STATISTICAL AND SYNOPTIC STUDIES OF HEAVY RAIN IN KOREA

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Abstract The areal characteristics and the causes of heavy rain in Korea were analysed from the statistical and synoptic points of view. In Korea heavy rain mostly occurs during the two rainy seasons: Changma and Kaul-Changma. The seasonal concentration of heavy rain is more marked in Korea than in Japan. The heavy rain results from such pressure systems as extratropical cyclone, stationary front and typhoon. These causes appear in various ways by seasons and regions. The area with frequent heavy rains is mostly located on the windward side of the mountains. Regardless of the cause, heavy rains were accompanied by low-level jet and "moist tongue".

1. Introduction

Kim (1973) stated the precipitation characteristics of Korea as follows: 1) summer concentration of precipitation, 2) occurrence of heavy rains and 3) large year-to-year variation of precipitation. The former two inseparably result in disasters every year in Korea.

In Korea 28 per cent of the disasters (309 out of 1154) were caused by heavy rains for the period of 67 years from 1904 to 1971 (Central Meteorological Office of Korea, 1973), which cost great damage to the human activities. This heavy rain is a matter of concern in Korea from meteorological and social points of view.

Many analyses of heavy rainfalls have been conducted from the statistical and synoptic standpoints. The former researches were made concerning: 1) the regional patterns of the occurrence frequency and the causes of heavy rains (Fukui, 1967, 1968, Hosokawa, 1965, Okuta, 1970, Lee, 1974) and 2) the estimation of maximum one-day precipitations to be expected for some return periods (Mizukoshi, 1958, 1965, Suzuki, 1957). The latter researches were made in two ways: 1) synoptic analyses of heavy rainfalls (Akashi, 1961, Isono et al., 1975, Yamamoto et al., 1975) and 2) regional analyses of heavy rain characteristics (Mizukoshi, 1979, Central Meteorological Office of Korea, 1969, 1973).

These researches were conducted from either regional or synoptic viewpoints. As Mizukoshi (1968) stated, the mechanism of heavy rainfall should be examined in terms of both regional and synoptic aspects of heavy rainfall. In this paper the author aims to clarify the regional characteristics of heavy rains and their mechanisms in Korea from both statistical and synoptic standpoints. It may lead to a correct understanding of the heavy rains in Korea.

2. Data and Method

Definition of heavy rain

The term heavy rain is qualitatively applied to the rainfall with a large amount of precipitation received in a short time interval. Quantitatively, it may be defined in various ways according to the purpose of the research. First, the heavy rainfall may be measured during a given duration or an individual rainstorm. Concerning the precipitation amount two different measures are used. One is the absolute value of precipitation over a given time interval. The other is the relative value of precipitation which exceeds a given rate of the total precipitation for the year at the meteorological station concerned.

Data and method

The author used the following weather materials: Central Meteorological Office of Korea: Annual Report (1904–1975) and Monthly Report (1966–1975), Japan Meteorological Agency: Daily Weather Maps (1966–1975), Aerological Data (1966–1975), and Miniature Historical Weather Maps (1907–1955) and Nihon Kisho Kyokai (Japan Meteorological Society): Miniature Historical Weather Maps (1956–1965, 1966–1970, 1971–1975).

In this paper the author made analyses of heavy rainfall from the statistical-climatological and the synoptic-climatological standpoints.

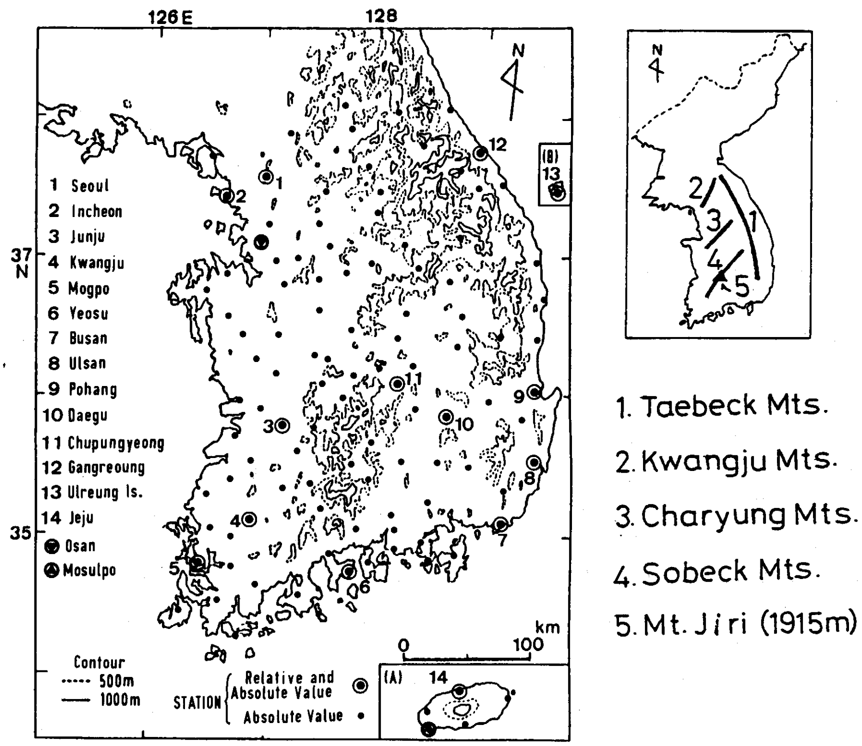

Fig. 1 Location of observation stations. (A) Jeju Island (B) Urleung Island

From the statistical-climatological point of view the heavy rainfall was examined by categories of rainfall intensity which were defined by the absolute and relative values of precipitation. From the synoptic-climatological standpoint the distribution pattern of the precipitation and the transfer of water vapor in upper air, the arrival of low-level jet stream and the vertical stability of the atmosphere were examined.

Although as Mizukoshi (1962) stated, the daily precipitation amount is not a measure sufficient to analyse the characteristics of heavy rainfall in time and space the author used one-day precipitation as a fundamental measure to be examined, since it is convenient for comparing this study with the previous ones in Korea and Japan. As the data used only covered the realm of the Republic of Korea the research was limited to the central and southern parts of the Korean Peninsula. In this study the author uses the term Korea instead of the Republic of Korea for brevity's sake.

In Korea there are not any continual meteorological records for many years at many places. In the analysis based on the relative value of precipitation only 14 stations have the data available for this research. As a result, the spatial analysis could not be made in detail. The analysis based on the absolute values of precipitation was made by using the data of daily precipitation for ten years (1966–1975) at 105 stations: 23 meteorological stations, 61 auxiliary meteorological stations, 21 raingauge stations. The location of the stations is indicated in Figure 1.

3. Precipitation Characteristics in Korea

In order to investigate the climatological characteristics of heavy rains it is necessary in the first place to examine the regional pattern of precipitation characteristics in general in Korea.

Table 1 (a) Maximum observed values of precipitation in Korea and Japan except mountain stations. All stations

Heavy rain \ Country		Korea			Japan		
Duration	Order	Amount of precipitation	Observed point	Date	Amount of precipitation	Observed point	Date
10 minutes	1	47.2mm	Seoul	June 22, 1956	49.0mm	Shimizu	Sept. 13, 1946
	2	40.5	〃	Aug. 29, 1945	40.0	〃	Oct. 17, 1944
	3	34.7	〃	Aug. 5, 1942	39.6	Chichibu	July 14, 1952
	4	33.0	〃	Sept. 13, 1964	39.2	Sumoto	Sept. 2, 1949
	5	30.8	Yeosu	July 31, 1969	38.0	Murotomisaki	Sept. 17, 1942
1 hour	1	118.6	Seoul	Aug. 5, 1942	150.0	Shimizu	Oct. 17, 1944
	2	116.0	〃	Sept. 13, 1964	134.0	Miyazawa	Oct. 16, 1939
	3	109.6	Jeonju	May 26, 1951	123.8	Murotomisaki	July 5, 1949
	4	103.3	Incheon	Aug. 13, 1953	123.2	Owase	Oct. 7, 1952
	5	89.0	Busan	Aug. 10, 1970	120.0	Murotomisaki	July 5, 1949
24 hours (Japan- 1 day)	1	480.9	Seoul	Aug. 1~2, 1920	683.6	Owase	June 6, 1945
	2	456.8	Ulsan	Sept. 14~15, 1969	587.2	Miyazaki	Oct. 16, 1939
	3	446.8	Seoul	Aug. 18~19, 1972	557.3	Yakushima	Aug. 27, 1942
	4	416.4	Gangreung	Sept. 13~14, 1954	523.1	Owase	Oct. 17, 1952
	5	360.1	Incheon	Aug. 18~19, 1972	519.7	Chichibu	Sept. 15, 1947

Table 1 (b) Maximum observed values of precipitation in Korea and Japan except mountain stations.
Selected stations for same latitudes

Heavy rain \ Station		Seoul (L. 37°34′N.) Annual pre. 1259.1mm			Gangreung (L. 38°45′N.) 1282.1mm			Niigata (L. 37°55′N.) 1807mm			Sendai (L. 38°16′N.) 1230mm		
Period	Ranking	Depth	Date	Period	Depth	Date	Period	Depth	Date	Period	Depth	Date	Period
10 min	1	47.2	56.6.22	1904–1975	17.1	70.8.22	1904–1975	20.8	42.8.4	1937–1950	30.0	50.7.19	1937–1960
	2	40.5	45.8.29	″	14.7	64.10.29	″	17.0	58.8.1	″	29.1	44.9.12	″
	3	34.7	42.8.5	″	14.4	65.10.5	″	16.4	48.7.31	″	21.0	52.8.6	″
	4	33.0	64.9.13	″	14.0	69.7.30	″	16.2	58.9.1	″	21.0	50.8.27	″
	5	29.0	66.7.15	″	13.6	72.9.19	″	15.5	37.8.30	″	20.6	48.9.16	″
I hr	1	118.6	42.8.5	″	58.7	36.8.28	″	42.0	30.7.20	1914–1960	94.3	48.9.16	″
	2	116.0	64.9.13	″	51.0	36.9.27	″	41.2	47.7.28	″	67.0	50.7.19	″
	3	83.0	66.7.15	″	43.5	66.8.13	″	39.0	22.7.30	″	66.0	44.9.12	″
	4	81.0	45.8.29	″	40.2	72.9.19	″	38.9	58.7.24	″	57.2	45.6.8	″
	5	80.7	56.6.22	″	39.2	71.8.5	″	38.5	25.8.2	″	55.2	50.8.27	″
I day	1	480.9	20.8.1–2	″ F	416.4	54.9.13–14	″ T	140.7	58.7.24	1286–1960 F	328.5	48.9.16	1926–1960 T
	2	446.8	72.8.18–19	″ T	327.3	71.8.5–6	″ T	132.7	17.8.7	″ F	266.3	44.9.12	″ F
	3	238.9	40.7.10	″ CF	324.4	36.9.26–27	″ L	116.6	05.9.14	″ F	172.4	58.9.26	″ T
	4	273.8	40.7.5–6	″ L	305.5	21.9.24	″ F	114.3	30.7.20	″ T	169.7	47.9.15	″ T
	5	254.7	15.8.22	″ CF	292.3	72.8.18	″ F	111.9	47.6.28	″ L	148.8	39.10.27	″ L
I month	1	1354.2	40.7.1–7.22	″	684.7	25.6.27–7.26	″	511.8	58.7	1939–1960	480.9	48.9	″
	2	1070.4	26.7.11–8.10	″	660.5	36.7.29–9.28	″	411.2	47.7	″	466.7	50.8	″
	3	996.2	66.7.12–8.11	″	657.8	54.9.11–10.10	″	397.1	60.12	″	442.4	58.9	″
	4	910.9	72.8.4–9.3	″	620.9	71.8.3–9.2	″	366.5	52.12	″	390.0	47.9	″
	5	854.3	25.6.23–7.22	″	539.4	72.8.4–9.3	″	352.2	45.12	″	386.8	44.9	″

Heavy rain \ Station		Busan (L. 35°06′N.) Annual pre. 1259.1mm			Mogpo (L. 34°47′N.) 1126.0mm			Hamada (L. 32°04′N.) 1632mm			Tokyo (L. 35°41′N.) 1566mm		
Period	Ranking	Depth	Date	Period	Depth	Date	Period	Depth	Date	Period	Depth	Date	Period
10 min	1	27.0	56.9.25	1904–1975	21.0	49.7.17	1904–1975	20.1	59.8.22	1940–1960	32.5	53.8.23	1940–1960
	2	25.0	56.7.11	〃	21.0	55.9.22	〃	20.0	54.7.29	〃	29.5	47.8.28	〃
	3	35.0	60.7.1	〃	20.0	63.7.1	〃	19.3	56.8.14	〃	24.0	60.9.1	〃
	4	23.0	69.9.14	〃	19.5	74.7.22	〃	18.0	59.7.10	〃	22.6	43.8.15	〃
	5	20.8	48.7.23	〃	18.1	51.9.30	〃	17.2	55.7.6	〃	22.0	40.6.20	〃
1 hr	1	89.0	70.9.10	〃	51.4	55.7.13	〃	85.2	59.8.22	1912–1960	88.7	39.7.31	1876–1960
	2	77.2	73.5.1	〃	50.3	60.7.25	〃	59.9	57.7.29	〃	78.1	60.9.1	〃
	3	71.0	69.9.14	〃	48.4	33.8.17	〃	53.0	54.9.29	〃	76.0	58.9.26	〃
	4	67.6	42.8.15	〃	46.0	38.8.23	〃	53.0	20.7.8	〃	71.5	49.8.24	〃
	5	66.3	48.8.3	〃	45.5	64.9.18	〃	50.0	50.9.16	〃	70.5	35.10.27	〃
1 day	1	285.7	69.9.14–15	〃 L	228.4	26.5.27–28	〃 L	246.7	54.7.29	1893–1960 F	392.5	58.9.26	〃 T
	2	282.3	63.6.24–25	〃 CF	225.7	40.6.24–25	〃 L	228.5	43.9.20	〃 T	278.3	38.6.29	〃 F
	3	269.8	12.7.16–17	〃 L	225.1	07.7.14–15	〃 L	226.7	20.8.17	〃 L	193.7	20.9.30	〃 T
	4	260.7	33.9.19–20	〃 T	210.0	63.6.18–19	〃 L	226.1	58.6.30	〃 CF	175.9	29.9.10	〃 T
	5	249.6	04.7.22–23	〃 T	187.2	42.7.1	〃 CF	202.7	59.8.22	〃 F	171.5	06.8.24	〃 T
1 month	1	1027.8	05.7.18–8.17	〃	760.6	63.6.16–7.15	〃	703.2	57.7	〃	673.7	41.7	〃
	2	938.2	63.6.2–7.1	〃	730.6	34.7.16–8.15	〃	590.2	43.9	〃	673.1	58.9	〃
	3	723.4	48.6.25–7.24	〃	524.7	36.7.30–8.29	〃	565.5	23.6	〃	649.0	38.6	〃
	4	687.7	25.7.1–31	〃	491.9	72.6.26–7.25	〃	507.4	17.9	〃	642.3	45.10	〃
	5	673.9	34.7.13–8.12	〃	478.2	16.6.5–7.4	〃	503.8	54.7	〃	419.9	10.8	〃

Observed maximum precipitation

The author examined the maximum precipitation over different durations. In Korea there are not enough data to analyse the regional details of rainfall intensity. For this reason, the maximum precipitation records of the meteorological stations in Korea and Japan are indicated in Table 1-a and 1-b.

Table 1-a shows the absolute maximum values of Korea in comparison with those of Japan. This table serves to give some valuable information as to the rainfall intensity in both countries. Table 1-b shows the absolute maximum values of the coupled stations located at the same latitude and facing the opposite coasts of the Korean Peninsula and Honshu respectively. The characteristics revealed by the comparison between both countries are as follows:

Absolute maximum values are greater in Japan than in Korea in any time period as supposed from the fact that the annual precipitation in Japan on an average is greater than that in Korea.

Comparing two places at the same latitude:

a) In the northern part of Korea maximum values of precipitation in any time period are greater on the western coast than on the eastern coast. In the southern portion of Korea maximum values of precipitation are greater on the southern coast than on the western coast. This suggests the tracks of cyclonic turbulences in and around Korea. In Japan absolute maximum values of precipitation is greater on the Pacific Ocean coast than on the coast of the Japan Sea, being independent of latitudinal location. b) Comparing the precipitation record of both countries, it is noted that each precipitation extreme for different time durations in Seoul is greater than those observed at the same latitude. In the area near 35°N the extremes are much the same in Japan and Korea. Considering the difference of the annual precipitation in both countries, it is noticed that the rainfall intensity is relatively greater in Korea than in Japan. c) As the time interval becomes longer, the maximum value of precipitation in Korea becomes greater. In particular, the extremes of monthly precipitation are greater in Korea than in Japan. This is one of the precipitation characteristics in Korea which indicates the concentration of precipitation during summer months. d) The maximum values of precipitation most frequently occur in September on the Pacific coast of Japan, while they take place on the Japan Sea side of Japan and the whole area of Korea except for Gangreung in July. As seen in Figure 1-b, the maximum daily precipitation was mainly caused by typhoons on the Pacific side of Japan and on the east coast of Korea, while on the Japan Sea side of Japan and on the west and south coast of Korea it was caused by various factors.

Areal correlation of precipitation

In order to understand the areal correlation of precipitation, a correlation coefficient of the year-to-year variation of the monthly precipitation is needed. April, July, September and December were selected as the representative months of each seasons. The correlation coefficients are shown in Table 2. Some of the distribution patterns related to each month stated above are indicated in Figure 2. At the significance level of 1%, correlation coefficients of more than 0.3 are significant. In the areas with high correlation coefficients rainfall may be caused by much the same factors.

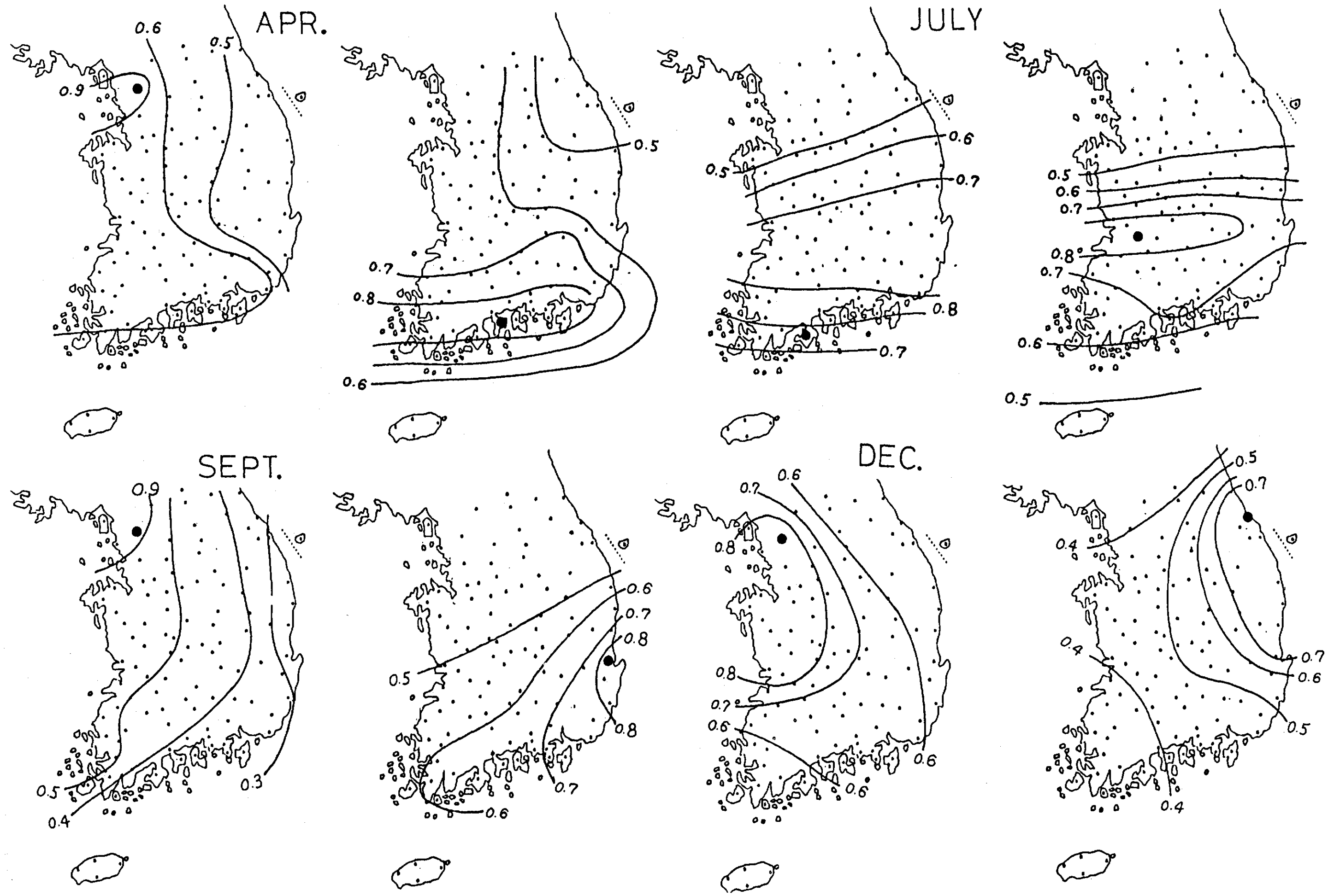

Fig. 2 Distribution of correlation coefficients

Table 2 Correlation coefficients of monthly precipitation between each station during 1931–1960

(Apr.)

	Seo.	Inch.	Gang.	Ulr.	Jun.	Dae.	Poh.	Kwa	Mog.	Yeo.	Bus.	Uls.	Jeju
Seoul		0.964	0.483	0.516	0.676	0.378	0.397	0.689	0.656	0.622	0.602	0.191	0.273
Incheon	0.956		0.500	0.420	0.654	0.639	0.356	0.509	0.699	0.689	0.657	0.200	0.274
Gangreung	0.619	0.616		0.663	0.303	0.478	0.436	0.085	0.085	0.254	0.385	0.364	−0.108
Wreung Do	0.328	0.320	0.620		0.470	0.644	0.687	0.420	0.394	0.557	0.557	0.620	0.397
Junju	0.319	0.277	0.306	0.443		0.789	0.664	0.765	0.761	0.676	0.667	0.644	0.312
Daegu	0.048	0.297	0.302	0.519	0.828		0.819	0.746	0.749	0.735	0.801	0.841	0.332
Dohang	0.181	0.168	0.304	0.507	0.740	0.826		0.509	0.538	0.532	0.662	0.723	0.394
Kwangju	0.212	0.202	0.278	0.432	0.701	0.748	0.728		0.926	0.783	0.692	0.620	0.320
Mogpo	0.255	0.202	0.272	0.422	0.664	0.636	0.639	0.882		0.847	0.718	0.727	0.500
Yeosu	0.292	0.249	0.326	0.530	0.723	0.707	0.757	0.790	0.869		0.865	0.678	0.483
Busan	0.346	0.311	0.444	0.530	0.686	0.750	0.769	0.648	0.777	0.780		0.817	0.483
Ulsan	0.188	0.238	0.332	0.520	0.692	0.821	0.988	0.702	0.726	0.779	0.875		0.411
Jeju	0.182	0.191	0.337	0.362	0.406	0.423	0.388	0.485	0.673	0.622	0.622	0.545	

(July)

(Sept.)

	Seo.	Inch.	Gang.	Ulr.	Jun.	Dae.	Poh.	Kwa.	Mog.	Yeo.	Bus.	Uls.	Jeju
Seoul		0.903	0.379	0.201	0.535	0.415	0.288	0.488	0.506	0.381	0.376	0.374	0.398
Incheon	0.892		0.435	0.196	0.420	0.321	0.105	0.386	0.361	0.293	0.223	0.202	0.180
Gangreung	0.79	0.449		0.097	0.267	0.392	0.221	0.294	0.344	0.245	0.209	0.292	0.152
Wreung Do	−0.177	−0.172	0.276		0.072	0.295	0.231	0.064	−0.030	0.077	0.077	0.152	−0.052
Junju	0.819	0.857	0.421	−0.175		0.706	0.583	0.763	0.764	0.484	0.543	0.537	0.271
Daegu	0.660	0.745	0.597	0.10	0.852		0.667	0.607	0.706	0.680	0.699	0.681	0.448
Pohang	0.542	0.600	0.709	0.02	0.613	0.853		0.667	0.633	0.658	0.793	0.810	0.487
Kwangju	0.626	0.623	0.354	−0.102	0.886	0.796	0.540		0.776	0.681	0.562	0.540	0.607
Mogpo	0.371	0.400	0.281	0.067	0.611	0.625	0.451	0.788		01796	0.654	0.549	0.586
Yeosu	0.686	0.766	0.400	−0.064	0.783	0.752	0.608	0.758	0.730		0.667	0.650	0.642
Busan	0.604	0.644	0.419	−0.064	0.668	0.749	0.775	0.557	0.496	0.680		0.855	0.520
Ulsan	0.438	0.612	0.509	0.032	0.541	0.681	0.789	0.552	0.358	0.503	0.938		0.596
Jeju	0.512	0.503	0.300	0.013	0.569	0.046	0.594	0.634	0.785	0.782	0.782	0.446	

(Dec.)

April:

During spring months the heavy rains are caused mainly by extratropical cyclones. In this season, the retreat of the Siberian air mass results in the northward displacement of polar front around Japan. Migratory anticyclones separated from weakened Siberian air mass frequently move eastward, and, in their rear cyclogenesis becomes more active than in winter. The places of origin of extratropical cyclones are classified into three regions according to the Research and Development Department, Central Meteorological Office of Korea (1976): (1) East China Sea, (2) the river basin of the Yangtze and (3) the river basin of the Hwang Ho. The most depressions of the East China Sea type and the Yangtze type move over the southern part of the Korean Peninsula. The directions of their tracks are classified into four types: (1) those from WSW to ENE, (2) those from SW or SSW to NE or NNE, (3) those from NW or WNW to SE or ESE and (4) the recurved type from the northeastward to the southeastward direction. Among them the WSW-ENE type appears most frequently. In this case, although the areal extent of a rainstorm covers the entire country, areas of heavy rain are limited mainly to the southern part of Korea. The Hwang Ho type depression moves mostly from W to E over the central and northern part of the Korean Peninsula. In this case the areal extent of a rainstorm covers the entire country, being similar to the types as stated above. However, the area of heavy rain is concentrated in the northern part of Korea. It occurs less frequently in the western part of the south. The characteristics of the spatial relationship of precipitation for April are as follows:

(1) The area with a high correlation coefficient extends zonally in the southern coastal region. This fact is supported by the cyclonic activity for this reason: cyclones of the East China Sea type and the Yangtze type pass frequently over the southern part of the Korean Peninsula, and their tracks run in WSW-ENE direction with high frequency more than 50%.

(2) The area with a high correlation coefficient along the west coast extends from the south to the north. This pattern may be attributed to the cyclone paths of the Yangtze type moving towards NE or NNE and those of the Hwang Ho type moving towards SE and the related fronts. On the other hand, in the east coastal region the correlation coefficient between the north and the south is low. This pattern is caused by the lack of cyclones moving northwards or northeastwards along the east coast, and results from the orographic controls of the Taebeck Mountains lying from the north to the south.

(3) The correlation coefficients between Jeju Island and the northern part and between Gangreoung and the southwestern area are less than 0.3 which is a significant level in this case. This means that these two regions are not within the areal extent of a single rainstorm caused by the passage of cyclones.

July:

During the summer depressions frequently develop in the lower river basin of the Yangtze and the Hwang Ho. Most depressions move northeastward along the stationary front, so-called Changma front, which gives rise to much precipitation in Korea.

The characteristics of the occurrence frequencies and the tracks of depressions for June and July from 1966 to 1975 are as follows: in June the depressions of the Yangtze type occur more often than those of the Hwang Ho type. Most of the Yangtze type depressions moving eastward pass over the southern coastal area of Japan, followed by those which proceed northeastward over the southern part of Korea. In July the depressions of both types occur with much the same frequency. Most of the Yangtze type depressions moving northeastward pass over the southern part of Korea and some of them pass over the central and northern parts of Korea. Most of the Hwang Ho type depressions move eastward over the northern part of Korea or the southern part of North Korea, followed by those which move northeastward over the northern part of North Korea or the southern part of Manchuria. In general, the frequency of the passage of the depressions is high in the southern half of Korea in June, while it is high in both the northern and the southern portions of Korea in July.

During these months most of the depressions proceed eastward or northeastward along the Changma front. The location and the track of the depression are closely associated with the northward or southward displacement of the Changma front. The depressions of both the Yangtze and the Hwang Ho types contribute greatly to the precipitation during the Changma season of Korea. The depressions of Hwang Ho type proceed northeastward over the northern part of North Korea or the southern part of Manchuria, resulting in heavy rain frequently due to occluded front which was blocked by the Okhotsk Anticyclone. In July, the culminating stage of the Changma season, thus the area west of northern part of the Taebeck Mountains receives most frequently heavy rains due to the activity of the Changma front which is intensified by the passage of the depressions passing on the three different tracks: the depressions of the Yangtze type proceeding northeastward over the northern portion of Korea and those of Hwang Ho type which move eastward over the northern part of Korea or proceed northeastward over the northern part of North Korea or the southern portion of Manchuria. On the other hand, only the Yangtze type depressions associated with the Changma front result in less precipitation in the southern part of Korea than in the area were of northern part of the Teabeck Mountains.

The pattern of the areal correlation for July differs from that for April. It is summarized as follows: (1) The isopleths of correlation coefficient run nearly parallel with each other from east to west. In the whole country the correlation coefficients between the places on the east coast and those on the west coast show large values more than 0.6. (2) In the meridional direction the correlation coefficients decrease rapidly. This tendency is recognized on both sides of Korea. (3) The longitudinal expansion of the area which has close correlation over 0.6 covers half of Korea. The correlation coefficients are under 0.3 between the places in the southern coastal area, including Jeju Island, and such places in the northern part as Seoul and Gangreung. From the above stated fact the following results are obtained: the location of the Changma front and the tracks of cyclones are closely related to the zonal pattern of the correlation coefficient.

September:

The Northern Pacific High which covers the Korean Peninsula from the end of the Changma season to midsummer weakens after the middle of August and at the same time the Siberian air mass forms on the continent. Thus the polar front is located again over the Islands of Japan in the east-west direction. When the polar front stagnates over the Korean

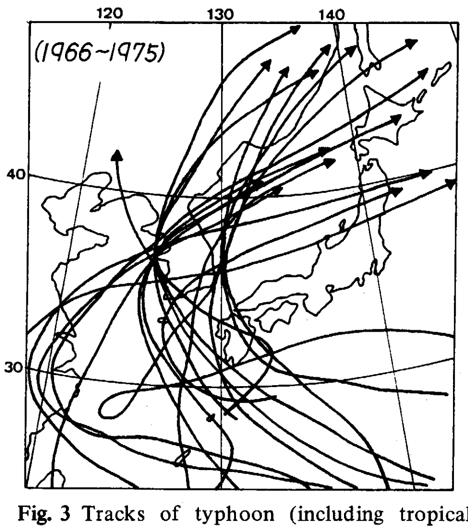

Fig. 3 Tracks of typhoon (including tropical cyclone) with daily precipitation 150mm or more (1966–1975)

Peninsula the Kaul-Changma, the autumnal rainy season, appears. During this season typhoons frequently hit there along the western edge of the Northern Pacific High. The Kaul-changma phenomenon does not last as long on the Korean Peninsula as in Japan and is less marked. September is the month typical of the autumnal rainy period which is greatly affected by typhoons under the conditions of less developed stationary front. Judging from the causes of heavy rain the rainfall for September is caused mostly by extratropical cyclones which are followed by fronts and next by the typhoons. The tracks of typhoons which brought the daily precipitation over 150mm for 10 years from 1966 to 1975 are shown in Figure 3. Out of seventeen typhoons, four passed over the southern coastal area and the southern part of Korea, four along the east coast towards the north after the passage over the southern coastal area, four along the west coast toward the north, and five across the northern part of Korea from the west to the east. The pattern of areal correlation for monthly precipitation of September shows a different tendency from that in April and July. Its characteristics are summarized as follows:

(1) In the southern part of Korea the area with the correlation coefficient of more than 0.6 extends zonally and covers almost the southern half of Korea. It may be attributed to the typhoons and cyclones passing eastward over the southern coast.

(2) In the northern part of Korea the isopleths of correlation coefficients run longitudinally. This pattern may result from the typhoons proceeding northward along both sides of the Korean Peninsula and by the front developing frequently in the direction NW-SE or NE-SW.

(3) The area with the correlation coefficient below 0.3 extends more widely than in April and July. On the whole, the correlation coefficients are small. This fact suggests that the areal extent of the rainfall which is caused by typhoons and the front is more limited than in the case of depressions and stationary fronts.

(4) Ulreoung Island forms an independent area with the correlation coefficient below 0.3.

December:

In winter, a dry season, daily precipitation of over 80mm has never been recorded for the ten years of this study. In winter, when the Siberian High and the Aleutian Low are established, a northerly monsoon circulation regime develops. When the pressure gradient decreases the Siberian High expands southeastward and sometimes a portion of the huge air mass separates from the main body which forms a migratory anticyclone. It sometimes happens that Siberian High extends into the Okhotsk Sea through the northeastern part of China. In both of the above stated cases, a weak trough is generated in the Yellow Sea and a northeasterly air stream develops. Under such a circulation regime the polar front shifts to the north up to the area of 30°N, and depressions are apt to develop over the East China Sea. When these depressions pass over the southern coastal area of the country it brings rain in the western coastal area and rain or snow in the eastern coastal area, and cloudy or rainy weather prevails in the northern part of Korea.

The areal characteristics of rainfall for December are summarized as follows:

(1) In the southern coastal area the area with a large correlation coefficient extends continuously from the southwest to the northeast. This is caused by a cyclone passing through the southern coastal area.

(2) In the western coastal area the area with a large correlation coefficient extends widely from the northwest to the southeast. It is understood that these areas are influenced by

rainfall caused by the northwesterly monsoon.

(3) In the eastern coastal area in contrast with the western coastal area the area with a high correlation coefficient extends in a direction from the northeast to the southwest. It appears in the eastern coastal strip and it is caused by the influx of northeasterly air stream and the orographic controls of the Taebeck Mountains.

(4) The correlation coefficients between Ulreong Island and the rest of the country are less than 0.3. This is the only winter humid area in the Korean Peninsula. The phenomena and causes of this are the same as those on the Japan Sea side of Northern Honshu.

The description above is helpful to understand the climatological characteristics of heavy rains in Korea.

4. Statistical Analysis of Heavy Rain

Analysis based on relative values

Fukui (1968) stated the reason why the relative value of precipitation should be used: whether heavy rain leads to disaster or not does not depend on a definite amount of rainfall in general but on different values from region to region.

The definition of heavy rain according to relative value of precipitation has two cases in Japan. One is the case in which the daily precipitation is in excess of 5% of the annual precipitation (Fukui 1968, 1970) and the other is the case in which the daily precipitation is in excess of 10% of the annual precipitation (Fukui 1967). In this paper the characteristics of heavy rain are analyzed according to these two definitions.

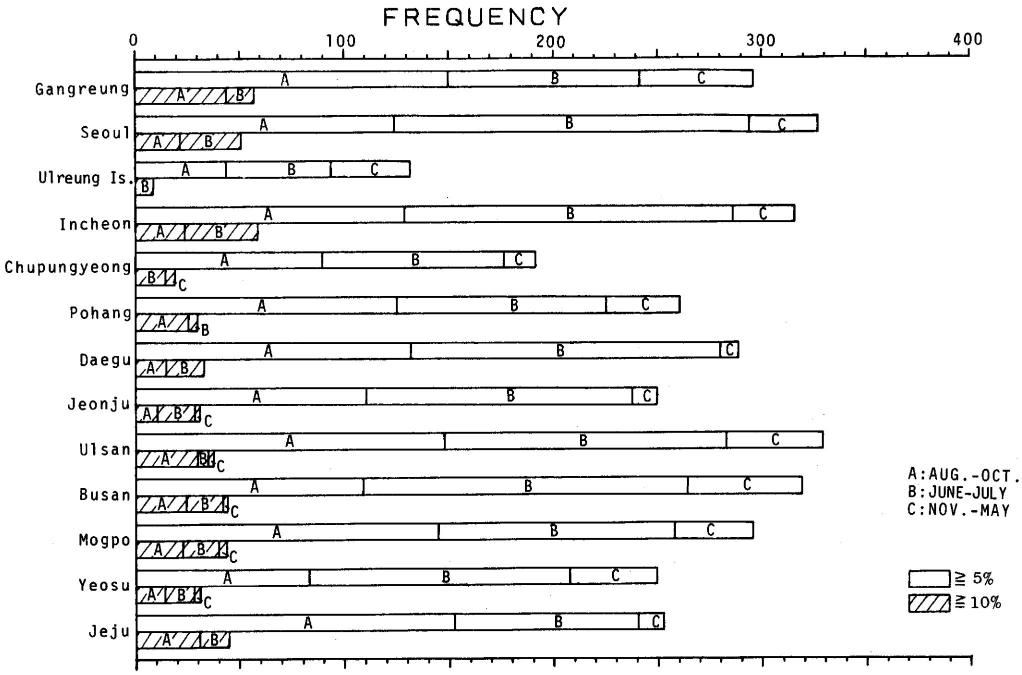

Fig. 4 Seasonal frequency of daily precipitation exceeding 5% and 10% of annual total precipitation in the respective year per 100 years

Table 3 Occurrence frequency of daily precipitation exceeding 5% and 10% of the annual total precipitation of the respective year

Heavy rain / Station	Total frequency (A)		Observed total years (B)	Mean annual frequency A/B		June-Oct/Year (%)	
	≧5%	≧10%		≧5%	≧10%	≧5%	≧10%
Gangreung	157	31	53	2.96	0.58	80.3	100.0
Seoul	167	25	51	3.27	0.49	89.8	100.0
Ulreundo	29	2	22	1.32	0.09	69.0	100.0
Incheon	139	27	44	3.16	0.61	90.6	100.0
Chupungyeong	50	5	26	1.92	0.19	90.0	80.0
Pohang	60	7	23	2.61	0.30	86.7	100.0
Daegh	160	18	54	2.96	0.38	96.3	100.0
Jeonju	135	17	54	2.53	0.45	96.3	94.1
Ulsan	112	14	34	3.29	0.41	84.8	92.4
Busan	172	21	54	3.19	0.39	81.4	95.2
Kwangju	47	4	19	2.47	0.21	91.5	100.0
Mogpo	157	24	54	2.91	0.44	86.0	91.7
Yeosu	72	9	24	3.00	0.38	83.3	88.9
Jeju	129	23	51	2.53	0.45	93.8	100.0
Total	1539	227	Mean	2.72	0.38	87.2	93.9

In Korea only 14 meteorological stations have kept meteorological records over a long period of time. Even worse, meteorological records were made for different years in each area. Therefore, occurrence frequencies per year were examined. The occurrence frequencies are indicated in Table 3. The highest values of occurrence frequency of heavy rain with daily precipitation more than 5% of annual precipitation appear 3 times a year at Seoul, Pusan, Incheon, and Yeosu. These places, except Seoul, are located in the coastal area. The lowest values appear at Chupungyeong in the interior and Ulreoang Island which has much rain in winter. Their occurrence frequencies are 1.92 times and 1.32 times per year, respectively. Heavy rain with daily precipitation more than 10% of annual precipitation occurs at Incheon, Gangreung and Seoul 0.61 times, 0.58 times, 0.49 times per year, respectively. The areas with the lowest occurrence frequencies are Ulreoung Island and Chupungyeong, where the frequencies are 0.09 times and 0.19 times per year. In general the southern and the northern parts of Korea show the highest occurrence frequencies. The central part shows the lowest occurrence frequencies and they are lower in the interior than in the coastal area. This distribution is similar to that of the annual precipitation.

Occurrence frequencies during each rainy season are shown in Figure 4. The areas that show the highest occurrence frequencies during the Changma season, June and July, are the west coastal region of the northern portion of Korea including Seoul and Incheon, and the southern part including Pusan and Yeosu. The places that show the highest occurrence frequencies during the Kaul-Changma season, from August to October, are Gangreung, Pohang, Mogpo and Jeju. The former two are located on the east coast and the latter two are in the southwestern part of Korea. These areas are on the tracks of typhoons, so heavy rain is prevalent. The places with much the same occurrence frequencies during the two rainy seasons are located in the central part of the interior of Korea, except Ulreoung Island.

The average monthly occurrence frequency of heavy rain is shown in Table 4. The fre-

Table 4 Monthly frequency of daily precipitation exceeding 5% and 10% of the annual total precipitation of the respective year per 100 year

Month	Jan.		Feb.		Mar.		Apr.		May		June		July		Aug.		Sept.		Oct.		Nov.		Dec.	
Station \ %	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%	≧5%	≧10%
Gangreung	5.3		1.9		3.8		11.3		11.3		26.4	3.8	64.2	9.4	54.7	15.1	75.5	22.6	17.0	7.5	11.3		13.2	
Seoul	2.0				2.0		17.6		11.7		43.0	3.9	125.0	25.0	80.0	13.7	41.0	5.8	3.9					
Ulreung Do	4.5		4.5				13.6		9.1		13.6		36.4	9.1	22.7		13.6		4.5		9.1			
Inchen	2.3				2.3		13.6		9.1		27.3	4.5	129.5	31.8	77.3	20.5	45.5	4.5	6.8				2.3	
Chupungyeong							7.7		7.7	3.4	15.4		69.2	15.4	38.5		46.2		2.7					
Pohang	4.3								17.4		21.7		78.3	4.3	69.6	17.4	43.4	8.7	13.0		4.3		8.7	
Daegu					1.8		5.5		1.8		40.7	7.8	107.0	11.0	78.0	9.0	48.0	4.0	5.5	1.8				
Jeonju							3.7		5.6	1.9	27.8	3.7	98.1	7.4	70.4	13.0	37.0	6.0	7.4					
Ulsan			2.9		8.8		11.8		17.6		44.1		91.2	5.9	79.4	17.6	52.9	14.7	11.8		2.9		5.9	2.9
Busan			1.8		3.7		18.5		22.2	1.8	72.2	1.8	81.5	13.0	40.7	11.1	51.9	11.1	16.7		3.7		3.7	
Kwangju					5.3		5.3		5.3		26.3	5.3	73.7		63.2		52.6	10.5	10.5	5.3	5.3			
Mogpo			3.7		1.8		20.4	1.8	11.1	1.8	44.4	5.6	66.7	13.0	75.9	16.7	50.0	5.6	13.0		1.8			
Yeosu					4.2		8.3		33.3	4.2	58.3	8.3	91.7	8.3	54.2	8.3	33.3	8.3	12.5		4.2			
Jeju							3.9		3.9		29.4	3.9	56.9	9.8	70.6	13.7	66.7	15.7	13.7	2.0	5.9			

quency of heavy rain with daily precipitation more than 5% of annual precipitation is the highest in July at every point except Jeju and Mogpo. August comes next and September follows. The frequency of heavy rain with daily precipitation more than 10% of annual precipitation is high in July in Seoul and Incheon, in the west coast of the northern part of the country, in Pusan on the south coast and in Daegu and Chupungyeong in the interior. It is high in August on Jeju Island and in the eastern coastal area.

The occurrence frequency of heavy rain with daily precipitation more than 5% of annual precipitation equals 43.5% during the Changma season (from June to July) and 43.7% during the Kaul-Changma season. The total of these two frequencies reaches to 87.2%. The occurrence frequency of heavy rain with daily precipitation more than 10% of annual precipitation amounts to 40.7% in the Changma season and 55.2% during the Kaul Changma. The total of these two frequencies reach to 95.9%.

The monthly average frequencies of heavy rain in both categories are higher in the Changma season than in the Kaul Changma season.

The seasonal concentration of heavy rain is more marked than that of monthly precipitation. Especially, in Incheon, Chupungyeong, Daegu, Junju, Kwangju and Jeju with the occurrence of the heavy rains with daily precipitation more than 5% of annual precipitation during the above-stated two rainy seasons shows more than 90%. The seasonal concentration of heavy rain during the two rainy seasons increases with the increase of daily precipitation delimiting the category of heavy rain. It becomes pronounced, generally, from the coast to the interior.

Analysis based on absolute values

Different definitions of heavy rain based on absolute values have been made by several other researchers. Hosokawa (1965, 1969) and Yamashita (1970) give a definition of heavy rain as that which has precipitation over a certain value measured during a rainstorm. Tsuchiya (1958), Sekiguti and Inoue (1967) and Okuta (1968) give a definition of heavy rain as that which has precipitation over a certain value measured by daily precipitation. Okuta counted number of days with heavy rainfall by using data from 137 meteorological stations. He classified it according to the following categories: more than 50mm, more than 100mm, more than 150mm, more than 200mm and so on, at 100mm intervals. He analyzed the regional characteristics and atmospheric turbulence which caused heavy rainfall.

In this chapter the spatial and temporal characteristics of the occurrence frequency of heavy rain in Korea are clarified. They are also compared with the results obtained in Japan. The data used are daily precipitation records from 1966 to 1975 of 105 meteorological stations.

The daily precipitation of heavy rain was examined according to the following categories: more than 30mm, more than 50mm, more than 80mm, more than 100mm, more than 150mm and more than 200mm. In Korea more than 30mm may lead to disaster, and more than 50mm leads to flood damage because of the peculiar natural and social conditions (characteristics of rock and forest, excessive land use, and lack of equipment to prevent disasters).

Distribution of occurrence frequency of heavy rain

A day of heavy rain is considered to be one in which heavy rain is observed at least at one of the survey points. The mean annual number of days with heavy rain decreases exponentially in proportion to the increase of precipitation according to the above-stated categories (Table 5). On an average the month with the maximum number of heavy rain days is July or August for all categories. The second month with the largest number of heavy rain days is September or June. However, September exceeds June as rainfall category increases. This indicates that heavy rains in higher categories often appear in the Kaul-Changma Season.

Concentration rate of number of days with heavy rain during the rainy season (from June to October) is 80.3% in the category more than 50mm, 84.4% in more than 80mm, 89.6% in more than 100mm, 90.3% in more than 150mm, and 95.5% in more than 200mm. The concentration ratio becomes greater in proportion to the increase of precipitation of rainfall. This shows the same tendency as the relative value of precipitation.

Distribution of annual number of days with heavy rain:

The distribution of annual number of days with heavy rain according to categories of precipitation is shown in Figure 5. Characteristics of this distribution are as follows:

a) Number of days with heavy rain more than 30mm

Generally the highest occurrence frequency appears particularly in the southeastern coastal area. The next highest one appears in the north and in the western part of the Taebeck Mountains. The lowest occurrence frequency appears in Ulreung Island and the southeastern part of the interior area between the Taebeck Mountains and the Sobe Mountains.

In Jeju Island the occurrence frequency is lower in the northern part than in the southern part.

b) Number of days with heavy rain more than 50mm

The general tendency of this category is similar to that of the more than 30mm category though it is more complicated. Areas with high occurrence frequency extend more widely over the southern coast than in the case of the more than 30mm category. The restricted northeastern coastal area including Gangreung and Yangyang shows high occurrence frequency. The area with high occurrence, west of the Taebeck Mountains, extends towards the south along the western coast. The Mogpo area in the southwestern part is of significance because of its low occurrence frequency.

c) Number of days with heavy rain more than 80mm

The tendency of this category is similar to that of the more than 30mm and more than 50mm categories. It is notable that the area with low occurrence frequency extends more widely towards the southeastern interior area than in the cases of the categories stated above.

Table 5 Occurrence frequency of heavy rain (1966–1975)

Month / Daily rainfall	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
50mm	7	8	13	38	42	75	146	147	82	27	9		594
80mm		3	5	16	14	37	102	80	48	14	2		321
100mm		2	2	11	8	21	74	62	34	7			221
150mm			1	1	5	3	22	25	13	2			72
200mm					1	1	8	8	3	1			22

d) Number of days with heavy rain more than 100mm

The highest occurrence frequency appears in the area to the south of Mt. Jiri. On the other hand, the lowest occurrence frequency area extends along the eastern foot of the northwest side of the Sobeck Mountains which are located in the interior part of southeastern Korea.

e) Number of days with heavy rain more than 150mm

Areas with high occurrence frequency appear in the southern coastal area and west of the Taebeck Mountains to the north. The central part of Korea between these two parts has an area with low occurrence frequency. This spatial tendency is more markedly represented in this category in comparison with the other categories. The area with low occurrence frequency, the core area of which is located in the southeastern interior, extends towards the west coast.

f) Number of days with heavy rain more than 200mm

Areas with annual number of days more than 0.2 spread over three regions: the south coastal area, the western portion of the north and the east coastal strip in the north. The area with occurrence frequency of zero spreads from the west coast to the east coast in the central part of Korea.

In all categories the southern coast area and area west of the northern part of Taebeck Mountains show the highest annual occurrence frequency. The Gangreoung and Yangyang area shows highest annual occurrence frequency for all categories except the more than 30mm one. These areas correspond also to those of the largest annual precipitation. On the other hand, the southeastern interior and Mogpo area are those with the lowest occurrence frequency of heavy rain which coincide with the areas of smallest annual precipitation. So the distribution of annual number of days with heavy rain is similar to that of annual precipitation. But Ulreoung Island forms an exception; it shows a large annual precipitation but heavy rain occurs less frequently. The south coastal area, particularly the area including Hadong, Suncheon, Namhae, and Chungma, shows high occurrence frequency. It is caused by orographic controls of the Sobeck Mountains and the Noryeong Mountains which is exposed to the southerly moist air stream (Meteorological Research Institute, Central Meteorological Office of Korea 1978). The high occurrence frequency in the northern part is also caused by orographic controls of the Taebeck, the Charyung and the Kwngju Mountains, which are exposed to the moist air mass from the southwest or the west. The northeast coastal area including Gangreung and Yangyang shows high occurrence frequency with increase in categorized amount of rainfall. In this area four heavy rains of more than 150mm occurred during the ten year period, 3 of which were caused by typhoons. This area is on one of the main tracks of typhoons as shown in Figure 3.

Jeju Island off the southern coast of the Korean Peninsula has a large amount of annual precipitation and great number of days with heavy rain. There heavy rain occurs more frequently in the southern coastal area than in the northern coastal area, which results from orographic controls of Mt. Hanra (1950m) extending in E-W direction in elliptical form in the central part of the island. The area with low occurrence frequency in the southeastern interior results from the leeward effect of the Sobeck Mountains and the Noryeong Mountains. The low occurrence frequency of Mogpo area in the southwest may also be controlled by the mountains and hills lying to the southwest and the south. Although

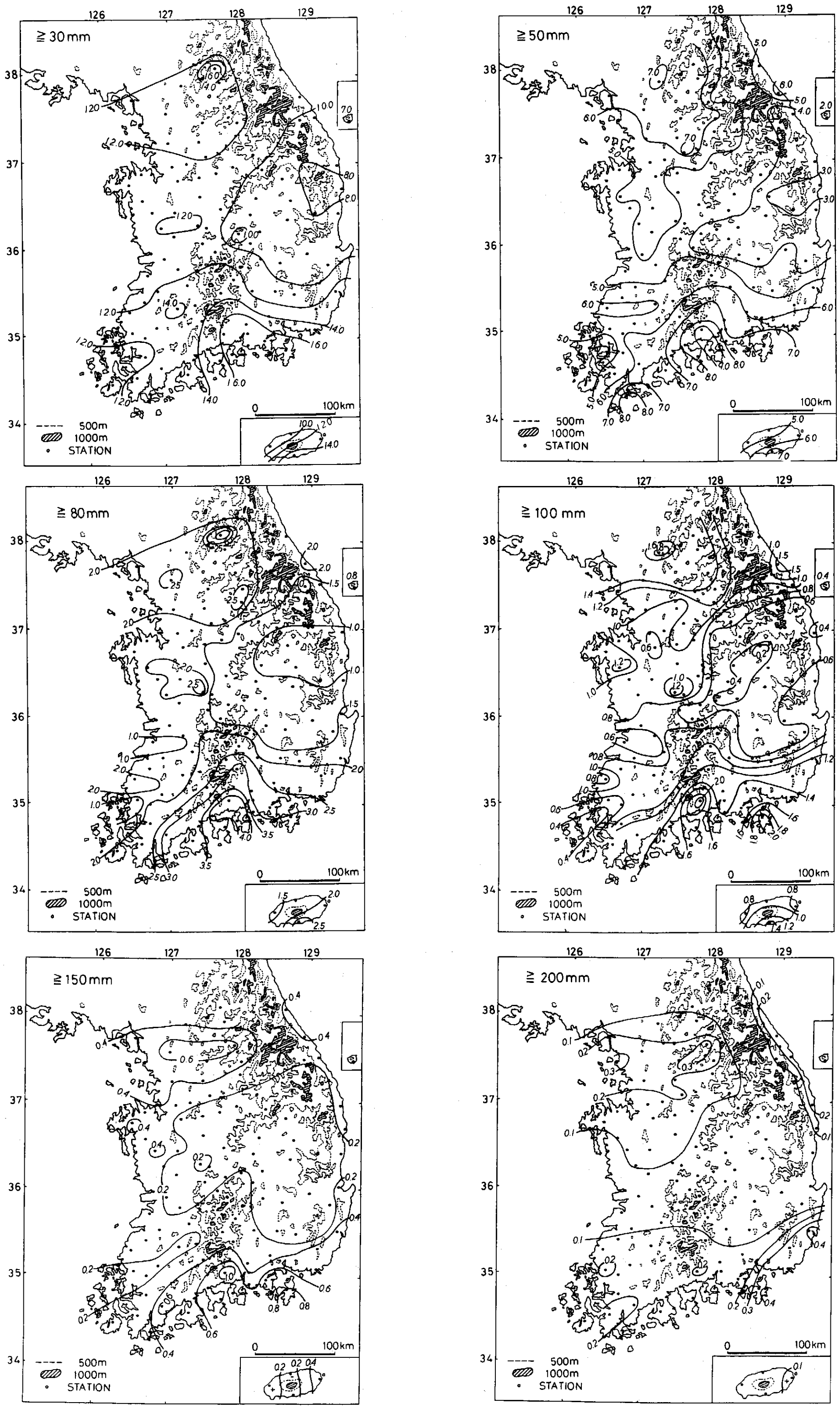

Fig. 5 Distribution of heavy rain frequency by daily precipitations

Ulreung Island has great annual precipitation, it has a low occurrence frequency of heavy rain, because of the leeward effect of the Peninsula. From the above facts, it can be noted that the regional characteristics of heavy rain occurrence are closely associated with the orographic controls of the mountains and hills exposed to the southwesterly or westerly moist air stream.

Distribution of monthly number of days with heavy rain:

Distributions of monthly number of days with heavy rain more than 30mm and more than 80mm are shown in Figures 6 and 7. The distribution characteristics for each month are as follows:

a) From November to February

This period is a dry season during which heavy rain seldom occurs. In November the regional pattern of the occurrence frequency of heavy rain of more than 30mm has a similar

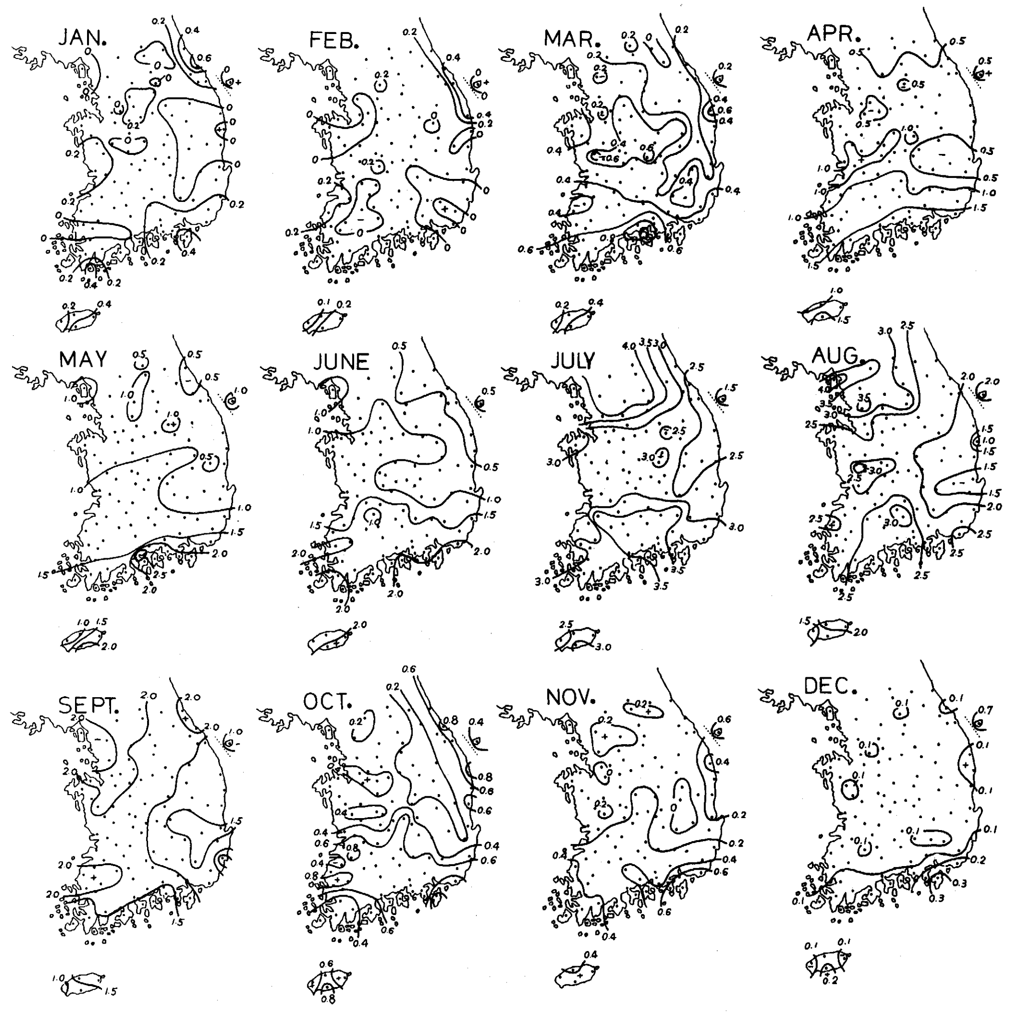

Fig. 6 Distribution of average monthly number of heavy rain days with daily precipitation 30mm or more (1966–1975)

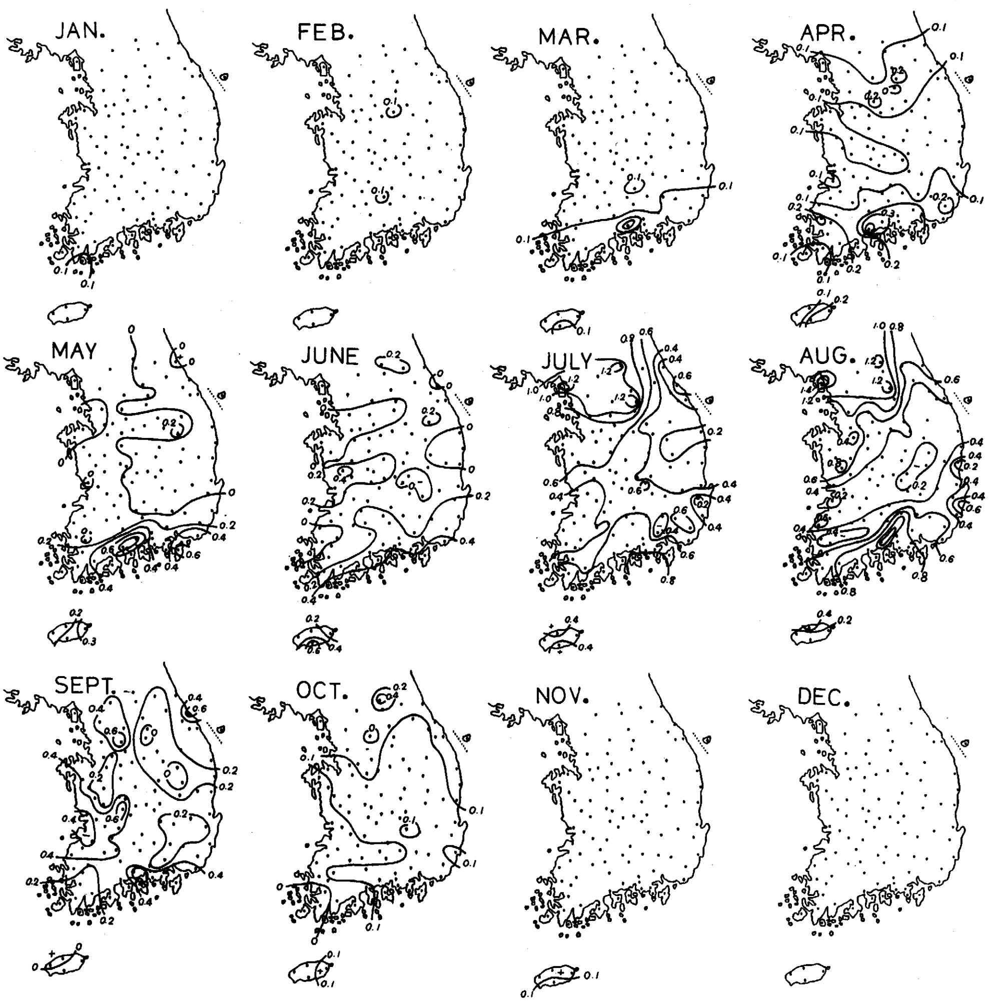

Fig. 7 Same as Fig. 6, but for daily precipitation 80mm or more (1966–1975)

tendency as that of October, though the occurrence is smaller on the whole. On the other hand, high occurrence frequency appears in Ulreung Island in November as in December. Heavy rain with daily precipitation more than 80mm was recorded only once on Jeju Island throughout the country during the years 1966–1975. The place with the greatest number of days with heavy rain of more than 30mm in December is Ulreung Island followed by the southern coastal area. In January high occurrence frequency appears in the southern and the northeastern coastal areas, while high occurrence frequency occurs only in the northeastern coastal area in February. The northeastern coastal area with high occurrence frequency for February extends farther southward along the coast than in January. The area with occurrence frequency of zero during the winter months from 1966 to 1975 extends far and wide in the interior part. Heavy rain of more than 80mm does not occur in December and January. In February heavy rain appears only once for two stations during the period from 1966 to 1975.

b) From March to May

Compared with the winter months, number of days with heavy rain more than 30mm and more than 80mm increases rapidly during the spring months. They are registered more in April and May than in March. In the case of the more than 30mm category in March, areas with high occurrence frequency appear in the south coastal area and the southern half of the east coast in the north and in the interior of central Korea. In April and May occurrence frequency shows a maximum in the southern coastal area, decreasing towards the north. In the case of the more than 80mm category the southern coastal area shows a high occurrence frequency. Maximum frequency appears particularly on the southern slope of Mt. Jiri. The area with occurrence frequency of zero appears on the east coast during the spring months.

c) From June to July

This period is a rainy season in Korea which is called Changma. Number of days with heavy rain for June is almost the same as that for May in both cases of the more than 30mm and more than 80mm categories. The distribution pattern for June is also much the same as that for May. In July, however, number of days with heavy rain increases rapidly. It means that most of heavy rain in this season is caused by the activity of the Changma front in July. In June maximum number of days with heavy rain of more than 30mm appears on the south coast, decreasing towards the north. In the east coastal area occurrence frequency is lower than in the west coastal area. Maximum monthly number of days with heavy rain occurs in July. The highest occurrence frequency appears in the north which is followed by the southern coastal area. As a result, low occurrence frequency appears in the central part of Korea. In particular, the east coastal area of the central part in which high occurrence frequency occurs in winter shows minimum occurrence frequency. In June number of days with daily precipitation of more than 80mm is smaller than in May over the entire country except Jeju Island. However, the area with occurrence frequency of zero is rather restricted. The number of days with daily precipitation more than 80mm is the highest in July or August for the whole year, and the area with occurrence frequency of zero does not appear. In July its areal pattern shows a similar tendency to the case of the more than 30mm category. In this month special attention should be paid to the appearance of the area with high occurrence frequency on the northeastern coast and the lack of an area with occurrence frequency of zero.

d) From August to October

This period includes the autumn rainy season which is called Kaul-Changma. Monthly number of days with daily precipitation more than 30mm and more than 80mm decrease suddenly from August to October. The distribution patterns in August are almost the same as those in July. The area with low occurrence frequency extends more widely in the southeastern interior than in July. In the case of heavy rain of more than 80mm a marked distribution pattern appears: the areas with high occurrence frequency are located in the north and the south with an intervening area of low occurrence frequency extending from west coast to east coast. In September the occurrence frequency decreases suddenly. In the case of heavy rain of more than 30mm the regional difference of frequency reaches its minimum for the whole year. In the case of heavy rain of more than 80mm the areas with high occurrence frequency appear on the west coast and on the southeastern coast and on the northeastern coast, while the area with occurrence frequency of zero appears in a part of the interior. The frequency for October is smaller than that for September. The area which has a large number of days with daily precipitation more than 30mm appears along the east coast in October.

Some considerations on the characteristics of the distribution of monthly number of days with heavy rain will be stated below.

In January high occurrence frequency appears in the northeastern coastal area which results from the forced uplifting of the northeasterly air flow by the Taebeck Mountains. In February and March the area with high occurrence frequency shifts to the south. This may be attributed to an increase in the numbers of depression passing over the southern part of Korea. From March to April and May occurrence frequency of heavy rain increases rapidly. This fact coincides with a rapid increase in the frequency of depressions passing over the southern coastal area. In July and August pressure systems which result in heavy rain occur most frequently over Korea and its environs. As a result, maximum number of days with heavy rain occurs in July or August. The zonal pattern of distribution in July may be the result of cyclone tracks, location of stationary front and orographic controls. In August the area with high frequency is rather limited to the northwestern and southwestern parts. This pattern indicates that the leading pressure systems which cause heavy rain in this month are extratropical and tropical cyclones instead of stationary fronts as in July. In September occurrence frequency becomes lower. In the case of heavy rain of more than 80mm high occurrence frequency appears in parts of the coastal area. This distribution pattern may result from the typhoons in this season (Fig. 3). In October and November occurrence frequency decreases rapidly. Its distribution pattern is similar to that for March. Minimum occurrence frequency appears in December in which northeasterly airflows do not yet develop.

Comparison with the results obtained in Japan

The distribution of number of days with heavy rain in Japan during the period from 1951 to 1960 was investigated by Okuta (1968). So the results of this study will be compared with those of Japan.

Distribution of annual number of days with heavy rain

In the Islands of Japan the Pacific seaside, west of the Boso Peninsula, has a large number of days with heavy rain but number of days with heavy rain decreases with increase in latitude. In general heavy rain occurs less frequently on the Japan seaside than on the Pacific coast. In Korea, on the other hand, the areas with high occurrence frequency appear in the southern and the northern parts, which are separated by an area of less frequent heavy rain in the central part. On the whole, the lower occurrence frequency appears in the eastern half of the country. The differences of the regional characteristics of occurrence frequency between Korea and Japan are caused by the difference in the alignment of mountains: in Korea the mountain ranges extend in the direction N-S or NE-SW, while in Western Japan they stretch in an E-W direction. In Japan it is generally recognized that in every category high occurrence frequency appears in the Pacific coastal strip west of the Boso Peninsula, as compared with the other parts of Japan which have rather low occurrence frequency. The regional contrast is more pronounced in Japan than in Korea. For example, annual number of heavy rain-days with daily precipitation more than 50mm, amounts to more than 10 days on the Pacific seaside west of the Boso Peninsula. In particular, in southern Kyushu more than twenty heavy rain days were recorded, while on the Japan seaside of Western Japan and in the eastern half of Honshu less than 5 days were registered. On the other hand, in Korea an area with as much high occurrence frequency as on the Pacific seaside of western Japan is not found. Only on the southern slope of Mt. Jiri a high occurrence frequency of more than 9 days occurs, whereas a small numbers of days (5 or less) is recorded in the interior of the central part of Korea, a considerably more limited area than in Japan.

Monthly number of heavy rain days

The distribution of monthly number of heavy rain days of more than 50mm and its seasonal variation in Korea will be compared with that of Japan.

In Japan a large number of heavy rain days (2 or more) appears on the Pacific side of Western Japan in May and June. In July the area with a large number of heavy rain days appears on the Japan Seaside of Western Japan. In August it occurs again on the Pacific side of Western Japan. In September and October the area shifts to the Pacific side of Central Japan with increasing number of days. In Korea a large number of heavy rain days appears in the south coastal area in May. This is the same as on the Pacific side of Western Japan. This pattern results from the activity of depressions passing over the southern coast. In June number of days more than 2 occurs on the Pacific side of Western Japan with its maximum value of more than 3.5 days in Kyushu. In contrast the largest number of days amounts to only 1 in the south coastal area of Korea, diminishing towards the north. This fact means that the Baiu front stagnates over the southern coast of Japan in this month, while it does not exert its influence on Korea. In July the area with 2 or more heavy rain days appears on the Japan Sea side of West Japan. In Korea the area with 2 or more heavy rain days in this month is found in the southern coastal area and the northern part of Korea. Over the entire country except the northeastern coast the largest monthly number of days occurs in July. Most of the heavy rains in this month are caused by the activity of the Changma or Baiu front. In August number of heavy rain days is as great as in July, although it decreases in Japan. The greatest values appear particularly in the southern coastal area and the northeastern coastal area, which result from the activity of typhoons. In September the area with large number of heavy rain days appears in the eastern part of the Pacific seaside of Western Japan and in Korea the corresponding area is the eastern coastal strip east of Taebeck Mountains in Korea. This may be the result of the eastward displacement of the typhoon tracks, because of the weakening of the Pacific High in this month. In October number of heavy rain days considerably decreases, while large values of 2 or more appear on the Pacific seaside of Central Japan.

This is caused by the stagnation of the polar front over the Pacific coast of Japan which is partly associated with typhoons.

Pressure patterns associated with heavy rain

By using the surface weather maps at 0900 and 2100JST the author classified the pressure patterns which result in heavy rain. The pressure patterns associated with the heavy rain are classified into five types:

1) Extratropical cyclone type
2) Stationary front type
3) Frontal or trough type (excluding stationary front type)
4) Typhoon type
5) Unclassified pattern

Monthly and annual occurrence frequencies of heavy rain by pressure patterns during the period from 1966 to 1975 are shown in Table 6. And, Figure 8 shows occurrence frequency of pressure patterns associated with heavy rains.

In all heavy rain categories except that of more than 200mm heavy rains result more frequently from extratropical cyclones.

The occurrence frequency of heavy rain caused by fronts or troughs decreases as the amount of heavy rain category increases, while that caused by stationary fronts remains nearly constant throughout all categories. The occurrence frequency of heavy rain due to typhoons increases with increase of the defined rainfall categories, reaching a maximum in

Table 6 Occurrence frequency of heavy rain by pressure patterns during the years 1966–1975

Daily rainfall	Synoptic situation	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total (%)
≧5mm	Extratropical cyclone	7	4	13	32	39	49	48	52	39	17	9		309(52.0)
	Other front and trough		4		5	3	4	23	41	27	4			111(18.7)
	Stationary front						20	53	18	4	3			98(16.5)
	Typhoon							14	26	7	1			48(7.9)
	Unclassified pattern				1		2	8	10	5	2			28(4.9)
	Total	7	8	13	38	42	75	146	147	82	27	9		594
≧80mm	Extratropical cyclone		3	5	15	13	21	26	30	23	8	2		146(45.5)
	Other front and trough				1	1	3	18	17	13	2			55(17.1)
	Stationary front						13	45	10	3	1			72(22.4)
	Typhoon							12	20	6	1			39(12.2)
	Unclassified pattern							1	3	3	2			9(2.8)
	Total		3	5	16	14	37	102	80	48	14			321
≧100mm	Extratropical cyclone		2	2	10	7	10	18	22	20	5			96(43.4)
	Other front and trough				1	1	3	10	14	9				38(17.2)
	Stationary front						8	36	10	3				57(25.8)
	Typhoon							10	16	2				28(12.7)
	Unclassified pattern										2			2(0.9)
	Total		2	2	11	8	21	74	62	34	7			221
≧150mm	Extratropical cyclone			1	1	4	2	6	7	10	2			33(45.9)
	Other front and trough					1	1	4	1	1				7(9.7)
	Stationary front							10	3	1				15(20.8)
	Typhoon							2	14	1				17(23.6)
	Unclassified pattern													
	Total			1	1	5	3	22	25	13	2			72
≧200mm	Extratropical cyclone						1	1	1	3	1			7(31.8)
	Other front and trough					1		1						2(9.1)
	Stationary front							4	1					5(22.7)
	Typhoon							2	6					8(3.64)
	Unclassified pattern													
	Total					1	1	8	8	3	1			22

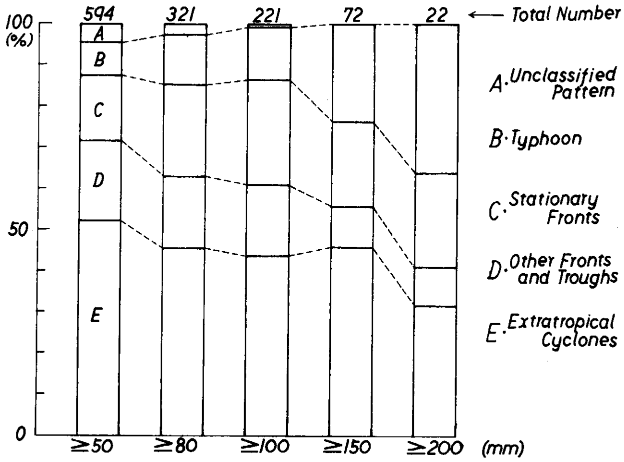

Fig. 8 Occurrence frequency of pressure patterns associated with heavy rains by daily precipitation categories during 1966–1975

the more than 200mm category.

The characteristics of the seasonal variation are as follows: during the period from June to September high occurrence frequencies concentrate in any pressure pattern. In particular, maximum frequency appears in July or August.

Such a seasonal concentration coincides with that of monthly precipitation. The frequency of heavy rain caused by extratropical cyclone increases rapidly from April and decreases abruptly from October. In particular, it is concentrated during the summer months from June to August.

Rleative frequency of heavy rain days caused by extratropical cyclone during the period from April to September equals 73.5 percent and 87.7 percent in the categories of more than 50mm and more than 80mm respectively. Concerning the heavy rain of frontal and trough type it concentrates from July to September. The relative frequency during this period amounts to 89 percent in the category of more than 80mm. The occurrence frequency of heavy rain days caused by stationary fronts is concentrated during the period from June to August, reaching its maximum in July. The relative frequency during these three months amounts to 92.8 percent in the more than 80mm category. The typhoon-type heavy rain occurs during the period from July to October, with its maximum in August. Detailed analyses of these kinds of heavy rains will be treated in the following chapter.

Figure 9 shows the dominant pressure patterns which result in heavy rain in both categories of more than 80mm and 150mm at each station.

Concerning the number of heavy rain days with daily precipitation more than 80mm the dominant cause is extratropical cyclone in the south coast, typhoon in the east coast, extratropical cyclone and stationary front in the north and stationary front in the central part. In Yangyang, Hwacheon, Gongyu, Pyeongtek and Muju frequency of heavy rain due to front or trough is the highest. In Jeju Island two different causes are noticed: typhoons in the north and extratropical cyclones in the south.

In the more than 150mm category the dominant cause is extratropical cyclone in the

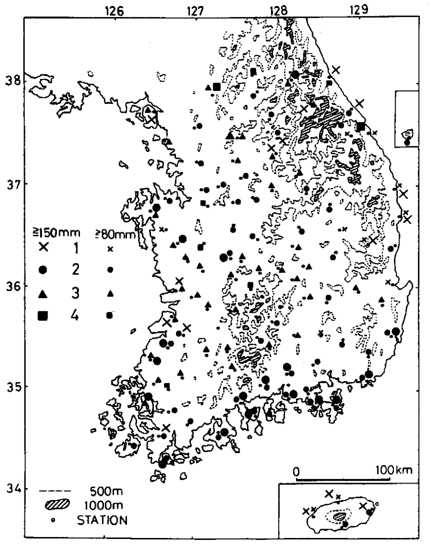

Fig. 9 Distribution of the leading pressure patterns associated with heavy rain
1: Typhoon (including tropical cyclone)
2: Extratropical cyclone
3: Stationary front
4: Other front

south coastal area and typhoon in the northeastern coastal area and the northern part of Jeju Island. The results obtained by Lee (1976) and Kim (1972) suggest that most heavy rains with precipitation more than 150mm in Gangreung on the northeastern coast and in the northern part of Jeju Island result from typhoons in the Kaul-Changma season.

Two different kinds of studies on the causes of heavy rain have been made in Japan: 1) One type is based on the daily precipitation exceeding a given amount. (Saito and Kikuchi (1955), Kasahara (1956), Sekiguti and his collaborators (1965)) 2) The other type is based on the maximum daily precipitation for the year (Mizukoshi (1962)). The former is limited only to the region of prefectural size, while the latter covers the entire country. Consequently, the author made a comparison of Korea and Japan by using the results obtained by Mizukoshi and the above-stated researchers, although different definitions of heavy rain were used in each study.

Most heavy rains which are caused by typhoons or tropical cyclones occur on the Pacific side of Japan and in the eastern coastal area of Korea. On the other hand, the fronts including stationary front give rise to heavy rain most frequently on the Japan Sea side of Japan and in the central and the northwestern parts of Korea. Furthermore, those resulting from extratropical cyclones appear most frequently in Hokkaido and in the southern coastal area of Korea.

One-day maximum precipitation expected in 100 years

Analysis of regional and seasonal aspects of the probable maximum daily precipitation for some return periods is significant from applied-climatological and hydrological points of view. By means of Gumbel's (1958) statistical theory of extremes and Jenkinson's (1955) distribution theory, Mizukoshi (1958, 1965) examined the characteristics of regional distribution of probable maximum daily precipitation for several return periods. Yoshino (1960) compiled distribution maps of the maximum one-day precipitation for the 10 years from 1941 to 1950. The areal pattern of these two results is similar to one another.

Table 7 Estimated values of the annual and seasonal maximum one-day precipitation for 5, 10, 25, 100-year return periods

Return period (years) / Station	June – July					Aug. – Oct.					Nov. – May					Annual				
	5	10	25	50	100	5	10	5	50	100	5	10	25	50	100	5	10	25	50	100
Hwacheon	148	184	239	285	336	137	161	185	201	216	59	73	94	112	131	172	206	252	290	330
Inje	139	178	239	292	353	106	128	156	178	200	53	65	81	93	106	155	193	250	297	351
Chuncheon						111	132	155	172	187	61	72	86	96	106					
Gangreung	167	145	183	213	245	162	194	231	257	282	68	80	91	99	106	172	203	243	276	310
Yangyang	119	143	167	183	196	156	190	238	277	321	68	79	90	98	104	174	204	245	278	312
Hoengseong	123	148	180	205	231	113	141	182	216	254	64	80	100	116	133	146	173	209	237	267
Dyeongchang	126	158	202	238	276	107	127	151	168	184	59	70	82	91	98	139	167	207	240	276
Yeongweol	109	123	145	162	182	98	119	143	161	177	46	53	62	68	73	125	141	159	172	183
Seoul	142	169	197	226	254	168	196	251	302	354	65	79	98	113	129	183	220	271	308	362
Suweon	127	148	166	178	187	142	182	242	292	351	67	82	99	113	126	163	200	254	299	354
Homaesil	119	142	174	199	226	160	199	255	301	353	84	103	124	139	153	181	217	265	303	352
Chungju	115	137	166	190	215	97	116	141	161	180	66	81	98	110	122	134	157	187	209	232
Danyang	111	134	164	187	211	79	88	97	103	108	51	63	78	90	102	113	133	160	182	205
Cheongju	117	141	173	197	221	125	160	214	259	310						148	180	229	270	318
Ogcheon	123	151	191	223	259	100	119	144	162	180	62	71	79	84	88	144	172	213	245	279
Chupungyeong	131	158	191	216	240	91	105	118	127	134	52	59	66	71	75	135	158	188	211	235
Seosan	131	161	197	224	251	130	160	199	299	260	61	73	88	99	111	162	192	223	245	265
Sosa											68	85	104	119	133					
Incheon	120	148	186	218	253	133	167	216	255	298	61	73	86	96	105	160	195	243	280	319
Icheon	124	145	171	191	209						66	81	101	116	132					
Yesan	128	155	193	225	260	87	104	130	151	176	80	101	131	154	178	155	181	210	230	249
Jochiweon						108	128	153	171	189	64	78	96	109	122					
Gongju	158	201	263	315	372	103	119	134	143	151	70	88	114	134	156	175	215	271	318	370
Daedug	133	161	193	218	242	119	139	160	175	188	69	83	98	109	119	158	189	236	274	317
Ulreung Do	92	113	140	161	182	107	133	170	199	230	69	84	106	125	148	129	153	185	208	233
Andong						91	109	129	142	154	52	60	67	72	76	108	120	131	139	145
Sangju	109	126	143	156	167	96	108	119	127	133						128	149	179	203	230
Uljin	77	93	112	125	138	125	158	208	250	299						130	161	207	245	289
Gimcheon	111	139	179	211	247	91	102	113	120	125	50	58	66	71	77	123	147	181	210	242
Pohang	103	122	139	150	159	120	142	165	182	197	50	57	66	72	77	134	151	167	176	184
Yeongcheon	109	125	140	149	157	104	122	141	154	166	57	69	81	90	99					
Daegu	109	131	160	183	206	104	124	148	165	182	46	54	62	67	71	128	149	175	195	215
Habcheon	106	128	157	179	201	128	154	182	201	219	66	78	93	104	115	148	169	189	202	212
Ulsan	116	143	182	212	244	169	216	286	344	410	72	83	93	99	105	178	220	284	340	405
Changnyeong	101	123	155	181	210	102	125	157	182	210	65	76	90	101	111	140	169	208	239	272
Hamyang	115	131	146	155	163	119	145	178	204	231	68	70	94	105	114	139	158	182	200	218
Milyang	103	120	136	147	156						86	105	128	145	162					
Yeongsan	148	188	242	284	329						94	116	144	166	189					
Fuiryeong	109	133	165	190	215	123	150	184	211	238	96	119	150	175	200	152	177	203	220	236
Samcheompo	132	162	200	228	258	129	162	207	243	283	86	106	130	148	166	165	194	236	270	308
Gimhae	107	126	145	157	167	119	146	180	205	232	114	140	173	193	223	142	164	190	210	230
Jinju	105	124	146	167	175	121	149	191	225	264	113	140	175	202	231	152	178	213	241	270
Busan	116	140	166	184	201	153	190	237	273	310	101	124	156	182	211	173	205	243	272	302
Sacheon						120	144	176	202	227	93	112	134	151	167	134	152	177	197	217
Haman	120	147	180	204	224	132	167	216	254	295	76	96	123	146	171	166	196	228	249	269
Hadong	137	168	204	231	258	170	209	256	290	324	144	177	220	252	285	196	226	259	282	303
Goseong	137	166	201	226	251						107	133	170	199	230					
Geoje	137	163	196	221	246	197	245	308	357	407	100	127	167	200	238	217	260	314	356	400
Chungmu	113	136	171	200	233	141	178	227	267	311	100	130	176	217	266	186	220	260	291	320
Namhea	129	157	197	229	265	165	201	248	283	319	114	140	170	193	216	187	221	266	300	330

Table 7 (continued)

Station \ Return period (years)	June – July					Aug. – Oct.					Nov. – May					Annual				
	5	10	25	50	100	5	10	5	50	100	5	10	25	50	100	5	10	25	50	100
Iri	129	156	188	213	237	114	134	160	179	198	75	91	109	121	134	149	173	201	223	244
Jeonju	121	148	187	217	251	135	173	229	274	326	64	80	102	121	142	167	204	252	291	331
Jinan	145	174	211	240	269	126	154	194	227	263	64	75	86	94	101	157	184	226	263	305
Imsil	136	173	230	281	338	123	156	208	253	305	62	72	84	92	101	167	208	269	323	385
Jeongeub	104	125	147	162	177	118	144	179	207	236	66	79	97	112	127	143	169	203	228	255
Gochang	111	128	143	153	161	124	149	182	207	233	75	97	130	159	192	138	159	187	210	233
Namweon	134	168	205	239	278	108	124	138	148	155	55	65	78	88	98	141	166	203	234	269
Sunchang	123	152	195	231	272	102	119	140	156	172	70	85	102	115	128	136	160	199	232	271
Gogseong	113	130	147	159	169	106	122	139	151	162	62	74	90	103	116	123	138	153	164	173
Jangseong						115	138	164	183	201	71	85	105	122	141					
Yeonggwang	118	136	155	167	177	118	146	185	216	249	93	120	160	193	230	139	165	198	224	250
Kwangju	118	139	160	175	186	112	138	174	201	231	66	79	95	107	119	139	163	191	212	233
Hwasun	108	124	139	149	157	114	135	156	171	115	69	85	109	129	151	133	148	162	171	177
Naju	112	133	157	173	189	122	154	200	238	280	72	85	101	112	122	150	178	215	243	272
Yeongsanpo	109	126	146	160	174	112	133	163	186	212	71	84	99	111	123	128	146	169	185	202
Suncheon						129	159	198	229	261	128	161	204	237	271	170	196	222	240	255
Mogpo	116	145	184	214	246	107	124	142	153	163	65	79	98	113	129	138	163	190	209	228
Yeosu	126	152	180	199	217	126	159	208	248	295	99	121	150	173	196	155	186	230	266	306
Jeju	116	140	175	202	232	150	181	214	237	257	56	64	73	79	85	162	191	221	242	260
Hanrim	102	124	151	172	191	104	121	136	147	155	56	67	82	94	107	124	142	158	168	176
Seogwipo	132	154	173	184	194	101	116	134	147	160	119	139	164	183	202	138	152	163	171	176

Data and method

In this study the author calculated the estimated maximum one-day precipitation expected to occur once in 100 years, by using the meteorological records for more than 15 years. Annual and seasonal maximum one-day precipitations were estimated according to Jenkinson's distribution theory, as Mizukoshi (1965) did, in order to make a comparison with the results obtained in Japan. These results are indicated in Table 7. The period of observation is not enough long in many stations to apply Jenkinson's distribution theory. In such cases the column remains as a blank in Table 7.

Distribution of estimated one-day maximum precipitation for 100 year return period

Figure 10 indicates the distribution of estimated one-day maximum precipitation for a 100 year period for each period, from June to July, from August to October, from November to May and for the entire year. On the distributional map for the period from June to July large values appear on the southern slope of the Charyung Mountains, the western slope of the Sobeck Mountains, and the southern slope where the Gwangju Mountains and the Taebeck Mountains meet. The largest values of 300mm or more are found in Hwacheon, Gongju and Jinan as shown in Figure 10-a. On the other hand, the areas with the smallest value are found on the east coast in the central part and in the restricted area around Mogpo on the southwestern coast. The distribution pattern of estimated one-day maximum precipitation during these months is considerably different from that of occurrence frequency of heavy rain days in July as shown in Figure 6: in the Gongju area heavy rain occurs less frequently, in spite of its extremely large estimated one-day maximum precipitation. In contrast, on the southeastern slope of Mt. Jiri heavy rain

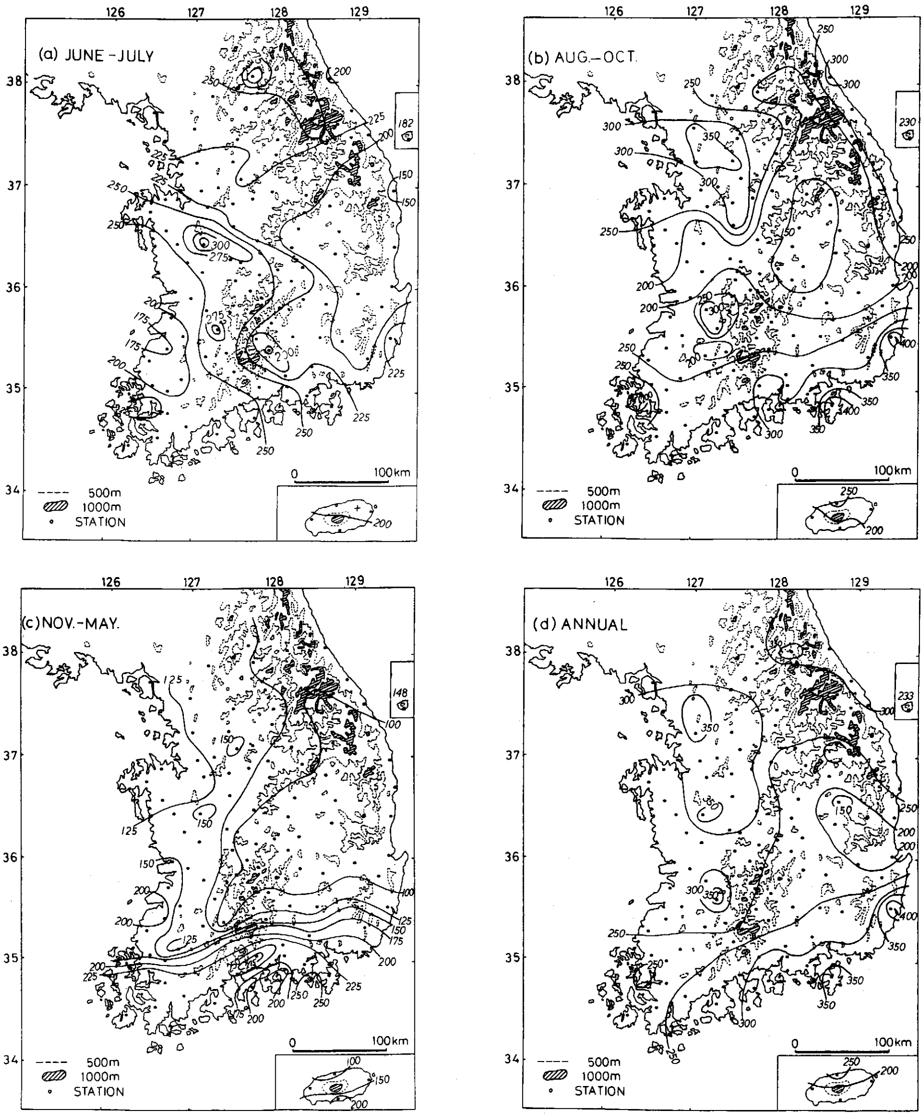

Fig. 10 a-d Distribution of estimated extreme daily precipitation for 100 year return period by periods. (unit: mm)

occurs more frequently, despite its relatively smaller one-day maximum precipitation.

From these facts it can be pointed out that the areas with a high occurrence frequency of heavy rain days do not always coincide with those which have a large estimated one-day maximum precipitation. The reason why the distribution pattern of estimated one-day maximum precipitation, as shown in Figure 10-a, occurs is as follows: the cyclones passing northeastward or eastward along the stationary front over the Korean Peninsula give rise to an influx of southwesterly or westerly air streams which bring the heaviest rains on the western and southern windward slopes of the mountains.

From August to October the areas with large estimated one-day maximum precipitation are found in the southeastern coastal area, on the western slope of the Sobeck Mountains, the northwestern portion of the interior and on the northeastern coast (Fig. 10-b). Heavy rains in this season, especially those with daily precipitation more than 200mm, are caused mostly by typhoons which are followed by extratropical cyclones as shown in Table 6. As typhoons pass frequently off the coast as shown in Figure 3, a large amount of expected one-day maximum precipitation appears in the coastal areas during this season. The large amount of one-day precipitation on the western slope of the Sobeck Mountains results from orographic controls against the southwesterly air stream as also occurs in June and July. The distribution pattern in this season is similar to that for the entire year.

From November to May the largest value is observed on the southern coast, decreasing gradually towards the north (Fig. 10-c). The western portion of the Peninsula has larger values than in the eastern part. This pattern is similar to that for May in which heavy rains most frequently occur during these months. Heavy rains in this season are caused mainly by developed extratropical cyclones (Table 6). This means that in spring and winter frequency of cyclone passage is the highest in the south. Smaller amounts of one-day precipitation in the eastern area are due to the leeward effect of the mountains.

The distribution of annual maximum one-day precipitation which may be expected to be exceeded once in 100 years is similar to that from August to October. This suggests that the heavy rains from August to October are caused mainly by typhoons. It is interesting to compare the maximum one-day rainfall to be expected to occur once in 100 years in the Changma season with that for the period from August to October.

The ratio of maximum value in June and July to that from Aguust to October are shown in Figure 11. The areas where maximum one-day precipitation may be expected to occur in the Changma season are found in the narrow area of interior extending in N-S direction, in the restricted area on the southwestern coast and in the northern part of Jeju Island. In the coastal area excluding the above-stated area maximum one-day precipitation is expected to appear during the autumn rainy season.

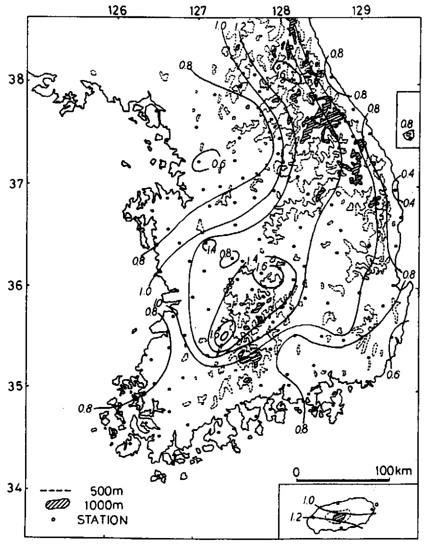

Fig. 11 Distribution of the ratio which is defined as the division of estimated maximum one-day precipitation for June-July to that for August to October

Comparison of estimated one-day precipitation between Japan and Korea

In order to compare the above-stated results with those obtained by Mizukoshi (1965) in Japan, maximum one-day precipitation to be expected to occur once in 100 years of both countries are shown in Figure 12. In Japan the area with large value of more than 300mm is found limitedly on the southern slope of the Kanto Mountains and the Pacific coastal strip west of the Boso Peninsula. On the other hand, small values appear in the Hokkaido and in the eastern half of Honshu where the estimated values are mostly less than 200mm. In Korea heavy rain as more than 500mm as estimated in the southeastern part of the Kii Peninsula and in the southern part of Kyushu does not occur, and one-day rainfall less than 200mm appears only in the south eastern restricted part of interior. As a result, in the most part of Korea estimated one-day rainfall ranges from 200mm to 400mm. Thus the regional difference is smaller in Korea than in Japan.

On the distribution map for June and July in Japan the largest value appears in the southern part of Kyushu, decreasing rapidly to the north. In other words, isohyets run in E-W direction. In Korea, however, isohyets run in N-S direction. The difference of the distribution pattern is attributed to that of the alignment of mountains exposed to the moisture-laden air flow. The distribution pattern during the period from August to October is similar to that for the entire year in both countries. This means that most annual estimated maximum one-day rainfalls may be caused by autumnal rain, especially typhoon. On the distribution map from December to May, it is noticed that maximum value of 150mm appears recorded in the southern part of Kyushu in Japan, while in Korea the area with one-day rainfall more than 200mm extends widely in the southern coastal area in Korea. This fact may be attributed to the cyclone paths which are located along the southern coast of the Korean Peninsula.

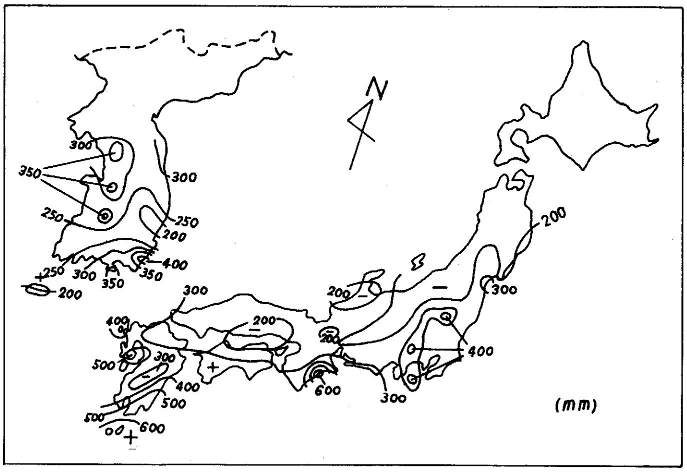

Fig. 12 Distribution of estimated maximum one-day precipitation for 100 year return period in Korea and Japan (Japanese data was adapted from Mizuikoshi 1965)

5. Synoptic Analysis of Heavy Rains

The studies of heavy rain are classified into two categories. One is the analyses of the mechanism of heavy rain which were conducted, for example, by Akashi (1961), Isono *et al.* (1975) and Yamamoto *et al.* (1975). The other is the analyses of the areal characteristics of heavy rain which were made, for example, by Central Meteorological Office of Korea (1969, 1973), Mizukoshi (1979), and Nakajima (1962).

In this chapter the author analyses the mechanism of heavy rain on a synoptic scale. The meso-scale analysis could not be made, because the lack of the data.

Data and method

The author analysed twenty cases of the heavy rains with daily precipitation more than 100mm. Taking into account of the distribution of heavy rain, these samples were selected according to the type of surface pressure system.

The following items were investigated by using the weather maps for the surface, 850mb-, 700mb- and 500mb levels, and the aerological data:

1. circulation pattern at 500mb level
2. low-level jet stream
3. mixing ratio and "moist tongue"
4. vertical stability of the atmosphere

The author defined the stream more than 15m/s in wind velocity at 850mb or 700mb level as low-level jet stream regardless of wind direction. As heavy rain occurred in the northern part of Korea, the aerological data for Osan were used. On the other hand, as the heavy rain area appeared in the southern part of Korea, the data for Mosulpo were used. The results are shown in the Table 8.

Heavy rain caused by extratropical cyclone (September 9, 1973)

Weather situation and distribution of precipitation

The extratropical cyclone which occurred in the lower part of the basin of the Yangtze moved towards the northeast and was located between the Chinese Mainland and Jeju Island, with the central pressure 1004mb. Around 09:00 JST of September 9 the extratropical cyclone passed over Jeju Island and around 21:00 JST it passed over the southeastern part of Korean Peninsula, with the deepened central pressures 1002mb and 1000mb, respectively. The track of the extratropical cyclone and the location of the front are indicated in Figure 13. On September 8, due to their movements the daily rainfall of about 30mm appeared in the southwestern part of the Peninsula, then on September 9, heavy rain with daily precipitation from 100mm to 200mm occurred in the southern coastal strip (Fig. 14).

Circulation at 500mb level

The trough which was located in the interior part near the coast of China at 09:00 JST on September 8 moved toward the east, reaching to the Korean Peninsula at 09:00 on September 9 (Fig. 15). At 09:00 on September 10 the trough was located over the Japan Sea. During this period the developed cold low was noticed at this level which corresponds to the depression on the surface weather map. The isotherm of -10°C was over the northern

Table 8 Summary of synoptic analyses of 20 heavy rains

Pressure patterm (sea level)	Heavy rain area	Date	500mb pattern	Wind				Moisture		Stability	
				850mb		500mb					
				Velocity	Direction	Velocity	Direction	Mixing ratio (gr)	Inflow direction	EP	EM
Extratropical cyclone	Southern part of Korea	73.9.9	T. C. -10°c line~S′	20 m/s	SW	20m/s	SW	15.0	SW–NE	U	PI
		72.5.4	T. -10°c line~K	15	NW	30	W	10.7	S–N	U	LI
		70.7.16	T	25	SW	20	SW	12.5	WSW–ENE	U	PI
	Central part of Korea	70.8.5	T	10	SW	15	WSW	14.5	SW–NE	U	LI
		70.10.24	T	15	SW	10	W	12.6	SW–NE	U	N
		70.9.9	T	20	SW	20	W	12.5	SW–NE	U	LI
Stationary front	Southern part of Korea	71.6.26~27	Z. C.	15	SW	25	W	13.8	SW–NE	U	LI
		68.6.28~29	Z.	15 (700mb)	SW	10	WSW	12.6	SW–NE	U	LI
	Central part of Korea	72.8.19~20	T -10°c line~N	15	SW	20	SW	12.6	SW–NE	S	LI
		72.7.8~11	T -10°c line~M	20	WSW	20	W	17.8	SW–NE	U	LI
	Whole country	66.7.24~26	T -10°c line~M	20 (700mb)	WSW	20	WSW	15.8	SW–NE	U	LI
		71.7.20~22	T. C. -10°c line~N	20	NW	20	NW	15.1	S–N	U	LI
Typhoon (including tropical cyclone)	East coast	71.8.5	T	20	NE	20	N	15.3	S–N	U	LI
	West coast	74.8.29	T	5	S	10	SW	13.5	SSE–NNW	S	PI
		74.7.21	T	15	SSE	30	WSW	14.1	S–N	U	LI
	Southern part of Korea	74.7.6	T	35	NE	35	NNE	14.5	SW–NE	U	N
		69.9.14~15	T -10°c line~S′	20	S	30	SSW	15.4	SW–NE	S	LI
	Whole country	68.8.15	T	15	SE	10	W	14.0	SSE–NNW	U	S
Front	Central part of Korea	66.6.26	T -10°c line~N	20	SW	15	SW	13.5	SW–NE	U	LI
		72.8.4	T	20	SW	15	SW	13.2	SW–NE	S	PI

T : trough type   Z : zonal type   C : cold low type
N : indicates that the isotherm of -10°C passes over the northern part of the Korean Peninsula
S : indicates that the isotherm of -10°C passes over the southern part of the Korean Peninsula
M : indicates that the isotherm of -10°C passes over the central part of the Korean Peninsula
K : indicates that the isotherm of -10°C passes over Kyushu
EP : analysis by using the equivalent potential temperatures
S : stable   U : unstable   N : neutral
EM : analysis by means of emagram
LI : latent instability   PI : pseudo-instability

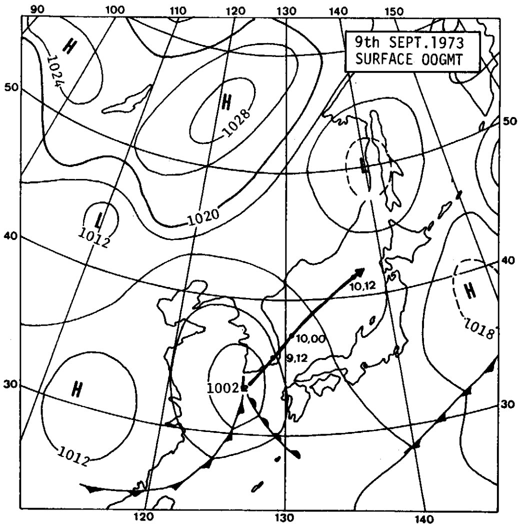

Fig. 13 Surface weather map for September 9th, 1973

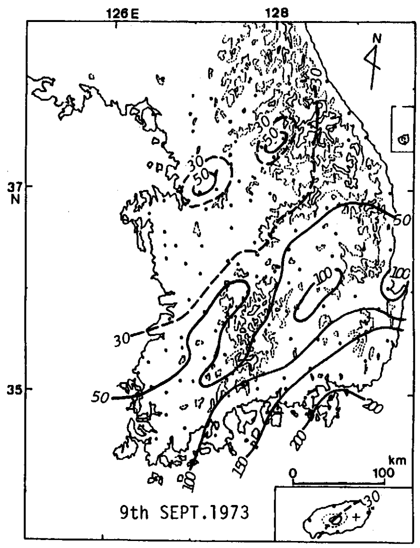

Fig. 14 Distribution of daily precipitation for September 9th, 1973

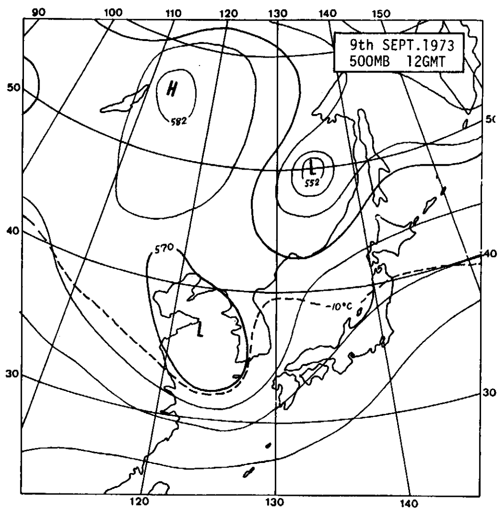

Fig. 15 500mm contour map for September 9th, 1973

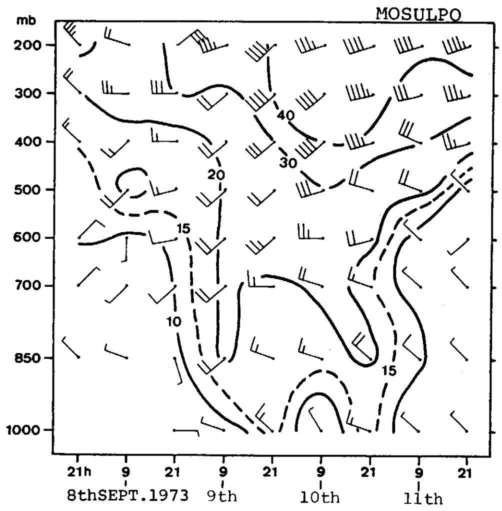

Fig. 16 Vertical time section of wind direction and velocity at Mosulpo

part of the Korean Peninsula on September 8, on the central part of September 9, and then over the southern coast on September 10. This means that upper cold air flows into the area with heavy rain.

Wind characteristics

Figure 16 indicates the wind direction and velocity at Mosulpo. At Mosulpo a low-level jet stream from 20m/s to 15m/s occurred in 850mb level from 09:00 JST on September 9 to 21:00 JST on September 10, closely associated with the heavy rainfall. In Osan far from the track of the cyclone lower-level jet did not appear. As a result, the precipitation less than only 30mm was recorded there. At 09:00 JST on September 9 southwesterly winds were observed at both 500mb and 850mb levels at Mosulpo, both velocities being 20m/s. Thus wind shear between the two levels were very small.

Mixing ratio and "moist tongue"

Figure 17 shows the temporal variation of mixing ratio at Mosulpo and Figure 18 is the time cross section of the stations along 128°E.

The much larger mixing ratio of 15gr appeared at 850mb level at Mosulpo at 09:00 JST on September 9 than on September 8 and 10, while such moist air did not invade Osan. At 500mb level at Mosulpo, on the other hand, larger amount of mixing ratio on the day before the heavy rain was not recorded on September 9. The area with large mixing ratio spreads widely with a shape of wedge from the southwest to the northeast. Otani (1946) called such an intrusion of highly moist air "moist tongue". (Fig. 19)

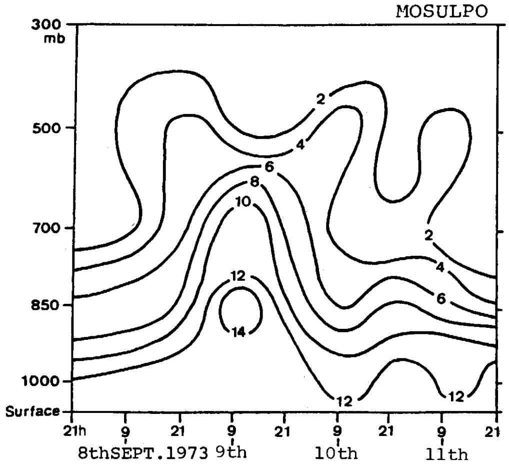

Fig. 17 Time section of mixing ratio at Mosulpo

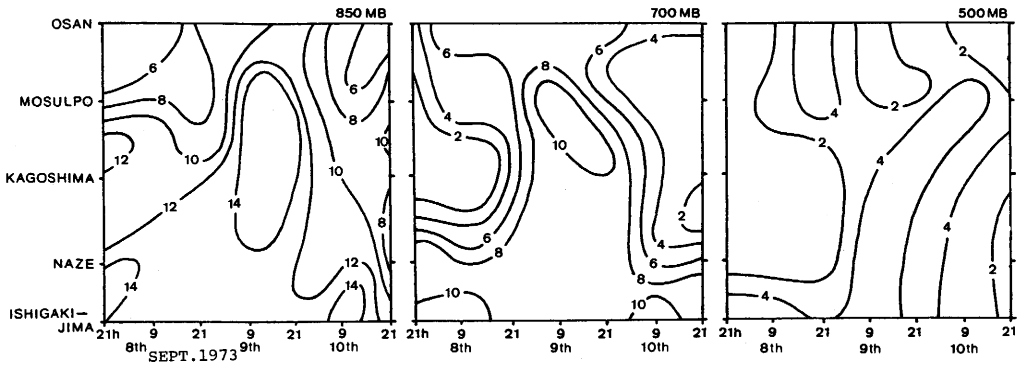

Fig. 18 Time cross sections of mixing ratio for 850mb- 700mb- and 500mb-levels for September 8th-10th, 1973

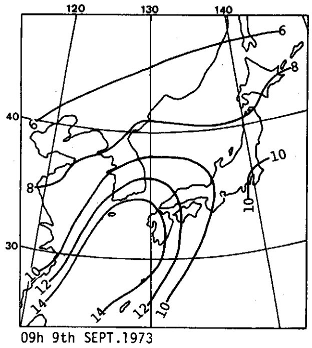

Fig. 19 Distribution of mixing ratio at 850mb level for September 9th 1973

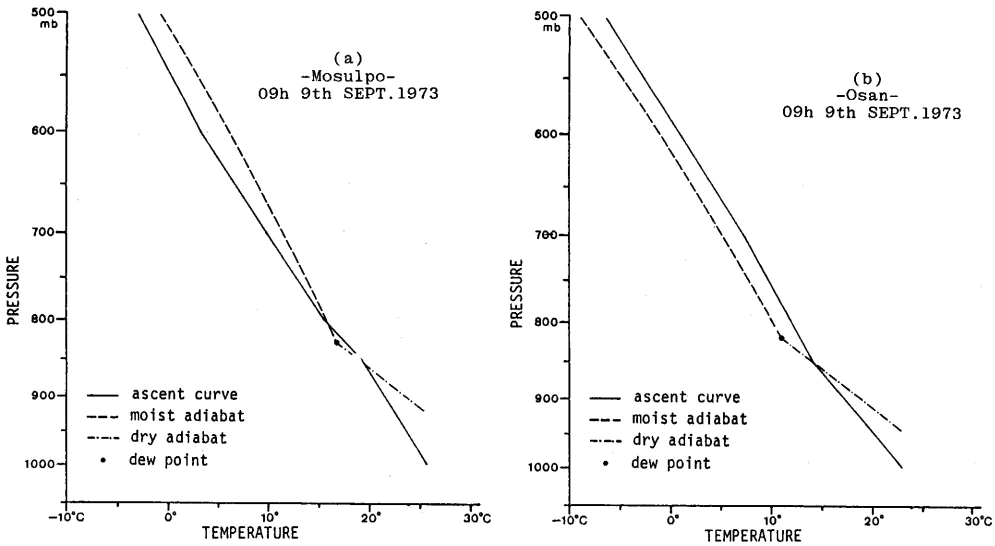

Fig. 20 Comparison of vertical stabilities between Mosulpo (a) and Osan (b)

Vertical stability

According to the analysis of stability based on the difference of equivalent potential temperature between 500mb and 850mb levels, the air over Korea and Kyushu was considered to be unstable on September 9. On the emagram, too, the air layer between 500mb and 850mb levels was in a state of latent instability at Mosulpo lying within the heavy rain area.

On the contrary, the air layer over Osan was stable at the same date (Fig. 20).

Considerations

A developed cyclone of the Yangtze type which passed over the southern part of the Korean Peninsula was accompanied with a marked cold low at 500mb level. As a result, the cold air flew into this cold low, resulting in the southward intrusion of the isotherm

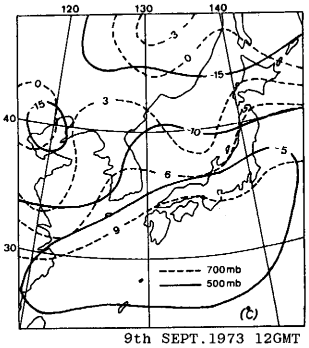

Fig. 21 Distribution of air temperature for 700mb- and 500mb-levels for September 9th, 1973 (unit: °C)

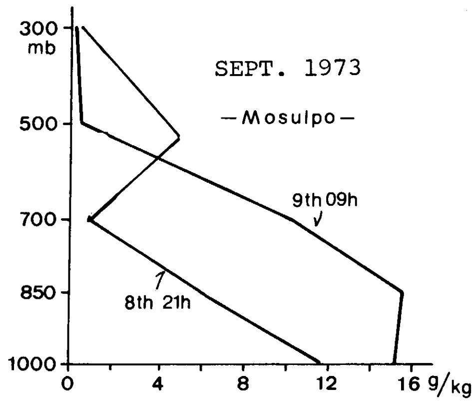

Fig. 22 Vertical distribution of mixing ratio at Mosulpo for September 8th 21h and 9th 09h, 1973

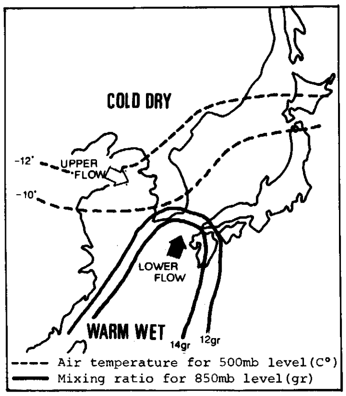

Fig. 23 A model of synoptic conditions associated with heavy rain which occurred for September 9th, 1973

–10°c to the southern part of Korea. On the other hand, at the 850mb level warm and moist tropical air invaded toward the center of cyclone, forming a low-level jet stream from the southwest.

Figure 21 indicates the air temperatures at 500mb and 700mb levels on September 9. From this it can be noticed that there prevail a cold air in the upper layer and a warm air in the lower layer. This means the existence of convective instability which caused the heavy rain. Figure 22 shows a comparison of the vertical distribution of mixing ratio at Mosulpo at 09:00 JST on September 9 and at 21:00 on September 8. At 500mb level a large mixing ratio 4.5gr on September 8, the day before the heavy rain occurred, whereas a low mixing ratio 0.5gr appeared on September 9. On the other hand, the mixing ratio at 850mb level abruptly increased on September 9 (Fig. 22). It is noted that the convective instability was caused by the existence of cold air in the upper layer and warm air in the lower one, and also of dry air in the upper layer and moist air in the lower one. A schematic representation of the mechanism of heavy rain which occurred at and around Mosulpo is indicated in Figure 23.

The characteristics of the distribution of heavy rainfall which is resulted from the passage of the low, along the southern coast of Korea are as follows:

1) The rainfall area covers the entire country, particularly, the area with a precipitation more than 50mm covers almost the southern half of Korea. This may explain the distribution pattern of precipitation in general and heavy rainfall which are caused by extratropical cyclones as stated in the previous chapter on the statistical analysis.

2) The area with much precipitation appears on the southern coast on the tracks of cyclones. The precipitation in this case decreases towards the north.

3) The distribution pattern of the area with heavy rain of more than 50mm reflects the orographic controls of the Sobeck Mountains. The elongated heavy rain area including Kwangju and Junju west of the Sobeck Mountains is a result of the forced uplifting of the moist air. In the eastern part the northern limit of the area with heavy rain of more than 50mm is determined also by the Sobeck Mountains. This proves that the orographic controls are bound to the northern slope of the Sobeck Mountains, when the depression moves eastward in the east of the Sobeck Mountains. The amount of precipitation decreases linearly with increase of the distance from the center of the depression, and it increases again in the mountainous areas, as proved by Yoshino (1955) in Japan.

Heavy rain caused by the Changma front (July 8–11, 1972)

Weather situation and distribution of precipitation

The Changma front which was located in the northernmost part of the Korean Peninsula began to move southward on July 7 and was located in the central part on July 8. After that it oscillated northward or southward around the southern coast of Korea. On the other hand, the cyclone with the central pressures of 996mb on July 8 and 998mb on July 11 passed over the Korean Peninsula, as seen in Figure 24. On July 8 a heavy rain of more than 100mm occurred in the central part of Korea, and on July 11 in the southern part, as seen

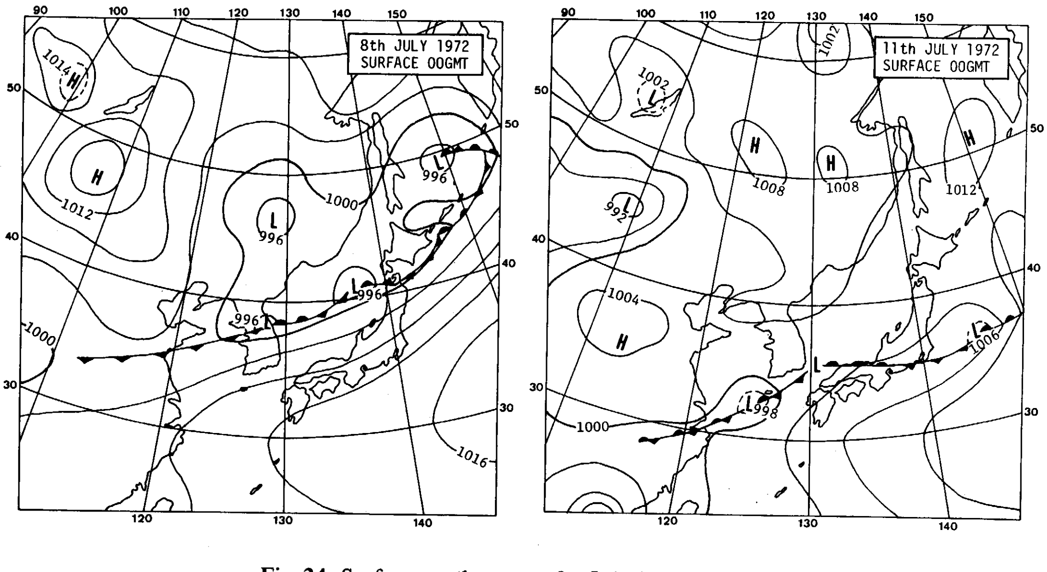

Fig. 24 Surface weather maps for July 8th and 11th, 1972

in Figure 25. For four days the precipitation amounted to 330.2mm at Seoungju, 292.7mm at Kwangju and 284.0mm at Naju. A maximum rainfall occurred particularly in the south-western part of the Korean Peninsula during this period.

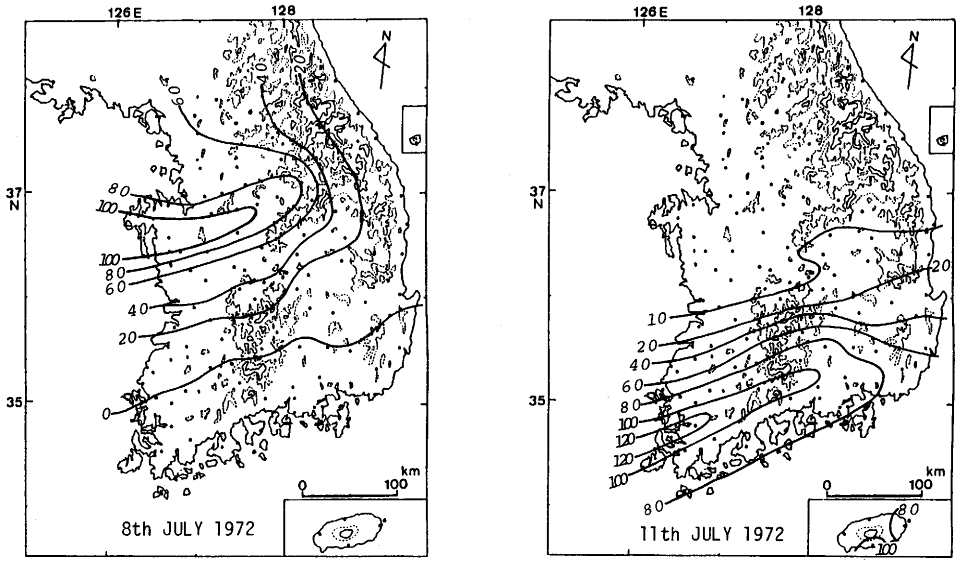

Fig. 25 Distribution of daily precipitation for July 8th and 11th, 1972

Circulation patterns at 500mb and 850mb levels

From July 8 to 11 a weak trough passed over the Korean Peninsula. At the same time the upper low was over the northern part of the Korean Peninsula. The isotherm of -10°c gradually moved southward and stagnated over the central part of the Korean Peninsula on July 11 (Fig. 26).

At 850mb level the front and the low corresponding with the Changma front and the depression on the surface map were found. On July 8 the tropical maritime air mass invaded the southern part of the Korean Peninsula, but on July 11 it retreated to the south coast of Japan, resulting in the oscillation of the Changma front. On July 8 the extremely moist air, "moist tongue", with a mixing ratio of more than 14gr flew into the northern part of Korea, resulting heavy rain in the central part of the country. On the other hand, the "moist tongue" with a mixing ratio more than 13gr reached barely to the southernmost part of Korea on July 11, resulting in heavy rain in the southern part of the country. On the same date the mixing ratio of only 8.5gr was recorded at Osan; (Fig. 27, Fig. 28, and Fig. 29)

As the heavy rain occurred on July 7 and 8 at Osan, the low-level jet stream with a velocity of 20m/s appeared at 850mb level there. At Mosulpo it didn't appear on July 7 and 8, but on July 11 the low-level jet with a velocity of 15m/s appeared (Fig. 30). Thus the occurrence of heavy rain was closely associated with the development of the low-level jet stream.

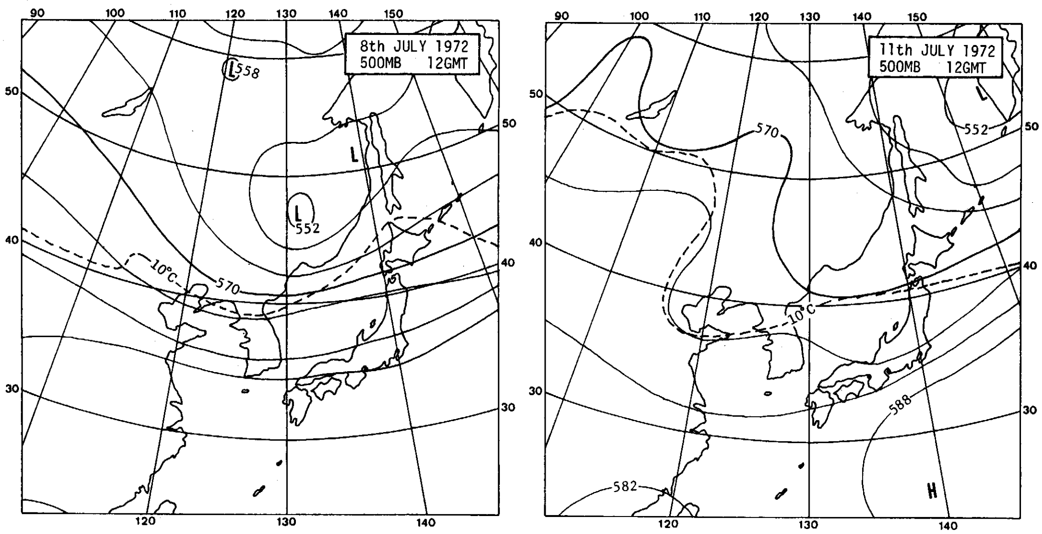

Fig. 26 500mb contour maps for July 8th and 11th, 1972

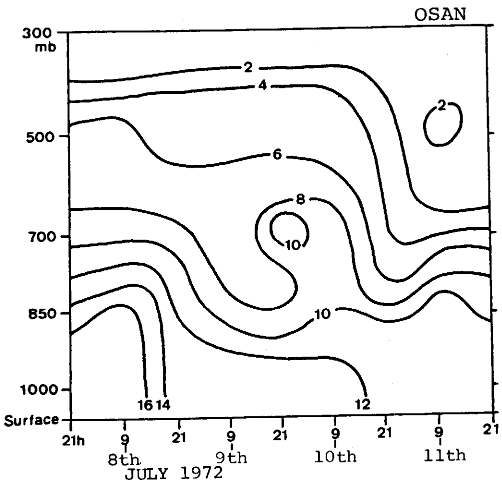

Fig. 27 Time section of mixing ratio for July 8th-11th, 1972 at Osan

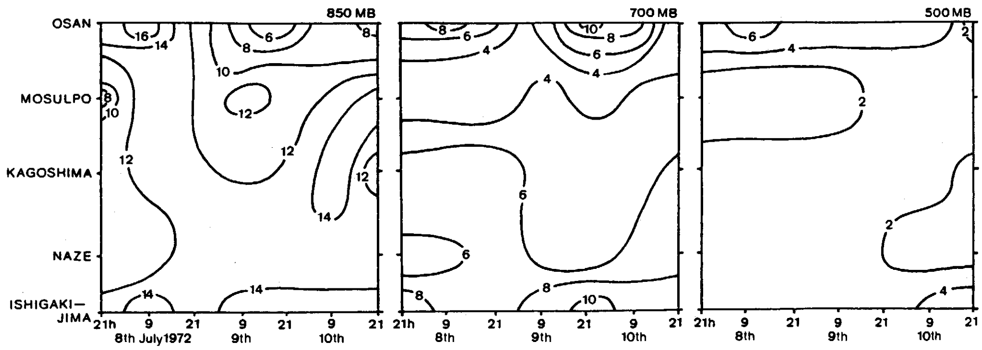

Fig. 28 Time cross section of mixing ratio for 850mb- 700mb- and 500mb-levels for July 8th-10th, 1972

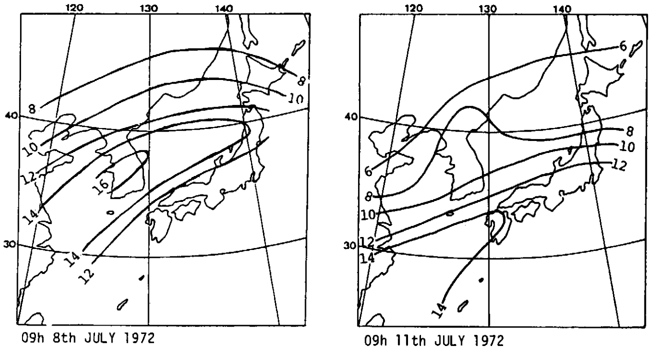

Fig. 29 Distribution of mixing ratio at 850mb level for July 8th and 11th, 1972

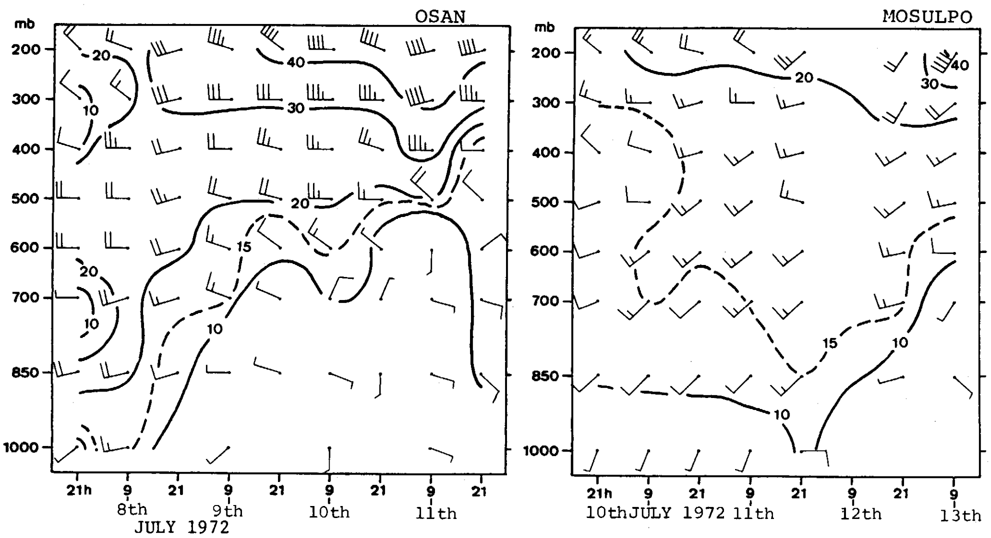

Fig. 30 Vertical time section of wind direction and velocity

Vertical stability

The stability of the air layer between 850mb and 500mb levels was examined by means of the difference of the equivalent potential temperature. On July 8 the air over the entire area of Korea was in a state of instability. On July 11 only the air over the southern part of Korea was unstable, while the air over the northern part of Korea was stable. On the emagram the upper air higher than 800mb level was in a state of latent instability on July 8 at Osan, but the air over Mosulpo was stable. As the heavy rain occurred in the southern part of Korea on July 11, the air over Osan and Mosulpo was stably stratified.

Considerations

From the above-stated analyses the following results are summarized:

1) In the case of heavy rain caused by the development of the Changma front the existence of "moist tongue", the development of low-level jet stream and vertical instability of air appear as well as in the case of the heavy rain caused by extratropical cyclone.

2) At 500mb level the trough less develops in the case of the heavy rains caused by the Changma front than in the case of those caused by extratropical cyclone and typhoon.
3) The amount of precipitation due to the development of the Changma front becomes larger when extratropical cyclone passes along the Changma front.
4) The location of moist tongue varies with the displacement of the Changma front. The area with heaviest rainfall mostly appears near the tip of the moist tongue.
5) The distribution pattern of precipitation caused by the development of the Changma front is closely associated with the alignment of the Changma front. This means that the distribution of the precipitation caused by the Changma front is less affected by orographic controls.

Heavy rain caused by typhoon (August 5, 1971)

Weather situation and distribution of precipitation

The typhoon, Olive, was located 150km south of Kyushu at 21:00 JST on August 4, 1971. At the same time the extratropical cyclone with a central pressure of 996mb was passing eastward over the northeastern part of the Korean Peninsula. These pressure systems formed a developed trough around Korea and Japan. The typhoon reached to the western portion of Kyushu at 09:00 JST on August 5, as shown in Figure 31. Then it passed through the Korean Strait and reached to the northern part of the Japan Sea. Consequently, the rainfall was registered over the entire area of Korea. In particular, the stormy weather and storm surge were observed in the coastal area east of the Taebeck Mountains. Heavy rainfall occurred in the coastal strip east of the Taebeck Mountains as shown in the Figure 32: 401.0mm and 289.9mm were registered at Samchuck and Gangreung, respectively.

Circulation pattern in the upper air

At 500mb level the developed trough was formed around Korea and Southwestern Japan

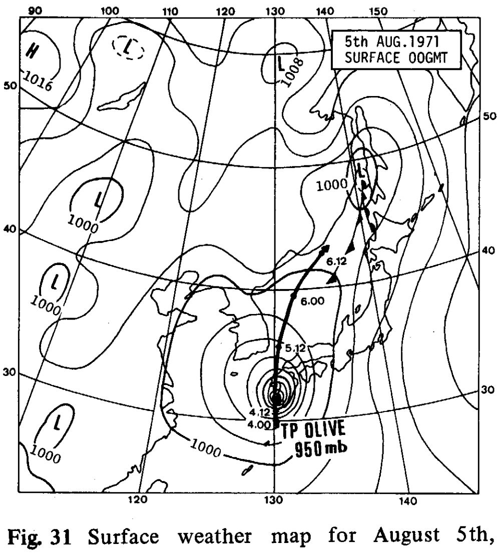

Fig. 31 Surface weather map for August 5th, 1971

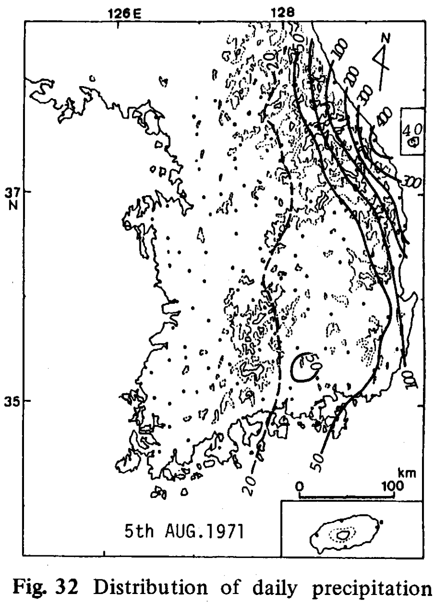

Fig. 32 Distribution of daily precipitation for August 5th, 1971

(Fig. 33), causing an incursion of the warm air.

At 850mb level the same pattern of the developed trough accompanied with the warm air as at 500mb level appeared. As shown in Figure 34, the wedge-shaped "moist tongue" was noted, the tip of which was directed to the center of the typhoon. At 21:00 JST on August 4 and at 09:00 JST on August 5 the mixing ratios of 18.8gr and 15.3gr were recorded at Mosulpo, respectively. At Osan a large amount of mixing ratio, 13.2gr, was also recorded at 09:00 JST on August 5. An increase of the mixing ratio caused by the typhoon was noticed not only at 850mb level but also at 700mb and 500mb levels at Mosulpo and Osan (Fig. 35 and Fig. 36).

At 850mb level the wind velocity of 24m/s was registered at 09:00 JST on August 5 at Mosulpo and that of 20m/s at 21:00 JST on August 5 at Osan. The vertical shear of the wind speed between 850mb and 500mb levels was as nearly zero as in the case of the cyclone or the Changma front (Fig. 37).

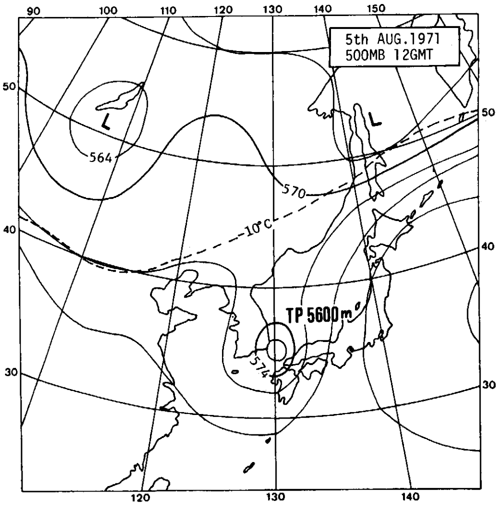

Fig. 33 500mb contour map for August 5th, 1971

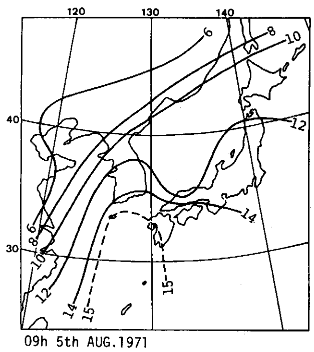

Fig. 34 Distribution of mixing ratio at 850mb level for August 5th, 1971

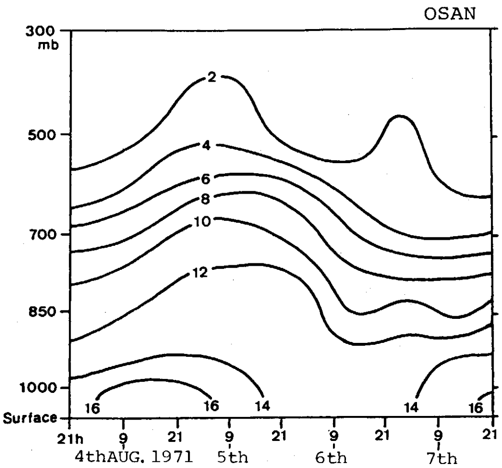

Fig. 35 Time section of mixing ratio for August 4th-7th, 1971 at Osan

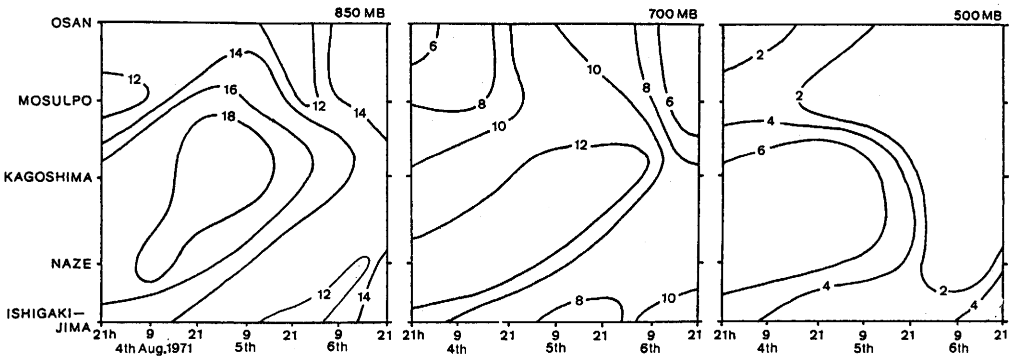

Fig. 36 Time cross sections of mixing ratio for 850mb- 700mb- and 500mb-levels for August 4th-6th, 1971

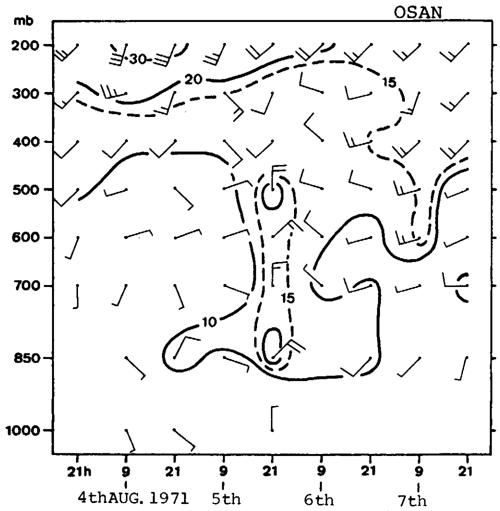

Fig. 37 Vertical time section of wind direction and velocity for August 4th-7th, 1971 at Osan

Vertical stability

At 09:00 JST on August 5 the air layer over the southern half of the Korean Peninsula was unstable by means of equivalent potential temperature. According to the emagram analysis the air over Mosulpo was neutral at 09:00 JST on August 5. At Osan the air layer higher than 700mb level was in a state of latent instability.

Considerations

The heavy rain was caused by an incursion of the warm and moist air from the south into the center of the typhoon which moved northward off the east coast of the Peninsula. The elongated area with heavy rain was resulted from the track of the typhoon and the orographic controls of the Taebeck Mountains. However, it is noticed that the precipitation amount decrease toward the interior. This means that the orographic factor did not exert a predominant influence on the distribution pattern of precipitation. However, the leeward effect was observed on the western slope of the Taebeck Mountains. In other words, the precipitation amount caused by the typhoon may depend primarily on the distance from the center of the typhoon. Such pattern is also reflected in an elongated area with large areal correlation of monthly precipitation in the eastern coastal area during the autumnal rainy season.

Summary

The results of the synoptic analysis of the heavy rains with precipitation more than 100mm are summarized in Table 8.

500mb level circulation

When heavy rain is caused by extratropical cyclone or typhoon, a developed trough exists at 500mb level over Korea. The result agrees with that obtained by Nakajima (1957). However, the upper trough rather poorly develops in the case of heavy rain caused by the Changma front. Heavy rain occurs when the advection of cold air from the north at upper level coexists with the inflow of very warm and moist air from the south at lower level. This means that the heavy rain occurs under the condition of latent instability. Accordingly, the location of the isotherm $-10^{\circ}C$ at 500mb level can be a measure of instability which leads to a heavy rainfall. This fact was indicated by Akashi (1961) and Isono et al. (1975) in Japan.

Low-level jet stream

As Borner (1968 a, 1968 b) and Matsumoto et al. (1962) pointed out, low-level jet occurs in most cases (18 out of 20) at 700mb or 850mb level. Without exception the beginning and the end of heavy rain coincide with the appearance and the disappearance of the jet stream. The low-level jet flows from between the south and the west, most frequently from the southwest. When a low-level jet appears at lower level, the vertical shear of wind velocity between 500mb and 700mb or 850mb levels is negligible.

Mixing ratio and "moist tongue"

The influx of very moist air at 850mb level is an essential factor to the occurrence of heavy rain, as indicated by Arakawa (1941). In most cases (19 out of 20) the large content of moisture with mixing ratio more than 12gr was observed. The wedge-shaped "moist tongue" appears very frequently (15 out of 20). It invades Korea from the direction of the southwest or the west which coincides with the direction of low-level jet. These results support those obtained by Akashi and Shitara (1964) and Flohn and Oeckel (1951).

Vertical stability

According to the stability analysis by means of equivalent potential temperature and emagram heavy rains occurred in most (16 out of 20) cases in a state of instability. As already Takahashi (1955) stated, three cases of heavy rain occurred in a stable state in this study.

Distribution pattern of precipitation

The distribution pattern of precipitation caused by extratropical cyclone and typhoon is closely related to the alignment of mountains, while that due to the Changma front is less affected by orographic controls.

6. Conclusion

In Korea, although the annual precipitation is smaller than that of Japan, the occurrence frequency of heavy rain is rather high and its seasonal concentration is more pronounced. Heavy rains results mainly from extratropical cyclones, but the heaviest rains are mostly caused by typhoons. Consequently, the distribution pattern of the occurrence frequency of heavy rain depends on the frequency of cyclone paths, and that of the maximum daily precipitation is closely related to the frequency of typhoon tracks.

Heavy rains mostly result from the advection of warm and highly moist air associated with the low-level jet stream from the southwest. In Korea the distribution pattern of the occurrence frequency and the maximum daily precipitation of heavy rains are determined to a degree by the alignment of mountain ranges in a direction N-S or NE-SW.

The heavy rains in Korea may be closely associated with those in Japan, because the pressure system resulting in heavy rain affects the area including Korea and Japan. The temporal variation and spatial structure of heavy rains in the area including Korea and Japan are the probelm to be solved.

Acknowledgment

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