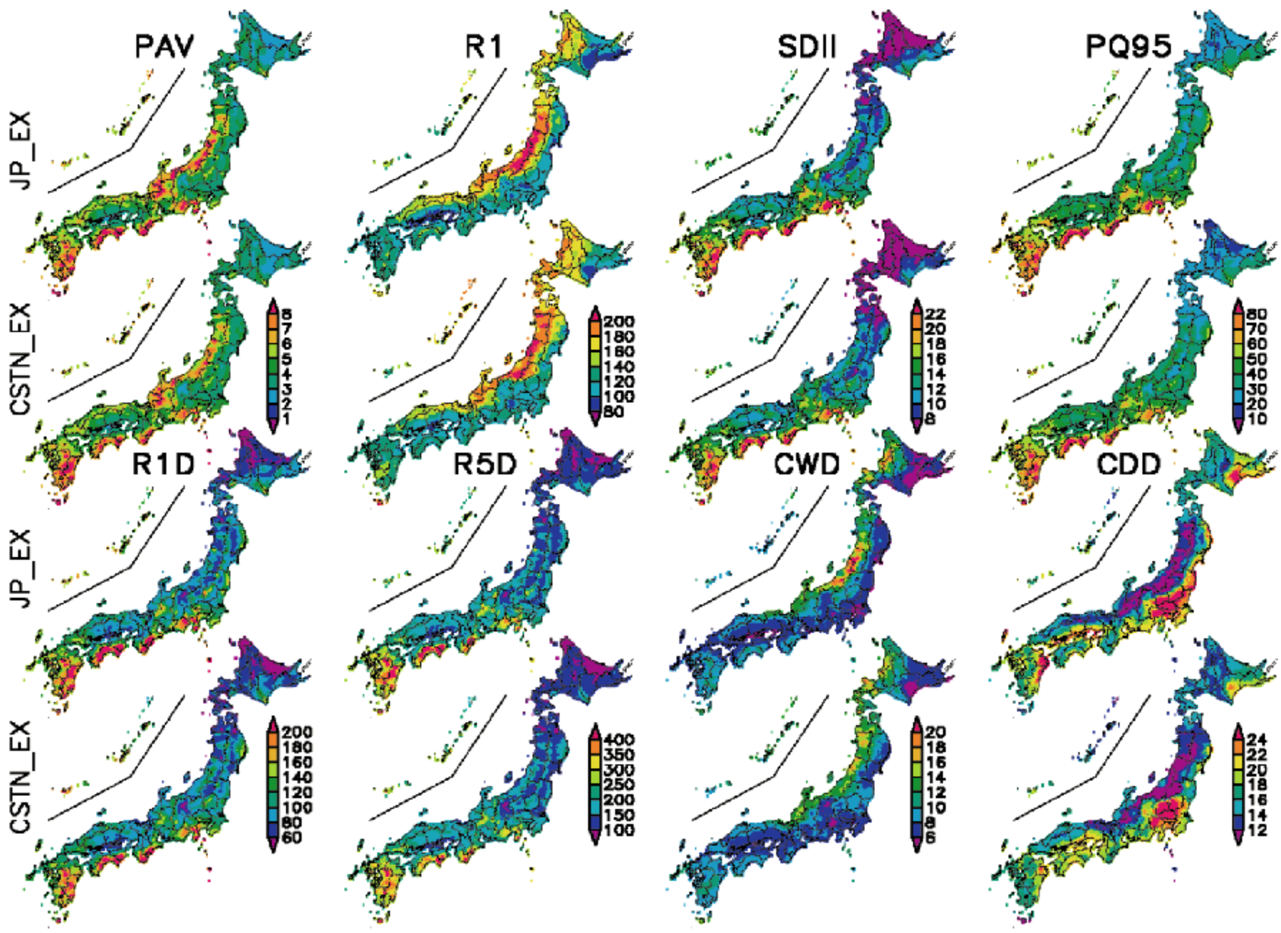

Fig. 2 Spatial distribution of extremes indices calculated with JP_EX and CSTN_EX. The values are 30-year averages between 1980 and 2009. (see Table 1)

we have defined "climatology" as the 30-year average from 1980-2009, because the rain-gauge density used in JP_EX is extremely high and has remained almost constant during the period due to the installation of AMeDAS prior to that. To determine the effects of rain gauge density on extreme indices, results by both JP_EX and CSTN_EX are displayed. The spatial densities of the rain gauges used in the former and the latter correspond to one station per 17 km and 80 km, respectively. Although CSTN_EX has a horizontal resolution of 5 km, it is unclear whether the index value has a spatial representation of such a resolution, considering its lower rain gauge density. Comparing JP_EX and CSTN_EX, no large difference between them is recognized, which indicates sufficient quality of CSTN_EX for analysis of regional extreme precipitation. Consequently, we use only CSTN_EX hereafter in our long term analysis.

The apparent regionality of each index is shown in Fig. 2. PAV, the annual mean precipitation, shows large values in two regions, the northern part of Japan, facing the Japan Sea, and the southwestern part facing the Pacific Ocean. The former region has much snowfall in winter while the latter has much rainfall during summer caused by the Baiu front and typhoons. The Baiu front is a typical stationary frontal system producing rainfall in early summer in Japan accompanied with high humid low level jets (Pham *et al*., 2008). Both regions have almost the same value of PAV, but the precipitation characteristics differ considerably. The former region has many wet-days (R1) with weak precipitation while the latter has small R1 and a large value of heavy precipitation indices (*e.g*., PQ95 and R1D). CWD and CDD also have an apparent regionality, taking large values on both the Japan Sea and the Pacific Ocean side.

Figure 3 shows long-term changes in this anomaly from the viewpoint of surface temperature climatology and eight extremes indices. The temperature anomaly data are nearly the same as those published by JMA, except for the period of climatology, which is a mean of 17 surface observatories in Japan less affected by urbanization. The anomaly of extreme precipitation indices is defined as the ratio to the climatology at grid

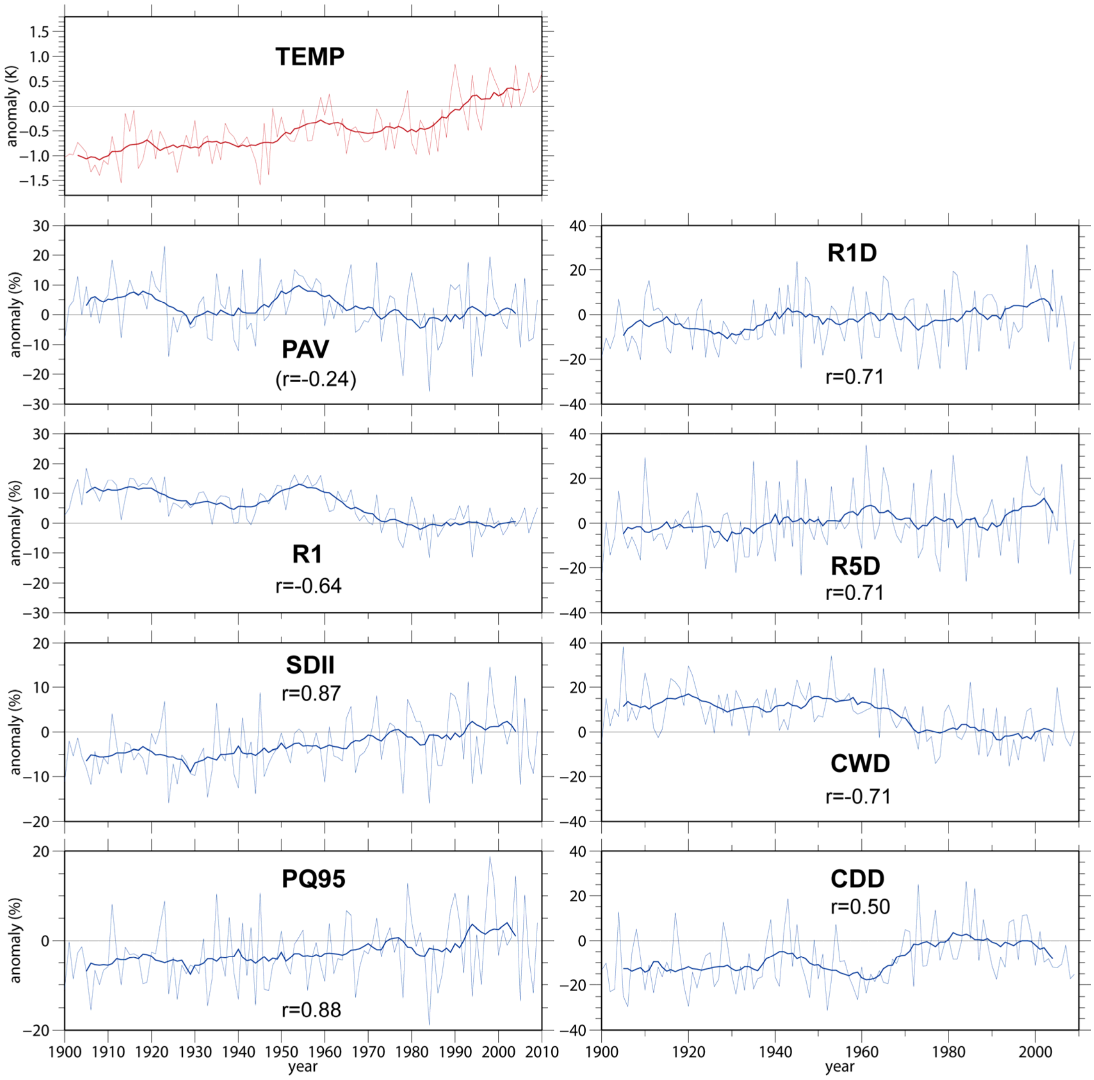

Fig. 3 Anomalies of surface temperature and extremes indices. The thick lines are the graph of the 11-year moving average. The figures are the correlation coefficient between the moving-averaged temperature and extremes indices, and parentheses indicate the correlation is not significant at the 99 % confidence level. (see Table 1)

cells, and its average in the study area is shown in the figure. The climatology period is the 30 years from 1980 to 2009 for both temperature and extremes indices. The correlation coefficient between the 11-year moving-average temperature and extremes indices is also shown in the figure.

Surface temperatures have been almost consistently rising since the beginning of the 20th century, though a relatively cold period was seen around the 1970s. PAV underwent some remarkable changes (1923/1924, 1953, 1984), though the trend during the entire period is not clear. This result is consistent with a previous study done by Xu *et al*. (2003), which examined monotonic trends and step changes of spatially averaged annual precipitation at 46 rain gauges in Japan from 1897 to 1999, using a parametric t-test, and nonparametric Mann-Kendall and Mann-Whitney techniques. Their results indicated that although several step changes occurred in Japanese precipitation, the time series did not exhibit significant evidence of a monotonic trend during the past century. The mechanism of an abrupt change around 1983 was examined by Inoue and Matsumoto (2007) who explained that shifts in the positions and tracks of typhoons were responsible for this change in precipitation. What is most remarkable in the PAV time series is the large interannual variation after the 1970s. The three lowest PAV values were all recorded in this period (1984, 1994 and 1978). Considering that there is no significant correlation between it and the surface temperature, PAV seems to be more affected by natural variability than by global warming. The sudden shifts shown in PAV are called regime shifts (Minobe, 1997), and are suggested to be related to the Pacific decadal oscillation (*e.g.*, Mantua *et al*. 1997).

R1 is similar to PAV in annual variation, but its downward trend is clearer than that of PAV. The value changed greatly around 1960, and low values have been found after that. Although its negative correlation with temperature is high (r = – 0.64), R1 has undergone no major changes since the 1970s, while surface temperature has been continuously rising. SDII and all heavy precipitation indices (PQ95, R1D and R5D) have large annual variations. However, an upward trend is very clear and almost monotonic without step changes, unlike those of PAV and R1. Changes in heavy precipitation have also been reported by Fujibe *et al.* (2006), who noted that the frequency of Japanese heavy precipitation in the upper 10% of their definition increased by 2.3% per decade during the 20th century. Positive correlation with temperature is also high especially for SDII (r = 0.87) and PQ95 (r = 0.88), implying that heavy precipitation might be more affected by global warming than by natural variability. CWD and CDD have almost the same and opposite time series, respectively, to R1. The major changes are found around 1960, as seen for R1, indicating progression of meteorological dryness in recent years. A high positive correlation with surface temperature has also been shown for CWD (r = 0.71).

In order to investigate historical changes in annual variations, we looked into the statistical distribution of extremes indices. The total period was separated into three equal sub-periods of 36 years (1900-1935, 1937-1972 and 1964-2009; hereafter, referred to as FP, MP and LP, respectively) and the index value at the percentiles of 90, 75, 50 (median), 25 and 10 were compared in each period. For example, the 90th percentile means the top quarter of values during the 36 years. The percentile value at the grid box was normalized by dividing it by the grid climatology, and then the normalized values were averaged throughout Japan.

Figure 4 shows box-whisker graphs of the 17 indices in the three periods. The median of PAV and R1 are

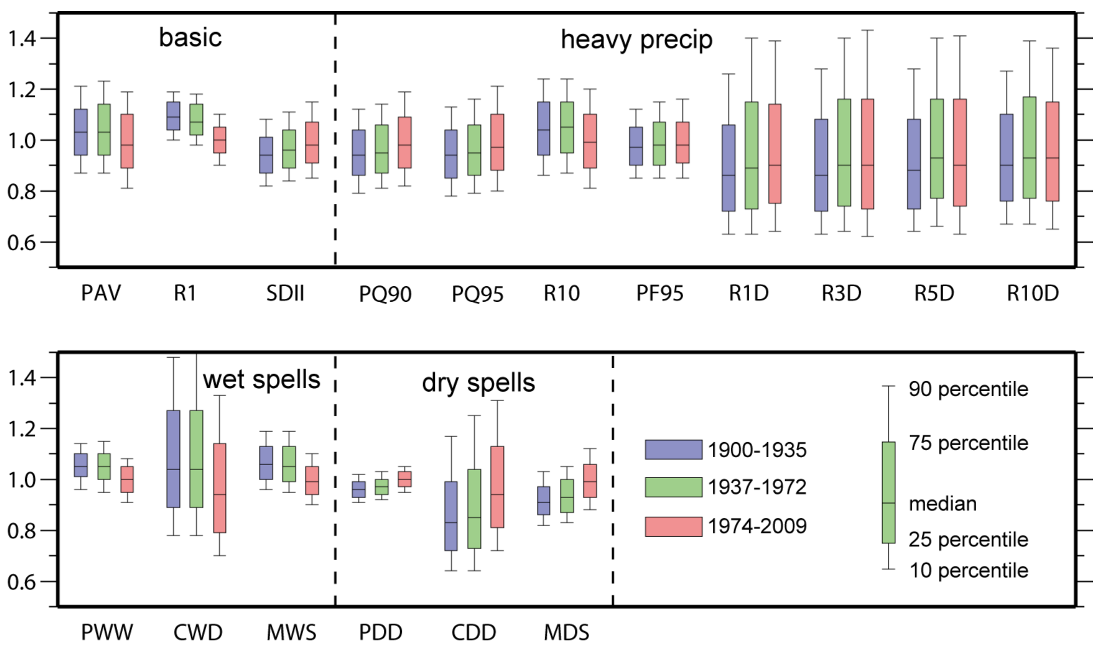

Fig. 4 Box-whisker plot of 17 extremes indices in three periods: the former period (FP: 1900-1935), the middle period (MP: 1937-1972) and the latter period (LP: 1974-2009).

clearly smaller in the LP period than in the other periods. For R1 in particular, the median in LP was almost the same as the 10th percentile in MP which means that rare events occurred once per ten years in MP, but once per two years in LP. Indices of heavy daily precipitation, PQ90 and PQ95, increased in LP, while R10, by contrast, decreased. The number of days with heavy precipitation exceeding 50mm/day (R50) increased in LP, but the number of days with precipitation intensity of less than 40 mm/day decreased in Japan (not shown). Changes in distribution width (*e.g.* 75 percentile – 25 percentile) are noticeable in indices of the annual maximum n-day precipitation (R1D, R3D, R5D and R10D), although the changes in the median are not so large. The extension of the upper distribution tail found in these indices may have a higher impact, especially on hydrological disasters, than the increase in the median. On the other hand, obvious changes in the median are recognized in wet spell and dry spell indices, although the distribution width did not change so much. The progression of meteorological dryness in LP is evident from the figure.

Finally, the linear trends of eight indices during 1900-2009 were calculated in each prefecture to quantify the effect of global warming on local extreme precipitation in Japan. The calculation was done for each of the 47 prefectures, whose names and locations are listed in Table 2 and Fig. 1. Normalization by climatology as done in the previous analyses was not applied because precipitation characteristics are not so diverse over small prefectural areas. As shown in Fig. 5 and Table 3, PAV has shown a downward trend in almost all prefectures, but not many of these are significant. Large decreases are remarkable in western Japan on the Pacific Ocean side. Decreases in R1 are statistically significant in all prefec-

Table 2 Prefecture number, name and code. Locations are shown in Fig. 1. All Japan includes all 47 prefectures.

no	name	code	no	name	code	no	name	code	no	name	code
1	Hokkaido	HKD	13	Tokyo	TKY	25	Shiga	SIG	37	Kagawa	KGW
2	Aomori	AOM	14	Kanagawa	KNG	26	Kyoto	KYT	38	Ehime	EHM
3	Iwate	IWT	15	Niigata	NGT	27	Osaka	OSK	39	Kochi	KOC
4	Miyagi	MYG	16	Toyama	TYM	28	Hyogo	HYG	40	Fukuoka	FKO
5	Akita	AKT	17	Ishikawa	ISK	29	Nara	NAR	41	Saga	SAG
6	Yamagata	YGT	18	Fukui	FKI	30	Wakayama	WKY	42	Nagasaki	NGS
7	Fukushima	FKS	19	Yamanashi	YMN	31	Tottori	TTR	43	Kumamoto	KMM
8	Ibaraki	IBR	20	Nagano	NGN	32	Shimane	SMN	44	Oita	OIT
9	Tochigi	TCG	21	Gifu	GIF	33	Okayama	OKY	45	Miyazaki	MYZ
10	Gunma	GNM	22	Shizuoka	SZO	34	Hiroshima	HRS	46	Kagoshima	KGS
11	Saitama	SIT	23	Aichi	AIC	35	Yamaguchi	YGC	47	Okinawa	OKN
12	Chiba	CHB	24	Mie	MIE	36	Tokushima	TKS	48	All Japan	JPN

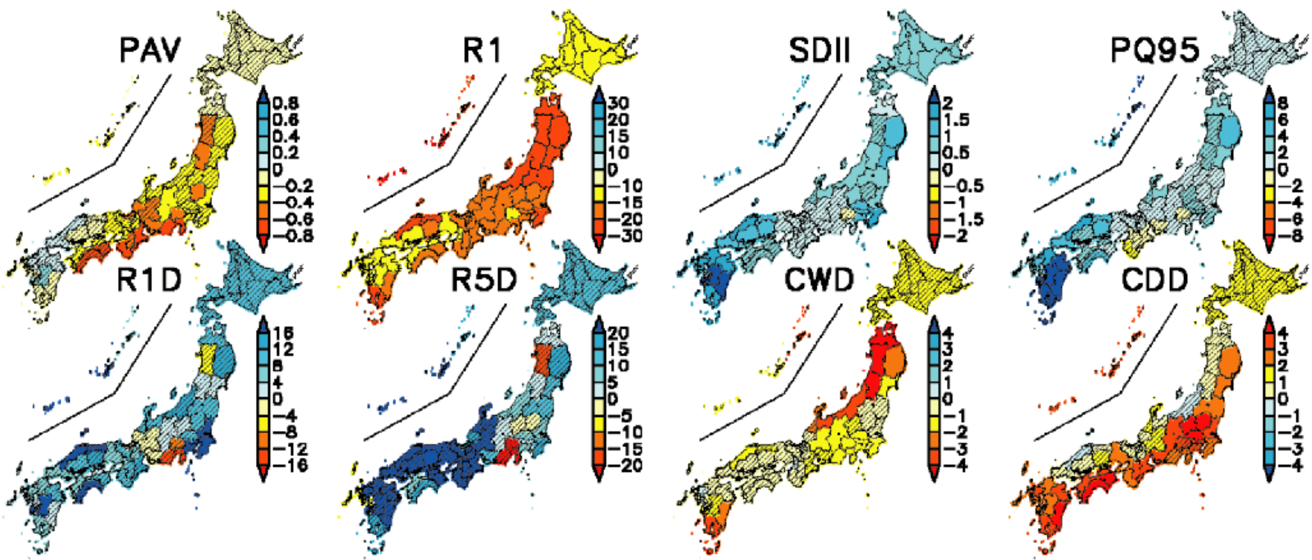

Fig. 5 Linear trends of extremes indices in the period of 1900-2009. The values are the rate of change per 100 years. They were calculated using the mean value in each prefecture (see Table 2 and Fig. 1). Hatched areas indicate that the trend is not statistically significant at the 95% level.

Table 3 The climatology of extremes indices (means of 1980-2009) and its linear trend per 100 years in each region (47 prefectures and all of Japan). Bold style indicates that the trend is statistically significant at the level of 95%.

PAV

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	3.4	4.0	4.1	3.6	5.4	5.5	4.1	3.8	4.3	3.7	3.7	4.4	5.3	5.1	6.1	6.9
TREND(1900-2009)	0.0	-0.2	-0.2	-0.3	-0.4	**-0.4**	-0.3	**-0.4**	**-0.4**	-0.3	-0.2	-0.3	-0.4	-0.4	-0.4	-0.3
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	6.5	6.6	4.4	4.3	6.5	6.5	5.1	6.0	5.1	4.8	3.8	4.3	5.5	6.0	5.6	5.1
TREND(1900-2009)	-0.3	**-0.5**	**-0.6**	**-0.4**	-0.5	**-0.7**	**-0.5**	**-0.7**	-0.4	-0.3	-0.3	-0.3	-0.6	**-0.8**	-0.1	0.0
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	3.9	4.4	5.1	6.2	3.3	5.0	7.5	5.3	5.8	5.7	6.7	5.5	7.7	7.3	6.2	4.8
TREND(1900-2009)	0.0	-0.1	0.0	-0.6	-0.2	-0.3	-0.6	0.1	0.0	-0.1	0.2	0.1	0.0	-0.1	-0.4	-0.2

R1

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	154.2	181.4	154.3	124.3	190.6	179.8	146.5	118.5	119.8	116.4	109.6	116.4	126.1	113.6	186.3	184.5
TREND(1900-2009)	**-11.0**	**-20.1**	**-26.8**	**-23.9**	**-24.5**	**-23.3**	**-21.9**	**-19.2**	**-19.5**	**-18.5**	**-17.9**	**-21.3**	**-18.7**	**-18.6**	**-21.7**	**-19.7**
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	182.5	182.0	105.2	119.6	154.5	123.8	120.1	123.6	150.4	150.0	106.8	120.0	118.7	116.4	158.7	149.8
TREND(1900-2009)	**-17.5**	**-18.2**	**-12.3**	**-15.9**	**-15.5**	**-15.6**	**-15.3**	**-17.2**	**-17.0**	**-17.0**	**-11.2**	**-13.9**	**-15.2**	**-17.5**	**-22.6**	**-22.2**
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	120.3	120.3	128.4	118.1	104.7	118.7	124.4	125.6	126.1	126.5	132.6	121.7	136.3	155.1	161.7	143.9
TREND(1900-2009)	**-16.1**	**-13.8**	**-13.2**	**-17.6**	**-14.4**	**-12.5**	**-16.5**	**-12.7**	**-12.7**	**-13.4**	**-14.2**	**-12.8**	**-18.1**	**-20.6**	**-30.5**	**-16.8**

SDII

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	8.0	7.9	9.7	10.4	10.1	10.8	10.1	11.6	12.7	11.5	12.3	13.5	15.0	16.1	11.7	13.5
TREND(1900-2009)	**0.5**	**0.5**	**1.2**	**1.1**	0.5	**0.6**	**0.8**	**0.8**	0.8	**0.8**	**1.2**	**1.5**	**1.1**	**1.3**	**0.6**	**0.8**
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	12.8	13.0	14.9	12.7	15.1	19.0	15.1	17.5	12.3	11.5	12.8	12.8	16.5	18.3	12.7	12.3
TREND(1900-2009)	0.6	0.2	-0.2	0.5	0.4	0.3	0.3	0.2	0.5	0.5	0.2	0.5	0.3	0.2	**1.4**	**1.7**
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	11.5	13.2	14.3	18.5	11.4	14.9	21.7	15.1	16.5	16.1	18.1	16.3	20.4	17.2	13.9	12.4
TREND(1900-2009)	**1.2**	**1.1**	**1.3**	0.7	0.7	0.7	0.8	**1.6**	**1.6**	**1.2**	**2.3**	**1.9**	**2.5**	**1.9**	**1.7**	**0.8**

PQ95

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	26.6	25.0	34.1	36.6	33.1	35.6	32.8	35.9	39.6	37.2	39.2	43.5	49.4	52.2	36.9	42.5
TREND(1900-2009)	1.5	**2.6**	**4.7**	**3.9**	2.0	2.4	1.9	1.2	1.1	3.0	3.5	3.2	2.1	1.6	1.8	**3.3**
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	38.6	39.0	48.9	41.7	51.5	63.8	48.3	58.1	40.0	38.1	40.5	41.7	54.3	62.3	42.4	41.5
TREND(1900-2009)	2.4	0.7	-0.2	0.4	0.6	0.0	-0.2	-1.5	1.0	1.1	-0.7	0.9	-0.9	-2.1	**5.9**	**6.9**
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	38.5	44.5	49.6	65.3	37.1	49.6	78.3	52.9	60.0	57.2	63.8	56.5	71.9	61.0	50.4	41.5
TREND(1900-2009)	**4.5**	3.9	**5.2**	1.6	2.2	3.9	4.7	**6.5**	**6.0**	3.4	**8.9**	**8.0**	**13.1**	**9.2**	**7.2**	**2.9**

R1D

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	73.5	65.2	97.0	85.2	77.2	94.0	85.6	101.1	110.2	93.0	111.4	118.0	140.5	147.6	92.4	102.9
TREND(1900-2009)	9.7	8.2	14.6	1.3	-6.2	0.3	11.1	18.9	9.6	1.3	9.4	**24.2**	16.8	17.4	12.2	11.1
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	92.0	91.9	126.0	92.8	125.1	159.3	114.3	162.8	100.7	96.9	95.2	96.9	139.3	156.6	108.0	106.4
TREND(1900-2009)	10.9	-2.9	-11.5	0.2	-0.2	-13.7	-0.4	14.9	4.4	8.6	7.7	7.2	11.6	11.5	18.8	**18.7**
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	86.6	100.1	115.1	171.5	81.8	113.7	197.7	122.0	134.0	132.9	163.4	141.4	172.8	153.7	157.4	105.4
TREND(1900-2009)	12.6	9.5	5.1	10.0	3.5	5.7	21.0	5.6	4.4	3.0	**30.1**	8.1	1.2	5.8	21.7	**8.2**

R5D

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	116.7	109.5	150.4	140.8	140.9	160.7	138.8	145.0	167.0	148.8	169.2	173.5	215.7	220.1	164.3	204.5
TREND(1900-2009)	10.9	4.9	16.3	11.0	-15.5	3.1	11.2	9.5	-1.5	-3.2	7.2	19.5	4.3	6.5	6.3	27.5
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	181.0	188.3	200.7	163.7	243.8	262.6	205.9	275.0	192.4	182.2	172.7	182.2	252.9	284.9	207.6	200.2
TREND(1900-2009)	26.1	18.2	-41.3	2.1	20.7	-33.6	10.6	29.1	31.2	33.9	26.9	28.4	30.7	24.3	**41.4**	34.2
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	174.0	198.2	234.5	318.7	160.7	216.3	354.4	262.7	288.9	267.8	334.0	261.4	311.1	281.0	269.0	185.8
TREND(1900-2009)	**42.2**	27.3	26.1	34.5	26.3	8.8	18.9	33.9	23.3	-5.0	57.4	25.9	30.3	18.9	**45.8**	14.5

CWD

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	10.0	13.9	9.1	7.1	14.1	11.9	9.1	8.4	9.0	8.4	7.5	6.8	8.0	7.1	12.3	12.3
TREND(1900-2009)	-1.1	**-4.2**	**-2.6**	**-1.5**	**-4.4**	**-4.0**	-0.7	-0.3	-0.6	-1.3	**-1.8**	**-1.9**	**-1.7**	**-1.7**	**-3.4**	**-3.0**
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	13.1	13.0	6.9	7.3	9.2	7.8	7.6	7.7	8.6	8.7	6.9	7.5	7.7	7.5	8.9	8.3
TREND(1900-2009)	-2.1	-0.5	**-1.3**	**-1.2**	**-1.7**	**-1.4**	-1.2	-1.1	-0.6	-0.6	0.2	-0.4	-0.3	-0.4	-1.7	**-2.0**
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	7.0	7.2	8.0	7.7	6.6	7.9	8.8	8.4	8.6	8.8	9.6	8.7	10.2	11.0	10.9	9.4
TREND(1900-2009)	-0.3	-0.8	-0.7	-0.8	-0.7	-0.6	-0.9	-0.6	0.1	-0.3	-1.6	-0.4	**-2.2**	**-3.1**	**-1.5**	**-1.5**

CDD

AREA	HKD	AOM	IWT	MYG	AKT	YGT	FKS	IBR	TCG	GNM	SIT	CHB	TKY	KNG	NGT	TYM
AVE(1971-2000)	15.3	13.5	14.0	16.6	12.6	12.1	14.3	22.6	25.0	25.2	27.9	21.3	22.0	24.2	12.1	12.6
TREND(1900-2009)	1.5	0.1	**2.1**	**2.8**	0.1	0.3	**2.4**	**3.7**	**4.9**	**6.1**	**5.9**	2.8	3.1	3.6	-0.1	0.8
AREA	ISK	FKI	YMN	NGN	GIF	SZO	AIC	MIE	SIG	KYT	OSK	HYG	NAR	WKY	TTR	SMN
AVE(1971-2000)	14.4	13.5	25.7	18.5	13.8	21.2	20.0	19.2	14.1	14.1	20.7	18.9	19.2	19.8	14.3	15.4
TREND(1900-2009)	1.2	0.5	3.7	**3.8**	1.1	2.4	**3.3**	**3.7**	0.9	0.7	**2.9**	**2.7**	**3.1**	**2.9**	0.7	-0.2
AREA	OKY	HRS	YGC	TKS	KGW	EHM	KOC	FKO	SAG	NGS	KMM	OIT	MYZ	KGS	OKN	JPN
AVE(1971-2000)	18.8	18.4	17.4	20.5	22.6	19.7	21.1	17.8	17.8	17.5	17.4	20.8	19.4	15.4	15.2	16.9
TREND(1900-2009)	1.9	0.5	1.0	**4.1**	**3.8**	**3.2**	**5.0**	**2.8**	**3.1**	**2.4**	**3.0**	**3.2**	**4.2**	**3.2**	**3.7**	**2.2**

tures and the rate of decrease is larger in Tohoku in the northeastern part of Japan. If we look at the average throughout Japan, we can see that Japan has lost 16.8 wet days per year during these past 100 years. Kimoto *et al*. (2005) projected a decrease in R1 in Japan of 8.5 days during the 100 years between the end of 20th century and the end of 21st century, using a high-resolution coupled general circulation model (CGCM). SDII and other heavy precipitation indices have shown an upward trend, especially in the western part of Japan, including Kyushu and Okinawa, in which the climatology is large. A model experiment study by Mizuta *et al*. (2005) using a 20-km mesh AGCM projected an increase in heavy precipitation in the western part of Japan at the end of the 21st century. Our results are almost consistent with theirs. CWD and CDD show clear regionality in their trends: the former has decreased on the Japan Sea side and the latter has increased on the Pacific Ocean side. The magnitude of the trend is large in the regions in which the climatology is large. The decrease in winter snowfall on the Japan Sea side greatly affects the reduction of CWD in that region.

4. Discussion

Future projection of extreme weather events is being vigorously promoted in Japan. In the KAKUSHIN program (Innovative Program of Climate Change Projection for the 21st Century), a 20-km-mesh AGCM and 5-km-mesh cloud-resolving regional model have been developed (Kitoh, 2009). Using these models, future changes in tropical cyclones and extreme precipitation are being investigated. The KAKUSHIN program also focuses on application studies such as regional projection for natural disaster prevention. For example, Takara *et al*. (2009) examined the potential impact of climate change on Tokyo metropolitan water resources in the Tone River basin (16,840 km^2) using a 20-km-mesh AGCM. The results indicated that the yearly standardized precipitation index (SPI) predicts more frequent dry conditions, indicating increased future vulnerability to subtle droughts.

However, model studies always have the problem of uncertainty in their predictions. To cope with this, elucidation of past changes and model evaluation using observation data are essential. Japan fortunately has had high quality rain gauge data since the late 19th century owing to the great efforts of our foregoers. Utilizing the derivatives of such data, we produced APHRO_JP_EX, a suite dataset of extreme precipitation indices, and analyzed their long-term changes to quantify the effects of global warming on local extreme precipitation in Japan.

In this study, we found that precipitation in Japan has become more extreme overall since the beginning of the 20th century, with surface temperatures rising, as is consistent with previous studies such as Fujibe *et al*. (2006). In addition, we could newly reveal regional differences in historical changes owing to the high spatial resolution of APHRO_JP_EX. Our results are easy to compare with those of other similar studies because the extremes indices used here are widely used in both observation and model data. For example, using HadEX, Alexander *et al*. (2006) showed that SDII in Japan has had a negative trend during the latter part of the 20th century, which is the opposite of our result. Although the reason for such a discrepancy is unclear, the quality and number of rain gauge data used in APHRO_JP_EX are superior to those in HadEX.

This study analyzed only annual indices of extreme precipitation. However, because Japanese precipitation has a wide variety of features in different areas and different seasons, the climate mechanisms provoking the local changes in extreme precipitation should be further examined. We were also unable to divide the effects of global warming from those of natural variability on extreme precipitation sufficiently in this study. Those will be targets of further research.

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