ANALYSIS OF FLOOD OCCURRENCE THROUGH CHARACTERIZATION OF PRECIPITATION PATTERNS

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ABSTRACT. This study aims to investigate the occurrences of floods by analyzing the monthly precipitation time sequence utilizing ordinary Kalman filter (OKF) and adaptive Kalman filter (AKF). OKF identifies the abnormal precipitation periods in the sequence by comparing the observed and average precipitation patterns. AKF detects the changes in the precipitation pattern by associating them with the abrupt changes in the parameters of the periodic model of the precipitation time sequence. The 92-year long precipitation record at Fukuoka City, Japan shows three types of abnormal precipitation periods, which exhibit different degrees of possibility of flood occurrence. In addition, it shows nine precipitation epochs with different precipitation patterns. The model parameters estimated by AKF in one epoch characterize its precipitation pattern and describe the occurrences of the abnormal precipitation periods, revealing whether the risk of flood occurrence is high or not in the epoch.

1. INTRODUCTION

Floods like droughts are often caused by adverse weather (Nemoto, 1974), and their occurrences usually result in losses of lives and properties. The need to limit these undesirable consequences of floods has increased society's interest on long-term prediction of adverse weather. Unfortunately, unlike daily weather forecasting, long-term weather prediction is up to now a guessing game. However we believe that the evaluation of the possibility of occurrence of adverse weather that would eventually result to flood can be improved if variations in meteorological and climatological parameters are fully understood.

One of the two most common parameters used to define weather is precipitation (the other is temperature), and its occurrence in abnormally high amounts is the major cause of flooding. Hence this study aims to investigate the occurrences of floods by characterizing the long-term variations in precipitation pattern utilizing ordinary Kalman filter (OKF) and adaptive Kalman filter (AKF). For this purpose, we use the 92-year long (1890-1981) monthly average precipitation sequence at

V. P. Singh (ed.), Hydrologic Frequency Modeling, 327–336.

Fukuoka City, Japan. In this investigation, OKF is used to detect the abnormal precipitation periods in the sequence and to determine quantitatively the periods' magnitude of abnormality. We classify the periods into three types and evaluate the degree of possibility of flood occurrence in each type. On the other hand, AKF is used to detect changes in the precipitation pattern by directly linking them with the abrupt changes in the parameters of the periodic model of the precipitation time sequence. These abrupt changes in the model parameters divide the sequence into several precipitation epochs, where each epoch is characterized uniquely by one precipitation pattern. The model parameters estimated by AKF in one epoch describe the precipitation pattern and the occurrences of the abnormal precipitation periods, where the occurrences of these periods reveal the risk of flood occurrence in the epoch.

2. METHODOLOGY

The use of the monthly average precipitation data provides a suitable approach to the investigation of long-term variations in precipitation pattern. However logarithmic transformation of the 1104 (92 years) monthly average precipitation data (in mm/day) is done to make them follow normal distribution. Also the log-transformed precipitation data is smoothed using the recursive low-pass filter shown in eq.1 (Bendat and Piersol,1976).

$$y(k) = (1-\alpha)\log\{z(k)\} + \alpha y(k-1) \tag{1}$$

where k is the time instant; y is the smoothed log-transformed monthly average precipitation (log (mm/day)); α is the smoothing coefficient and equal to 0.6; and z is the monthly average precipitation(mm/day). The smoothed log-transformed monthly average precipitation $y(k)$ at time instant k is modeled by a periodic function as follows.

$$y(k) = M_y + \sum_{i=1}^{q}(A_i \sin 2\pi f_i k + B_i \cos 2\pi f_i k) + w(k) \tag{2}$$

where M_y is the mean of the smoothed log-transformed sequence; q is the number of significant frequency components; f_i is the frequency component; A_i and B_i are the amplitudes of the frequency component; and $w(k)$ is the stochastic component which is assumed to be white Gaussian noise with zero mean and variance $W(k)$. The reasons for smoothing, choosing α=0.6 and modeling the sequence by a periodic function are mentioned in detail by Kawamura *et al.* (1985). In this study, q = 5, and the dominant frequency components used are f_1 = 1/48, f_2 = 5/72, f_3 = 1/12, f_4 = 1/3 and f_5 = 5/12 in cycles/month, having periods of 4-year, 1.2-year, one-year, 3-month and 2.4-month respectively. These periodicities are obtained by MEM spectral analysis of the smoothed-transformed data (Kawamura *et al.* 1985). Comparison of the power spectra of $z(k)$ and $y(k)$ shows similar dominant peaks, indicating that the periodic properties of $z(k)$ are retained in $y(k)$.

We now consider the problem of identifying the mean M_y and amplitudes A_i and B_i by OKF and AKF. The system equations for OKF and AKF are given respectively in eqs. 3 and 4, while the observation equation for both OKF and AKF is given in eq.5.

$$x(k+1) = \Phi(k)x(k) + \Gamma(k)u(k) \tag{3}$$

$$x(k+1) = \Phi(k)x(k) + \Gamma(k)u(k) + \delta_{k\theta}G(k) \tag{4}$$

$$y(k) = H(k)x(k) + w(k) \tag{5}$$

where x is the $(n\times 1)$ system vector; Φ is the known $(n\times n)$ state transition matrix; Γ is the known $(n\times p)$ system matrix; u is the independent, zero mean, white Gaussian $(p\times 1)$ system noise vector with known covariance matrix U; G is the unknown $(n\times 1)$ vector expressing the magnitude of abrupt change; θ is the unknown time instant when the abrupt change occurred; $\delta_{k\theta}$ is the Kronecker's delta ($\delta_{k\theta}=1$ if $k=\theta$ and $\delta_{k\theta}=0$ if $k\neq\theta$); y is the $(m\times 1)$ observation vector $(m \leqq n)$; H is the known $(m\times n)$ observation matrix; and w is the independent, zero mean, white Gaussian $(m\times 1)$ observation noise vector with known covariance matrix W. Here the dimension n of the state vector is 11 and the dimension m of the observation vector is one; $x=[M_y \quad A_1 \quad B_1 \quad \cdot\cdot\cdot \quad A_5 \quad B_5]^T$; $\Phi(k)=I$; the observation eq.5 corresponds to eq.2; and $H(k)=[\,1 \quad \sin 2\pi f_1 k \quad \cos 2\pi f_1 k \quad \cdot\cdot\cdot \quad \sin 2\pi f_5 k \quad \cos 2\pi f_5 k\,]$. The state variables are the model parameters M_y, A_i and B_i. Details of the parameter estimations by OKF and AKF and the various properties of the use of the two filters in the analysis of time series expressed by a periodic function are given by Ueda, *et al.* (1984), Kawamura, *et al.* (1984) and Kawamura *et al.* (1986).

OKF identifies the abnormal precipitation periods in the sequence by comparing the observed and average precipitation patterns through the abnormality detection index $\phi_*(k,l)$ defined by Ueda, *et al.* (1984). This index expresses quantitatively the magnitude of abnormality of an l-month long observed precipitation period at time instant k. Since the plot of the one-step ahead predictions by OKF is almost the same as the average precipitation pattern (Ueda *et al.* 1984 and Kawamura *et al.* 1984), $\phi_*(k,l)$ is calculated recursively using the l-month long series of residuals between the predicted and observed precipitation amounts. Consequently, the occurrence of a peak ϕ_* identifies one abnormal precipitation period. Here we set $l = 15$.

The shifts in precipitation pattern are associated with the abrupt changes in the model parameters M_y, A_i and B_i. In this case, AKF detects whether abrupt changes in the model parameters or state variables occur or not by evaluating the l-month long series of one-step ahead prediction residuals using generalized likelihood ratio test (GLRT). The GLRT compares the value of $\phi_*(\theta,l)$ with a threshold value η. If $\phi_*(\theta,l)$ is greater than η, the hypothesis (H_1) that an abrupt change occurred at time $k = \theta$ is accepted; otherwise, the hypothesis (H_0) that no abrupt change has occurred is accepted. When an abrupt change is detected, its time of occurrence and magnitude are estimated quantitatively, and the state variables are appropriately corrected, according to the magnitude of this abrupt change, to allow the filter to adjust to the new precipitation pattern. In this study, we detect the change in precipitation pattern, which recurs at an interval of about 10 years *on the average*; for this, we set $\eta = 5.0$.

3. RESULTS

The 92 annual precipitation totals are plotted on normal paper using Weibull plotting method as shown in Fig.1. Although the annual precipitation appears normally distributed, the abnormally wet and dry years deviate significantly from the normal line. Also result of the chi-square test shows the hypothesis that the annual totals obey normal distribution being rejected at 10 % level of significance. From these results, we may conclude that the years with abnormally high and low precipitation belong to a population different from those close to or on the normal line. On the other hand, the extent of departure from the normal line provides a qualitative description of the magnitude of abnormality. For instance, the annual precipitation total in 1980 is the most abnormal because its deviation from the normal line is the largest.

Table 1 shows the daily precipitation amounts of more than or equal to 150 mm found in the 92-year record, which are arranged in descending order. These amounts, except for one (rank 6), happened in June, July, August and September. In the next section, this data is used to explain the incidence of floods in the different precipitation patterns and types of abnormal precipitation periods.

In the 92-year sequence, OKF detects 19 abnormal precipitation periods with a 5-year recurrence interval, which are given in Table 2 where they are arranged in descending order of value of peak ϕ_* . Fig.2 illustrates the first five most abnormal precipitation periods (ranks 1-5 in Table 2).

Implementing GLRT, AKF yields eight changes in precipitation pattern in the 92-year sequence, dividing it into nine precipitation epochs (see Table 3). Table 4 presents the parameter estimates at the last time instant k by AKF for each epoch and by OKF for the whole sequence. Fig.3 exhibits the nine precipitation epochs identified by AKF and the occurrences of the 19 abnormal precipitation periods detected by OKF.

4. DISCUSSION

In Fig.2, the average precipitation pattern (full line histogram) shows three peaks, April, June-July and September, which correspond to spring rainy season, summer rainy season and typhoon season respectively. Notice also that the standard deviations of these months are greater than those of the rest of the months. As shown in Table 1, the first ten heavy daily precipitation amounts of more than 200 mm (ranks 1-10) took place in these months. We can therefore say that flood risk is high in these months.

The 19 abnormal precipitation periods detected by OKF are classi-

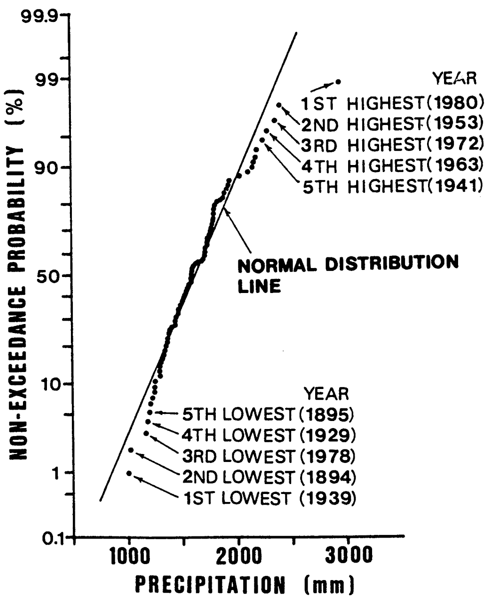

Figure 1. Plot of the annual precipitation data on the normal distribution paper.

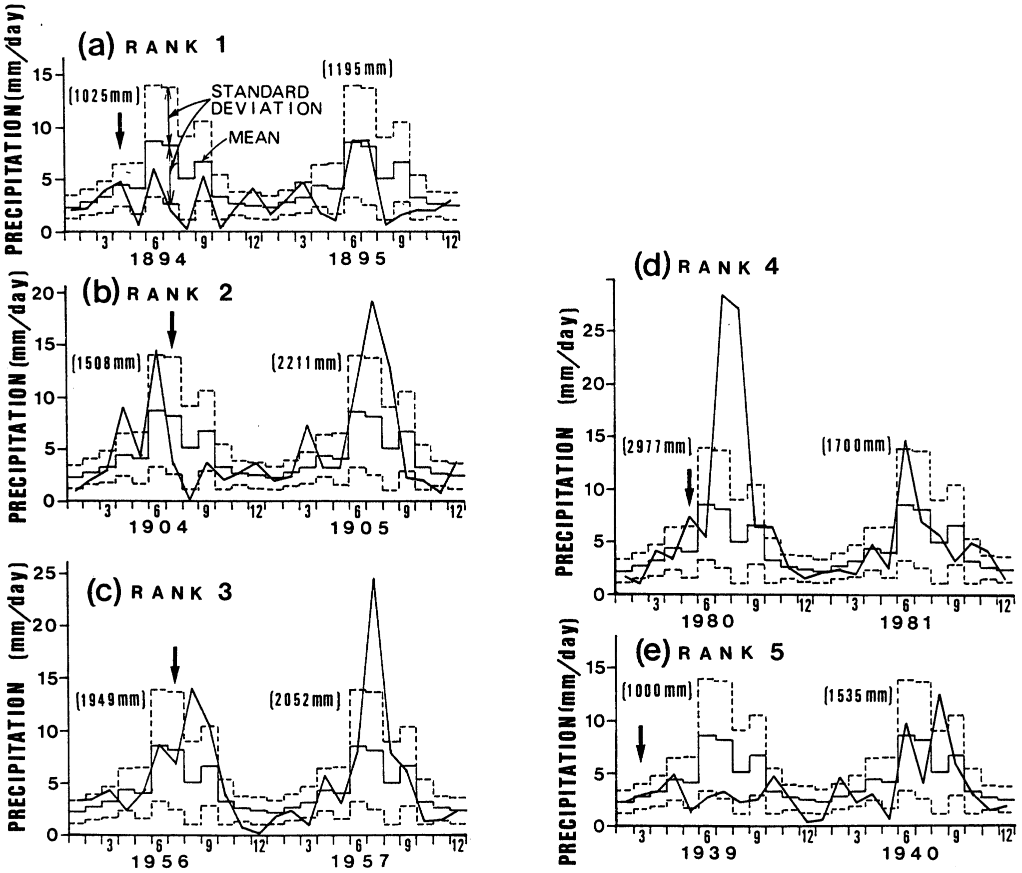

Figure 2. Abnormal precipitation periods (up to rank 5) detected by OKF. The terms in parenthesis are the annual precipitation amounts; downward-arrow indicates the time of occurrence of peak ϕ_* as detected by OKF.

TABLE 1 Daily precipitation of more than or equal to 150 mm (from 1890 to 1891) arranged in descending order.

Rank	Date	Precipitation (mm)
1	25 June 1953	307.8
2	26 July 1905	257.6
3	7 July 1948	245.0
4	29 June 1963	229.3
5	25 Sep. 1954	216.5
6	15 Apr. 1955	215.8
7	21 July 1891	208.7
8	17 Sep. 1925	207.4
9	28 June 1941	206.2
10	22 July 1891	206.1
11	30 Aug. 1980	190.5
12	26 June 1941	186.6
13	25 June 1904	185.6
14	29 Aug. 1980	185.0
15	17 Sep. 1945	182.3
16	28 June 1935	171.9
17	25 June 1941	171.6
18	11 Sep. 1948	168.2
19	10 June 1978	168.0
20	28 June 1953	168.0
21	6 June 1953	166.3
22	5 July 1948	158.6
23	30 June 1979	157.5
24	27 Aug. 1956	152.6
25	26 June 1928	150.7
26	8 Sep. 1934	150.1
27	24 July 1957	150.0

TABLE 2 The abnormal precipitation periods detected by OKF.

	Peak ϕ_*			
Rank	Magnitude	Time of occurrence	Type	Rank of daily precipitation
1	7.90	Apr. 1894	A	
2	7.85	July 1904	C	2,13
3	6.14	July 1956	C	24,27
4	6.09	May 1980	B	11,14
5	6.08	Feb. 1939	A	
6	6.02	Oct. 1944	C	15
7	5.68	Oct. 1971	C	
8	5.16	Aug. 1933	C	26
9	5.15	Oct. 1962	B	4
10	5.08	June 1902	C	
11	4.93	July 1899	C	
12	4.90	June 1948	B	3,18,22
13	4.72	May 1953	B	1,5,20,21
14	4.52	Jan. 1951	C	
15	4.45	July 1977	A	19
16	4.21	Apr. 1913	C	
17	4.19	Aug. 1936	C	
18	4.19	Apr. 1941	B	9,12,17
19	4.15	July 1976	C	

TABLE 3 Precipitation epochs identified by AKF.

Epoch			Rank of daily precipitation
Number	Inclusive dates	Duration (year, month)	
I	Jan. 1890 - Apr. 1894	4,4	7,10
II	May 1894 - May 1898	4,1	
III	June 1898 - July 1904	6,2	13
IV	Aug. 1904 - Aug. 1933	29,1	2,8,25
V	Sep. 1933 - Feb. 1939	5,6	16,26
VI	Mar. 1939 - Nor. 1947	8,9	9,12,15,17
VII	Dec. 1947 - July 1956	8,8	1,3,5,6,18,20,21,22
VIII	Aug. 1956 - Oct. 1971	15,3	4,24,27
IX	Nor. 1971 - Dec. 1981	10,2	11,14,19,23

TABLE 4 Identified system parameters by AKF and OKF.

		Mean	Frequencies(cycle/month) and their amplitudes									
			f_1 = 1/48		f_2 = 5/72		f_3 = 1/12		f_4 = 1/3		f_5 = 5/12	
	Epoch	M_y	A_1	B_1	A_2	B_2	A_3	B_3	A_4	B_4	A_5	B_5
AKF	I	0.53	0.06	0.02	0.06	-0.00	-0.10	-0.09	0.01	0.00	-0.01	0.00
	II	0.43	-0.15	-0.01	0.00	-0.12	0.01	-0.06	0.01	0.04	-0.04	0.02
	III	0.55	0.03	-0.02	-0.02	0.02	-0.12	-0.13	0.00	-0.01	-0.01	0.01
	IV	0.53	0.03	-0.01	0.03	0.02	-0.10	-0.10	0.03	0.02	-0.03	-0.00
	V	0.50	-0.03	-0.01	-0.01	-0.02	-0.18	-0.04	-0.00	0.01	-0.02	0.01
	VI	0.51	0.03	0.13	-0.05	0.02	-0.19	-0.09	0.01	0.03	-0.03	-0.00
	VII	0.61	-0.01	0.03	-0.03	0.04	-0.11	-0.12	0.02	0.02	-0.04	0.00
	VIII	0.53	0.02	0.01	0.01	-0.00	-0.14	-0.10	0.01	0.00	-0.02	-0.01
	IX	0.54	-0.12	-0.04	-0.02	-0.04	-0.14	-0.11	0.01	0.01	-0.01	-0.01
OKF	Total	0.54	-0.00	0.00	0.01	0.01	-0.12	-0.10	0.02	0.01	-0.02	-0.00

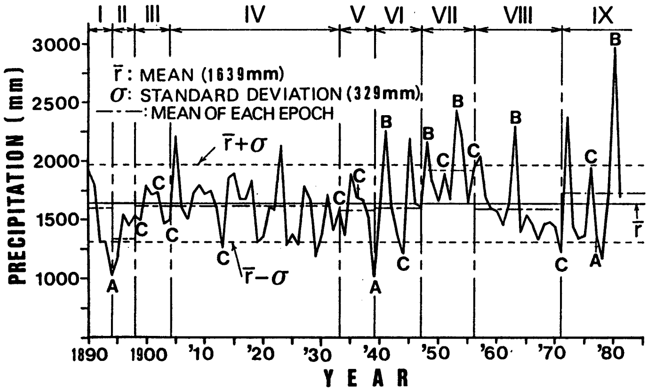

Figure 3. The annual precipitation sequence divided by AKF into nine different epochs. A, B and C are the types of the abnormal precipitation detected by OKF.

fied into three types. Type A is characterized by months with below average precipitation depths as shown in Figs.2(a) and 2(b). Type B is typified by months with above average precipitation amounts as illustrated in Fig.2 (d). As shown in Figs.2 (b) and 2 (c), Type C is characterized by both abnormally high and low precipitation amounts, which occur alternately at two or more months interval. The abnormal precipitation periods could span for one or two years. Of the 19 abnormal precipitation periods, three, five and eleven are Type A, Type B and Type C respectively, suggesting that Type C is most likely to occur whenever an increase of ϕ_* is detected. This increase of ϕ_* should warn us of the possible occurrence of both abnormally high and low precipitation.

As shown in Table 2, 20 out of 27 occasions of heavy daily precipitation occurred in the abnormal precipitation periods. Specifically the first five heavy daily precipitation amounts (ranks 1-5 in Table 1) occurred in these periods, four of them in Type B and one in Type C. This indicates that abnormally high daily precipitation is most likely to occur in Type B. Hence Type B has the highest flood risk. Heavy daily precipitation amounts tend to occur also in Type C, but they appear not as serious as those in Type B. Nevertheless Type C has high possibility of occurrence for both flood and drought. On the other hand, the severest drought ever experienced in the City took place in a Type A period (rank 15 in Table 2). Yet a heavy daily precipitation (rank 19 in Table 1) happened in this period. This suggests that flood could also occur in a Type A period. However higher ranked (1 and 5) Type A periods exhibit no trace of heavy daily precipitation. And flood in this type of abnormal precipitation period is a remote possibility.

As discussed above, we can evaluate the risk of flood occurrence in each period identified by OKF through the presence of abnormally heavy daily precipitation. In the succeeding paragraphs, we investigate the occurrence of flood in each epoch through the characteristics of its precipitation pattern.

As shown in Table 4, the average precipitation pattern defined by the parameters estimated by OKF has a very dominant one-year cycle, as indicated by amplitudes A_3 and B_3 which are much higher than the rest of the amplitudes which are almost equal to zero. Observe also in the same table that we can determine whether an epoch has much precipitation or less precipitation from the estimate of mean M_y and also which frequency component(s) is dominant in each epoch from the estimates of the amplitudes A_i and B_i of frequency component f_i. As presented in Table 4, epoch Ⅰ is characterized by the one-year cycle being the most dominant. Although amplitudes A_1 and A_2 are relatively prominent (compare with the other amplitudes), this epoch's precipitation pattern is basically similar to the average precipitation pattern identified by OKF.

The second and fifth lowest annual precipitation totals shown in Fig.1 occurred in epoch Ⅱ. This epoch is typified by less precipitation, as indicated by its mean being very much below the mean $(\bar{r})$ of the whole sequence (see Fig.3). In Table 4, the estimate of mean M_y of epoch Ⅱ is also the lowest in the nine epochs. However the amplitudes A_1 and B_2 are the most dominant in the epoch (higher than those of the one-year cycle), suggesting that the epoch's precipitation pattern differs much from the average precipitation pattern. Table 3 illustrates no heavy daily precipitation in this epoch; hence we can safely say that flood is least expected in this kind of precipitation pattern.

The precipitation patterns in epochs Ⅲ, Ⅳ, Ⅴ and Ⅷ are similar to the average precipitation pattern. And the number of occasions with heavy daily precipitation per epoch-duration is small in these epochs. In Table 3, for instance, the 29 years and one month long epoch Ⅳ has only three occasions of heavy daily precipitation. Therefore the risk of flood occurrence is not high in the precipitation patterns of these epochs.

The highest estimate of the mean M_y in Table 4 occurred in epoch Ⅶ which is characterized by much precipitation as indicated by its mean being very much above the mean ($\bar{r}$) of the sequence (see Fig.3). However the estimates of the amplitudes of the five frequency components in this epoch are practically the same as those estimated by OKF. Thus the epoch's precipitation pattern is very similar to the average precipitation pattern, except for the level of the mean. Moreover, eight of the 27 observed heavy daily precipitation amounts occurred in this short epoch (8 years and 8 months), as shown in Table 3. Four of these amounts are greater than 210 mm (see Table 1). As this epoch has the most number of heavy daily precipitation, resulting in the highest estimate of mean M_y, the risk of flood occurrence is certainly the highest among the nine epochs. Therefore, the higher the estimate of mean M_y is, the higher the flood risk is, in an epoch.

In epochs Ⅵ and Ⅸ (present epoch), the amplitudes A_1 and B_1 for the 4-year cycle are very dominant as shown in Table 4. The three types of abnormal precipitation periods (A, B and C) tend to happen at the same epoch characterized by a prominent 4-year cycle. In fact, the first lowest (1939) and the fifth highest (1941) annual precipitation totals appeared in epoch Ⅵ, whereas the third highest (1972), third lowest (the most severe drought ever experienced in the City took place in 1978), and first highest (1980) yearly precipitation totals were observed in epoch Ⅸ (see Fig.1). Hence a remarkable 4-year period is observed in these two epochs because abnormally wet and dry years took place alternately at two-year intervals as can be seen in Fig.3. However the means of these epochs appear normal because the occurrence of abnormally high precipitation is balanced by the occurrence of abnormally low precipitation. Although droughts happened in these epochs, there were also many occasions of heavy daily precipitation (see Table 3), making these two epochs next to epoch Ⅶ in terms of the number of incidence of heavy daily precipitation. Thus the risk of flood occurrence is regarded high in these epochs. However, we must pay attention to the occurrence of both flood and drought in this kind of precipitation pattern exhibited by the two epochs.

5. CONCLUSIONS

This paper has demonstrated the application of OKF and AKF in the analysis of flood occurrence through characterization of the precipitation patterns. OKF has been used successfully to identify periods with abnormal precipitation and AKF to detect changes in the precipitation pattern, where these periods and changes are usually indiscernible by visual inspection of the precipitation sequence.

Characterized by the highest estimate of mean M_y, epoch Ⅶ has therefore the highest risk of flood occurrence. In this epoch, Type B has the highest risk of flood occurrence, followed by Type C. The months with abnormally high daily precipitation amounts and with high flood risk in Type B and Type C periods (of this epoch) are April, June, July and September. Hence any combination of the epoch, period and month (e.g., epoch Ⅶ, Type B and June or epoch Ⅶ, Type C and July) has the highest risk of flood occurrence.

The epochs with the second highest flood risk have been Ⅵ and Ⅸ which are characterized by the occurrences of Types A, B and C abnormal precipitation periods. Among the three types, Type A and Type B have the lowest and highest risk of flood occurrence respectively; however, Type A has the highest risk of drought occurrence. In these epochs, the months with high risk of flood occurrence in each type of abnormal precipitation period are the same as those in epoch Ⅶ. For this epoch, we can also conclude that flood risk is high in an epoch where 4-year cycle is the most dominant.

On the other hand, the flood risk is lowest in the epoch typified by the lowest estimate of the mean M_y (epoch Ⅱ). The second lowest flood risk is when the precipitation pattern of an epoch is the same as the average precipitation pattern, e.g., epochs Ⅲ, Ⅳ, V and Ⅷ. In these epochs, the low points in the plot of ϕ_* indicate periods with low flood risk. The months with low risk of flood occurrence are January-March, May, and October-December.

As presented above, the characteristics of the precipitation pattern in each epoch can be used as a basis for evaluating the possibility of flood occurrence.

REFERENCES

Bendat, J. S. and Piersol, A. G. 1971. *Random Data: Analysis and Measurement Procedures*, John Wiley & Sons, Inc., New York, pp.291-299.

Kawamura, A., Jinno, K. and Ueda, T. 1984. 'On the characteristics of the adaptive Kalman filter for detecting abnormality in a periodic time sequence' (in Japanese), *Proc. of the 28th Japan Conf. on Hydraul.*, pp.383-390.

Kawamura, A., Ueda, T. and Jinno, K. 1985. 'Analysis of long-term pattern fluctuations in a precipitation sequence' (in Japanese), *Proc. of Japan Soc. of Civ. Engrs*, **363** / Ⅱ-4, pp.155-164.

Kawamura, A., Jinno, K., Ueda, T. and Medina, R. R. 1986. 'Detection of abrupt changes in water quality time series by the adaptive Kalman filter' In: *Monitoring to Detect Changes in Water Quality Series (Proc. Budapest Symp.*, July 1986), IAHS publ. **157**, pp 285-296.

Nemoto, J. 1974. *Search for Abnormal Weather* (in Japanese), Chuokoron Book Co., Tokyo.

Ueda, T., Kawamura, A. and Jinno, K. 1984. 'Detection of abnormality by the adaptive Kalman filter' (in Japanese), *Proc. of Japan Soc. of Civ. Engrs*, **345** / Ⅱ-1, pp.111-121.