Long-term Changes in the Spatial Concentration of Daily Precipitation in Japan

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Abstract

Daily precipitation data for 105 years (1901–2005) at 51 stations in Japan were analyzed to evaluate the trends in the spatial concentration of precipitation distribution. The index of spatial concentration was defined by the departure of precipitation amount from the average over the surrounding area. It is found that the degree of spatial concentration has an increasing trend, mainly for weak and moderate precipitation. A similar feature is found for precipitation over 5–31 days as well.

1. Introduction

Increasing trends of heavy precipitation have been found in many places of the world (Groisman et al. 2005). Fujibe et al. (2005, 2006) analyzed the data over a hundred years in Japan, and showed the increase of heavy precipitation and decrease of weak precipitation. Kimoto et al. (2005) obtained a similar change as a prediction of a global warming experiment. These changes imply the increase of temporal concentration of precipitation, in the sense that more precipitation tends to occur in a shorter time.

The change in the spatial scale of precipitation is also an interesting theme related to flood control and water resource management (Osborn 1997; Fowler et al. 2005). The 2xCO₂ experiment of Noda and Tokioka (1989) predicted an increase of convective precipitation with a decrease of precipitation area, although subsequent studies have shown more complicated relation of convective activity and global warming (IPCC 2001; Brinkop 2002; Min et al. 2006). On the other hand, an observational approach to long-term changes in the spatial scale of precipitation requires high-quality data having sufficient time resolution and spatial density, which are rarely satisfied at a time.

In the present analysis, the change of spatial concentration of precipitation in Japan was evaluated using quality-checked daily precipitation data at 51 stations (Fig. 1) from 1901 to 2005. These data are the same as those used by Fujibe et al. (2006) for the period 1901–2004.

2. Procedure of analysis

A possible index of spatial concentration of precipitation may be the variance and/or maximum precipitation amount within a precipitation area (Misumi 2002; Suzuki 2006). However, such approach requires determining the ‘shape’ and ‘boundary’ of precipitation area, which is difficult in the present study because spatial coverage of data network is too limited to capture complicated precipitation patterns. We instead attempt a simple method in which spatial concentration is defined by the degree of departure from spatially averaged precipitation amount.

Hereafter the symbol \( P(d, n) \) will be used to denote the precipitation at station \( i \) on day \( d \) of the year \( n \). The spatially averaged precipitation, \( \bar{P}(d, n) \), was obtained by interpolating the values at surrounding stations using the least-squares condition

\[
\sum_{j=1}^{n} w(r_{ij}) (P(d,n) - (ax_i + by_i + \bar{P}(d,n)))^2 \rightarrow \min.,
\]

where \( a, b \) and \( \bar{P}(d, n) \) are least-squares coefficients, \( x_i \) and \( y_i \) are eastward and southward coordinates with the station \( i \) as the origin, and \( r_{ij} = x_{ij}^2 + y_{ij}^2 \). The weight \( w(r_{ij}) \) was defined by

\[
w(r_{ij}) = \exp \left( - \frac{r_{ij}}{R_0^2} \right),
\]

with \( R_0 = 300 \text{ km} \), which is given so that it was not too small for the spatial density of stations. Our analysis is therefore targeted to the scale of a few hundred kilometers. The main features of the results do not change if the condition \( R_0 = 150 \text{ km} \) or \( R_0 = 450 \text{ km} \) is used.

The solution to (1) is described by a linear combination of \( P_i \) as

\[
P(d, n) = \sum_{j=1}^{n} s_{ij} P(d, n),
\]

where \( s_{ij} \) is determined by the distribution of stations, and satisfies \( \sum_{j=1}^{n} s_{ij} = 1 \) (see Appendix for details). Near the periphery of the analysis area, \( P_i \) is more or less inaccurate because (1)–(3) involves extrapolation rather than interpolation. In such a case, (3) includes some large positive and negative \( s_{ij} \) values which cancel with each other, so that the squared sum \( S_i = \sum_{j=1}^{n} s_{ij}^2 \) is considerably large. Thus \( S_i \) can be a measure of the accuracy of interpolation. In our analysis, stations with \( S_i < 0.5 \), which is satisfied by 39 stations (Fig. 1), were used to evaluate the spatial concentration of precipitation. The result hardly changes if the condition \( S_i < 1.0 \) is used.

The excess of \( P \) from \( \bar{P} \) was defined by

Fig. 1. Stations used for analysis. Hatching indicates the area higher than 600 m above the mean sea level.

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\[ \Delta P = \text{max}(0, P_i - \bar{P}_i). \] (4)

For each year \( n \), \( P_i \) and \( \Delta P \) was averaged in space and time on a specified condition, as
\[ <P>_n = \sum_{i,d} P_i(d, n), \] (5)
and
\[ <\Delta P>_n = \sum_{i,d} \Delta P_i(d, n). \] (6)

The ratio \( Q_n = \frac{<\Delta P>_n}{<P>_n} \) was used as an index of spatial concentration. The linear trend for the time series of \( Q_n \) was calculated from the least-squares method, with a confidence range based on the error matrix.

The advantage of \( Q \) is that it can be applied to all cases without regard of the shape of precipitation area, which often has a complicated pattern. On the other hand, it has a weak point of poor interpretability. In order to give physical insight of \( Q \), a simple analysis was made for the relation between \( Q \) and the scale of precipitation area for an idealized case of Gaussian precipitation distribution
\[ P(x, y) = P_A \exp\left(-\frac{x^2 + y^2}{A^2}\right), \] (7)
where \( A \) gives the size of precipitation area. The calculation was made for three values of \( R_0 \), with an assumption that stations are continuously and homogeneously distributed. As shown in Fig. 2, \( Q \) decreases monotonically with \( A \). Thus \( Q \) corresponds well with the size of precipitation area having the Gaussian shape. It is therefore not unreasonable to use \( Q \) as an index of spatial scale of precipitation, although its physical meaning may be less well-defined for actual cases, in which precipitation distribution is more complicated and variable.

Since there is considerable regional difference in the average precipitation distribution, the value \( Q \) defined above may have larger contribution of stations that receive more precipitation climatologically. As a spatially unbiased quantity, precipitation amount normalized with respect to the climatic mean was defined by \( p_i(d, n) = \frac{P_i(d, n)}{\bar{P}_d} \), where \( \bar{P}_d \) is the 105-year average precipitation on a calendar day \( d \), with 31-day running mean. Then the spatial concentration \( q_n = \frac{<\Delta P>_n}{<P>_n} \) was calculated in the same procedure as that used for \( P_i(d, n) \). Comparison of results with and without normalization will be made in the next section (Figs. 3 and 4).

3. Results

Figure 3a shows the time series of \( <P>_n \) and \( <\Delta P>_n \), averaged over the stations for all the cases. The average value of \( <P>_n \), equivalent to the annual total precipitation, has a weakly decreasing trend (7.2%/century). The trend of \( <\Delta P>_n \) is much smaller (2.5%/century), so that the ratio \( Q_n \) has a rising trend of 0.017/century, which is statistically significant at the 1% level. A similar result was obtained from the normalized data (Fig. 3b). The ratio \( q_n \) has a rising trend of 0.014/century, which is also significant at the 1% level.

Figure 4 shows the annual variation of the linear trends of \( Q_n \) and \( q_n \), averaged over the stations and in each region (Fig. 1). The monthly values of \( Q_n \) and \( q_n \) were calculated from summation over three months in (4) and (5) in order to remove irregular month-to-month variations. For example, the value for June was obtained using summation for May to July. Table 1 shows the trends for the whole year, and the warm and cold half years (May–October and November–April). Both \( Q_n \) and \( q_n \) have significant positive trends, especially in the warm season and in western Japan. The difference of trends obtained from unnormalized and normalized data is quite small. Hereafter we present the results from normalized data except for the analysis of extreme precipitation (Table 3).

Figure 5 shows the distribution of the trend in \( q_n \) at each station. There is not a clear signal of dependence on geographical factors, apart from irregular variation according to stations. In fact, the values are statistically significant at only 8 stations in (a) and 17 stations in (b), so that it is impossible to examine detailed regional features.

Figure 6 and Table 2 show the trends for four ranges of \( \bar{P}_d \). For \( \bar{P}_d < 1 \), which roughly corresponds to \( \bar{P}_d \), less
than several millimeters, positive trends are found in all the regions and seasons. The range 1 \( \leq \bar{p} < 3 \) is also accompanied by positive trends for the most part of the year. However, trends are weak or insignificant for \( \bar{p} \geq 3 \), although they are still positive for the most part of the year. On the other hand, \( Q \) for the annual maximum precipitation (Table 3) has weak negative trends except western Japan. Thus the increase of spatial concentration is more conspicuous for weak and moderate precipitation than intense one, which may show a decrease in spatial concentration.

Figure 7 and Table 4 show the trends of \( q \) obtained from 5, 11, and 31 day precipitations, which were calculated by the running sum of daily values. Positive trends are found irrespectively of duration. Thus increasing spatial concentration exists in precipitation from daily to monthly time scales.

Fig. 4. Linear trends of (a) \( Q \) and (b) \( q \) for each region and the average over the whole area. Vertical bars indicate the 95% confidence ranges of the values for the whole area.

Table 1. Long-term mean and trend (per century) of \( Q \) and \( q \) values.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Unnormalized</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole area</td>
<td>0.35</td>
<td>0.02</td>
<td>0.02</td>
<td>0.021</td>
</tr>
<tr>
<td>Northern</td>
<td>0.43</td>
<td>0.014</td>
<td>0.006</td>
<td>0.017</td>
</tr>
<tr>
<td>Eastern</td>
<td>0.35</td>
<td>0.014</td>
<td>0.014</td>
<td>0.013</td>
</tr>
<tr>
<td>Western</td>
<td>0.33</td>
<td>0.030</td>
<td>0.030</td>
<td>0.016</td>
</tr>
<tr>
<td><strong>Normalized</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole area</td>
<td>0.33</td>
<td>0.014</td>
<td>0.018</td>
<td>0.009</td>
</tr>
<tr>
<td>Northern</td>
<td>0.42</td>
<td>0.006</td>
<td>0.014</td>
<td>0.005</td>
</tr>
<tr>
<td>Eastern</td>
<td>0.30</td>
<td>0.010</td>
<td>0.015</td>
<td>0.005</td>
</tr>
<tr>
<td>Western</td>
<td>0.33</td>
<td>0.019</td>
<td>0.026</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Significant at 1%: \(-\), 5%: \(-\), 10%: \(\cdot\)

Fig. 5. Linear trend of \( q \) at each station, for (a) all cases and (b) \( \bar{p} < 1 \). Open and closed circles show positive and negative values, respectively. Red and blue colors correspond to stations with \( S < 0.5 \) and \( 0.5 \leq S < 1.0 \), respectively. Crosses indicates absolute values less than 0.1 for (a), and 0.02 for (b).

Table 2. Same as Table 1 (normalized) but for each range of \( \bar{p} \).

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<tr>
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</thead>
<tbody>
<tr>
<td>( \bar{p} &lt; 1 )</td>
<td>Whole area</td>
<td>0.63</td>
<td>0.037</td>
<td>0.038</td>
</tr>
<tr>
<td>Northern</td>
<td>0.68</td>
<td>0.045</td>
<td>0.050</td>
<td>0.041</td>
</tr>
<tr>
<td>Eastern</td>
<td>0.62</td>
<td>0.031</td>
<td>0.031</td>
<td>0.027</td>
</tr>
<tr>
<td>Western</td>
<td>0.60</td>
<td>0.042</td>
<td>0.044</td>
<td>0.034</td>
</tr>
<tr>
<td>( 1 \leq \bar{p} &lt; 3 )</td>
<td>Whole area</td>
<td>0.38</td>
<td>0.024</td>
<td>0.028</td>
</tr>
<tr>
<td>( 3 \leq \bar{p} &lt; 10 )</td>
<td>Whole area</td>
<td>0.26</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>( \bar{p} \geq 10 )</td>
<td>Whole area</td>
<td>0.21</td>
<td>0.017</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Fig. 6. Linear trends of \( q \) for each range of \( \bar{p} \).

Table 3. Same as Table 1 (unnormalized) but for annual maximum daily precipitation.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Trend</th>
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<tbody>
<tr>
<td>Whole area</td>
<td>0.54</td>
<td>-0.007</td>
</tr>
<tr>
<td>Northern</td>
<td>0.60</td>
<td>-0.103</td>
</tr>
<tr>
<td>Eastern</td>
<td>0.49</td>
<td>-0.100</td>
</tr>
<tr>
<td>Western</td>
<td>0.57</td>
<td>0.026</td>
</tr>
</tbody>
</table>
replaced by the tipping-bucket one, can cause some bias in the statistics of precipitation frequency. However, the trends of $q$, evaluated for 1901–1967 (Table 5) are only slightly smaller than those for 1901–2005. This fact indicates that the changes of raingauges do not affect the result of our analysis. On the other hand, application of the procedure to AMeDAS (Automated Meteorological Data Acquisition System), which provides data at about four-hourly data for a hundred years, did not yield a significant result because of the short time length.

4. Remarks

Our analysis has revealed the increase of the spatial concentration of precipitation in Japan on the scale of a few hundred kilometers. This change is more conspicuous for weak and moderate precipitation than intense precipitation. The increase in the spatial concentration of weak precipitation implies the diminution of precipitation area, possibly corresponding to the decrease in the frequency of weak precipitation reported so far (Fujibe et al. 2006).

The change in spatial concentration is found to be insignificant for heavy precipitation. This fact suggests that the increase in the frequency of heavy precipitation has not been accompanied by change in the size of precipitation area. It will be a subject of future studies how the size and intensity of severe mesosystems, which cause heavy precipitation, have changed and/or are expected to change as global warming progresses.

Table 5. Same as Tables 1 and 2 (normalized, whole area) but for 1901–1967.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Trend</td>
<td>Trend</td>
</tr>
<tr>
<td>5 day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All cases</td>
<td>0.33</td>
<td>0.012</td>
<td>0.014</td>
</tr>
<tr>
<td>$p &lt; 1$</td>
<td>0.03</td>
<td>0.006</td>
<td>0.009</td>
</tr>
<tr>
<td>1 $\leq p &lt; 3$</td>
<td>0.27</td>
<td>0.011</td>
<td>0.012</td>
</tr>
</tbody>
</table>

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References


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