HEAVY PRECIPITATION IN HONG KONG, 1951—2000*

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ABSTRACT

Daily precipitation amounts greater than 50 mm from 1951 to 2000 in Hong Kong were analyzed to determine their seasonal and annual frequencies. A total of 627 extreme rainfall days happened and 334 (53.27%) days occurred in summer. Non-significant increasing trends for annual precipitation and number of heavy rain days were detected. Daily surface weather maps were used to identify the synoptic weather types producing the heavy rainfall. It was discovered that tropical cyclone and low pressure induced most of the heavy precipitation. Seven out of twelve years with counts of heavy rain days over fifteen coincided with El Nino events.

Key words: heavy rainfall, synoptic weather types, tropical cyclone, Hong Kong

I. INTRODUCTION

Interest in the study of heavy precipitation events has increased recently. Heavy precipitation incidents will cause flash flooding and provoke landslides. Further, information on the rainfall regime is useful in water supply planning, drought estimation and flood frequency analysis, and is important to policy makers planning for unavoidable flooding. Since the society is susceptible to the change of frequency and intensity of climatic extremes, examination of changes in the extreme rainfall episodes is one of the most important aspects of studies of climate change.

Results of recent climate models indicated that precipitation extremes would increase and the return period for these extreme events would be shortened almost everywhere globally (Zwiers and Kharin 1998). The latest investigations on climate change revealed that prominent increases in heavy precipitation events would happen in areas with total precipitation increases, or vice versa. Also, precipitation was discovered to continue to increase in the Northern Hemisphere except the subtropics, where a downward trend was detected. Model simulations projected that there would be both areas with increasing and decreasing rainfall at the low latitudes (Houhton et al. 2001). Studies of heavy rainfall events in the low latitudes, particularly on regional or local scale, are necessary in order to have better insights into the changes of these extreme events.

Many previous studies on heavy precipitation events were pertinent to those happening in the United States and those related to El Nino-Southern Oscillation (ENSO). Precipitation events in the northeast and southeast United States, the Midwest,

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Minnesota and South Carolina were investigated (Thorp and Scott 1982; Winkler 1988; Huff and Angel 1990; Robinson and Henderson 1992; Changnon 1994; Keim 1996). Karl and Knight (1998) examined the trend of precipitation amount, frequency and intensity in the United States and discovered that the 10% precipitation increase since 1910 was reflected primarily in the heavy and extreme daily precipitation events. An overall upward trend of extreme precipitation events at a highly statistically significant level over southwest United States and the central Great Plain was detected (Kunkel et al. 1999). Brooks and Stensrud (2000) suggested that the Hourly Precipitation Dataset was useful in defining the climatological threat of flash floods. Some studies examined the upper level conditions leading to heavy precipitation (Faiers et al. 1994; Konrad and Meentemeyer 1994). Konrad (1997) related 14 synoptic features to the amounts of heavy rainfall over southeastern United States. Harnack et al. (1999) investigated the atmospheric conditions before and during heavy precipitation events in New Jersey. Lackman and Gyakum (1999) studied the synoptic patterns, heavy precipitation and flood events in northwestern United States. To assess the effect of ENSO on heavy precipitation events, Gershunov and Barnett (1998) discovered strong ENSO signals in the wintertime frequencies of extreme episodes only in the Southeast, Gulf coast and the Mississippi-Ohio River valley. Higgins et al. (2000) detected a large percentage of heavy rainfall events in the west coast happening just before El Nino onset.

Heavy precipitation was also examined in other regions. Brunetti et al. (2000) detected a positive trend in the proportion of total precipitation contributed by heavy precipitation events in northern Italy. Durkanoglu (1997) and Massacand et al. (1998) studied heavy rainfall incidents and their synoptic patterns in southern Black Sea coast and southern slopes of Alps respectively. Increasing trends in heavy rainfall and total rainfall were detected in Australia (Suppiah and Hennessy 1998). Liebmann et al. (2001) found that heavy precipitation events in the state of Sao Paulo, Brazil, were positively correlated with the sea surface temperature (SST) anomalies in the equatorial Pacific. Matsumoto (1989) studied heavy rainfalls over East Asia and discovered that the highest heavy rainfall frequency area was located along the southern coast of Japan and the second highest region was along the southern coast of China. Ma and Xi (1997) studied the regularities of heavy rainfall in Xinjiang, China. Zhai et al. (1999) discovered an increasing trend in rainfall intensity in China since 1950.

There are few studies on rainfall in Hong Kong. Jackson (1994) examined the characteristics of Hong Kong rainy seasons. Investigations of heavy precipitation were also done by scientists at the Hong Kong Observatory. Cheng and Kwok (1966) studied the hourly precipitation and provided a climatology of heavy rainfall in 1947—1965. Other heavy rainfall analyses considered merely the synoptic conditions generating the individual extreme rainfall events (Lee 1983; Lee et al. 1994; Au and Chang 1995; Fu and Chan 1998). Au and Chang (1998) and Chang (1999) examined the impacts of ENSO on Hong Kong rainfall.

The objectives of this study are to describe the temporal variations of daily precipitation amounts greater than 50 mm, both seasonally and annually, analyze the synoptic features related to the heavy precipitation events, and examine the association of

ENSO and the frequency of extreme rain days. This is a preliminary study of heavy rainfall events in Hong Kong and the results create a climatology of heavy precipitation.

II. DATA AND METHODS

Daily precipitation data from 1951 to 2000 were obtained from the Hong Kong Observatory. Daily precipitation greater than 50 mm is considered as heavy rainfall (Domros and Peng 1988; Changnon 1994). All daily precipitation events over 50 mm were identified for each year of the 50-year period. Frequencies of these extreme rainfall events for each month were counted and grouped into winter (December, January, February), spring (March, April, May), summer (June, July, August) and fall (September, October, November) seasons. Annual and seasonal total precipitation amounts produced by the over 50 mm daily events were computed. Frequencies and total rainfall amounts of these extreme rainfall incidents were graphed to examine interannual variations. Simple linear trend analysis was employed in order to determine whether trends existed. Frequencies and actual precipitation amounts of these extreme events of each 10-year period were compared using t-test to determine which period was the driest decade. Percentage of annual precipitation amount by season, derived from days with rainfall over 50 mm, were calculated in order to study seasonal variations.

Synoptic conditions leading to every heavy precipitation incident were determined by using the daily surface weather maps of the Hong Kong Observatory. The synoptic causal features were identified and classified into tropical cyclones (that affected Hong Kong and warnings were issued), low pressures (trough of low pressure or area of low pressure over southern China), easterly (influence of warm, moist air mass from western Pacific), southwesterly (southwest monsoon), tropical disturbance (rainbands or remnants of tropical disturbances that affected neighboring areas) and frontal (passage of cold front). A similar system was employed to examine the pressure patterns and associated weather in Hong Kong (Chin 1986). Also, alike systems were implemented by Matsumoto (1989) and Keim (1996) in the studies of heavy rainfall in East Asia and southeastern United States respectively. Frequencies of each synoptic weather-type were counted. Some heavy rainfall events may last for one day while others may persist for consecutive days. Frequencies of synoptic weather-types that lasted for one to four days for each month were counted. Variations of heavy rainfall episodes of different synoptic weather-types were examined by studying their frequency and persistence.

Variations in precipitation in many parts of the world are believed to associate with ENSO phenomena. To assess the impact of ENSO on heavy rainfall events, the Southern Oscillation Index (SOI) (by using correlation coefficients) was employed to examine their relationship. In addition, years with number of heavy rain days over 15 were identified and related to El Nino/La Nina activities.

III. RESULTS AND DISCUSSION

1. *Temporal Variations of Heavy Rainfall*

The average annual precipitation of the 50-year period was 2274. 5 mm. Figure 1

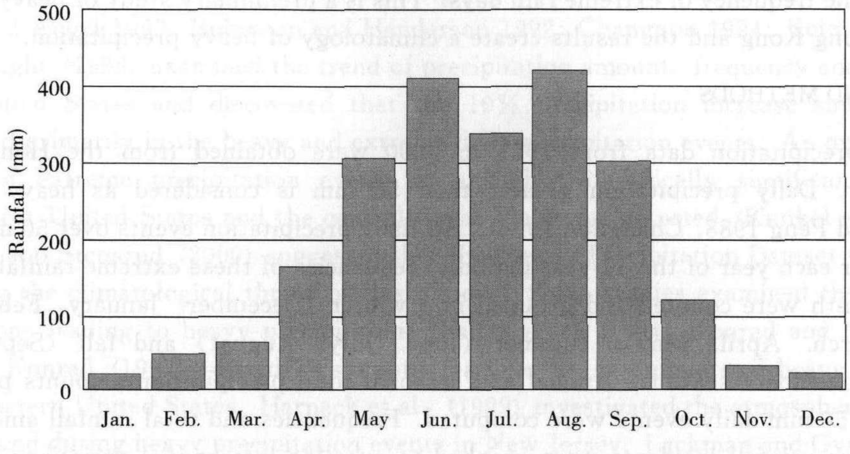

Fig. 1. Average monthly precipitation based on 50-year record.

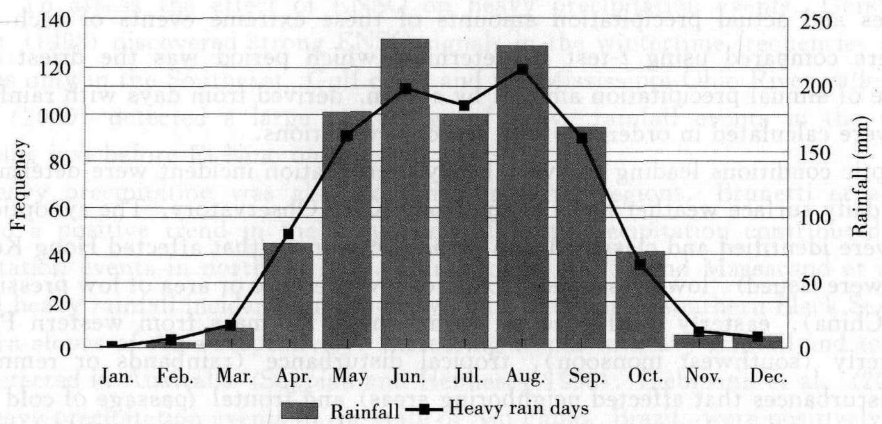

Fig. 2. Number and average rainfall amounts of days with precipitation over 50 mm.

shows the average monthly precipitation, revealing two main rainfall peaks in June and August as identified by Jackson and Hsu (1992). The June maximum was caused mostly by the thunderstorm activities (Chin 1986). The second peak was induced by the frequent occurrence of tropical cyclones (Jackson 1994). Figure 2 depicts the total number and average rainfall amount from days with precipitation above 50 mm by months. The pattern was similar to that in Fig. 1.

Figure 3 presents the temporal distribution of heavy rain days and annual rainfall and Fig. 4 shows rainfall amounts derived from days with precipitation above 50 mm and annual rainfall. Significant positive correlations were detected between the extreme rain days and annual precipitation ($r=0.870$, $p=0.000$), and rainfall amounts from days with precipitation over 50 mm and annual rainfall ($r=0.923$, $p=0.000$). These strong associations revealed that heavy rainstorms contributed to a great proportion of annual precipitation. Non-significant increasing trends for annual precipitation ($r=0.210$, $r^2=0.044$, $p=0.142$), number of heavy rain days ($r=0.213$, $r^2=0.045$, $p=0.138$) and

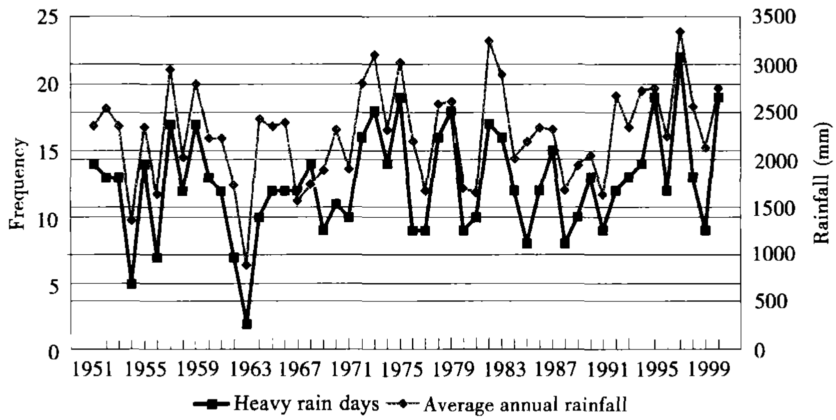

Fig. 3. Frequency of heavy rain days and average annual precipitation.

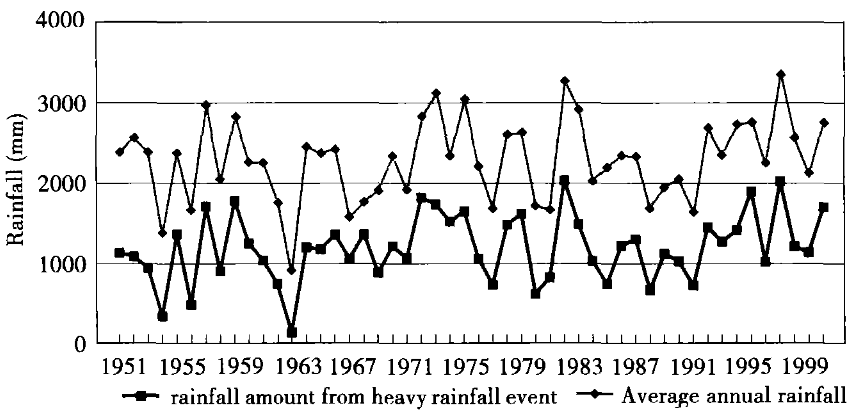

Fig. 4. Rainfall amount from days with rainfall over 50 mm and average annual precipitation.

total amount of rainfall of extreme incidents ($r = 0.256$, $r^2 = 0.066$, $p = 0.072$) were detected. These results were consistent with the investigations on climate change that increase in heavy rainfall events would occur in area with total rainfall increase, although the upward trends were not statistically supported. However, the tendency of increasing rainfall discovered in the present study was contrary to the downward trend detected in the subtropics due to global warming. Further examinations of precipitation variability in the subtropics are required to elucidate these uncertainties.

There were a total of 627 heavy rainfall days and 53.27% of which happened in summer. Only 10 heavy rain days (1.60%) occurred in winter and 23.92% and 21.21% happened in spring and fall respectively. The rainfall amounts derived from the extreme events by season were depicted in Fig. 5. The driest year was 1963 and the wettest years were 1982 and 1997.

To examine decadal difference, the frequency and precipitation amounts of heavy rainfall days of each 10-year period were compared using t-test. It was discovered that the 10-year period 1961—1970 had the least number of extreme rain days (101 days) and the

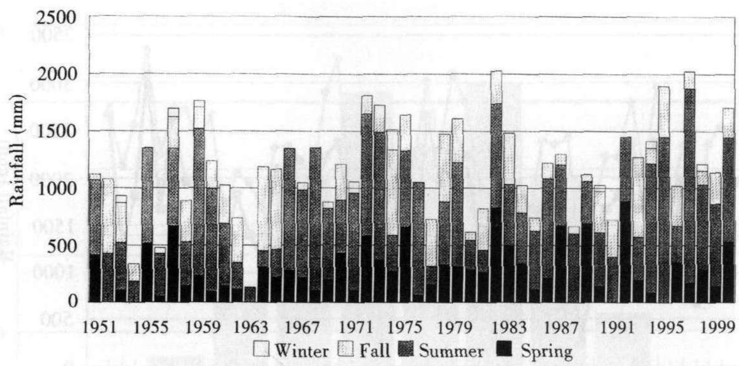

Fig. 5. Rainfall amounts from heavy rainfall events.

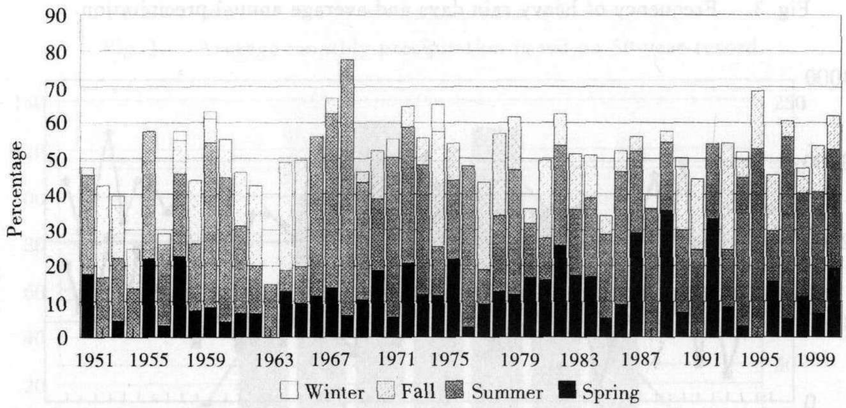

Fig. 6. Percentage of annual average precipitation derived from daily rainfall over 50 mm.

lowest average rainfall amount from the heavy rainfalls (1008. 37 mm), and the decade 1991—2000 had the greatest number of heavy rain days (142 days) and the highest average rainfall (1386. 35 mm). Only the decade 1961—1970 was found to differ significantly from the 10-year period 1991—2000 in the number of heavy rain days ($t=-2.641$, $p=0.027$) and heavy precipitation amount ($t=-2.287$, $p=0.048$).

Percentages of annual precipitation amounts derived from daily rainfall over 50 mm by season (Fig. 6) were used to investigate seasonal variations. Summer accounted for 27. 7%, followed by spring (11. 5%), fall (11. 0%) and winter (0. 7%). These results revealed that summer is the season with the greatest amount of precipitation derived from days with great rainfall amount because of the warmer atmosphere that can hold greater amount of water vapor and is convectively unstable (Henderson-Sellers and Robinson 1986).

The Southwest Monsoon and warm moist air mass from western Pacific affect Hong Kong during summer. Heavy rains and thunderstorm activities are very frequent. Also tropical cyclone frequency increases from July and reaches a maximum by the end of August (Chin 1986). The unstable atmosphere and tropical disturbances explain the high percentage of annual precipitation derived from summer heavy rainfall. In winter, Hong

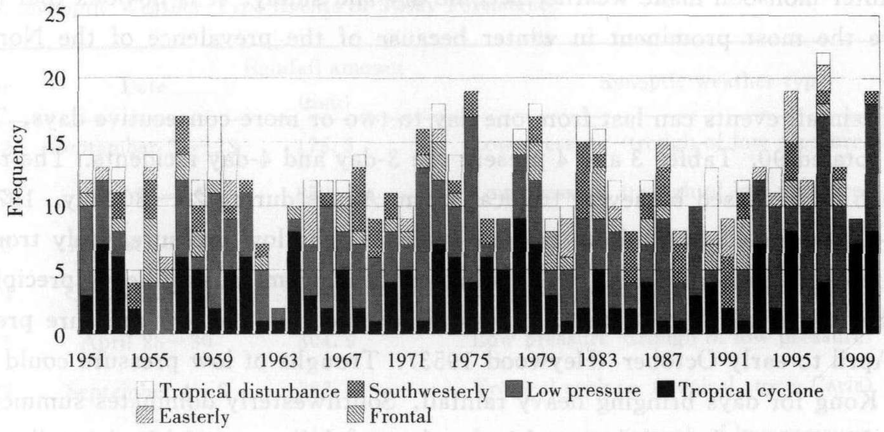

Fig. 7. Synoptic weather-type frequencies.

Kong experiences its dry season. The influence of cold dry air mass from Siberia and the Northeast Monsoon contributes to the low percentage of annual rainfall derived from winter heavy precipitation. During the transitional seasons, the incursions of warm moist air and onset of the Southwest Monsoon induce heavy rainfall in spring, while the onset of Northeast Monsoon and less frequent and intense tropical disturbances bring less extreme rainfall (Chin 1986).

2. *Synoptic Weather-Type Frequencies*

Heavy rainfall frequencies by synoptic weather types are shown in Table 1. Of the total of 627 events, 29.82% were induced by tropical cyclone, 38.76% were classified as low pressure, and only 5.58% were caused by easterly. Of all the low pressure induced events, 83.95% were troughs of low pressure and the remaining 16.05% belonged to area of low pressure over southern China. Figure 7 shows the annual synoptic weather-type frequencies. Tropical cyclones induced heavy rainstorms almost every year except 1955, 1956 and 1998. During those years, not a single tropical cyclone hit Hong Kong directly although warnings were issued.

The seasonal components of heavy precipitation by synoptic weather types (Table 2) revealed that tropical cyclone induced events peaked in summer and dropped in fall when the frequency and intensity decreased rapidly. It is extremely unusual to have tropical cyclone affecting Hong Kong in December (Chin 1986). However, it did happen on December 1—2 1974 when Typhoon Irma hit Hong Kong and brought 177.3 mm of rainfall on December 2. Low pressure, particularly trough of low pressure, was the second major mechanism provoking severe rainstorms. Its impact increased in spring, peaked in summer and decreased in fall. Spring is marked by very changeable weather. Although the Siberia high pressure weakens, occasional cold surges induce frontal events. Also the onset of Southwest Monsoon and the warm moist air from western Pacific cause unstable atmosphere that induces rainstorms. In fall, the strengthened Siberia high pressure and onset of winter monsoon make weather become dry and sunny. It is obvious that frontal events were the most prominent in winter because of the prevalence of the Northeast Monsoon.

Heavy rainfall events can last from one day to two or more consecutive days. The 2-day events totaled 90. Tables 3 and 4 present the 3-day and 4-day incidents. The rainfall event (450. 5 mm) caused by severe tropical storm Agnes during 26—30 July, 1978 was the only 5-day episode. Apart from tropical cyclones, the low pressure (only trough of low pressure over southern China) was the major mechanism causing heavy precipitation incidents that persisted up to 4 days. It was discovered that the low pressure prevailed from mid-April to early October (Heywood 1953). Troughs of low pressure could linger over Hong Kong for days bringing heavy rainfall. Southwesterly dominates summer with an average duration of about 4 days and it was frequently interrupted by easterlies (Chin 1986). Therefore, its effect was less substantial and powerful when compared with the influence of low pressure.

Table 1. Synoptic Weather Type Frequencies

	One day event	2-day persistence
Tropical cyclone	187 (29.82%)	42 (46.67%)
Low pressure	243 (38.76%)	26 (28.89%)
Easterly	35 (5.58%)	3 (3.33%)
Southwesterly	66 (10.53%)	11 (12.22%)
Tropical disturbance	44 (7.02%)	5 (5.56%)
Frontal	52 (8.29%)	3 (3.33%)
Total	627 (100%)	90 (100%)

Table 2. Synoptic Weather Type Frequencies by Season

	One day event				2-day persistence			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Tropical cyclone	7	108	71	1	1	24	17	0
Low pressure	86	129	28	0	10	14	2	0
Easterly	10	16	8	1	1	0	2	0
Southwesterly	10	52	4	0	2	9	0	0
Tropical disturbance	3	29	12	0	1	2	2	0
Frontal	34	0	10	8	2	0	1	0

Table 3. Synoptic Weather-Type Events of 3-Day Persistence

Year	Date	Rainfall amount (mm)	Synoptic weather type
1952	September 21—23	175.5	Low pressure (trough of low pressure)
1972	June 16—18	652.3	Low pressure (trough of low pressure)
1973	August 10—12	223.1	Tropical cyclone (Typhoon Georgia)
1974	October 18—20	459.5	Tropical cyclone (Typhoon Carman)
1975	April 28—30	304.9	Low pressure (trough of low pressure)
1977	September 4—6	267.6	Tropical cyclone (tropical storm Carla)
1987	July 28—30	311.2	Low pressure (trough of low pressure)
1991	June 8—10	228.4	Southwesterly
1993	September 24—26	416.9	Tropical cyclone (Typhoon Dot)
1995	August 12—14	448.3	Tropical cyclone (severe tropical storm Helen)
1996	June 22—24	244.5	Low pressure (trough of low pressure)
1997	July 1—3	321.4	Low pressure (trough of low pressure)

Table 4. Synoptic Weather-Type Events of 4-d Persistence

Year	Date	Rainfall amount (mm)	Synoptic weather type
1955	May 8—11	386.3	Frontal
1959	June 12—15	724.6	Low pressure (trough of low pressure)
1966	June 9—12	572.2	Low pressure (trough of low pressure)
1976	July 24—27	222.7	Tropical cyclone (severe tropical storm Violet)
1994	July 22—25	664.5	Low pressure (trough of low pressure)
1995	July 12—15	311.0	Easterly
1999	August 22—25	609.4	Tropical cyclone (Typhoon Sam)

3. *Relationship between ENSO and Frequency of Heavy Rainfall Event*

Results of correlation coefficients revealed non-significant negative relationship between SOI and number of heavy rain days. However, a negligible negative correlation was discovered with 3 month lag of SOI ($r = -0.08$, $p = 0.05$). It is apparent that there was minimal relationship between SOI and frequency of heavy rain days despite the discovery of strong association between ENSO and rainfall by Au and Chang (1998).

Table 5. Years with Number of Heavy Rainfall Events over 15 and Their Relation to El Nino/ La Nina Activity

Year	Rank	Number of heavy rainfall events	Annual rainfall (mm)	Nature of the year
1997	1	22	3343. 0	El Nino onset
1975	2	19	3028. 7	year following La Nina onset
1995	2	19	2754. 4	La Nina onset
2000	2	19	2752. 3	year following La Nina onset
1973	3	18	3100. 4	La Nina onset
1979	3	18	2614. 7	El Nino onset
1957	4	17	2950. 3	El Nino onset
1959	4	17	2797. 4	Neutral
1982	4	17	3247. 5	El Nino onset
1972	5	16	2807. 3	El Nino onset
1978	5	16	2593. 0	year following El Nino onset
1983	5	16	1893. 8	year following El Nino onset

Years with number of heavy rainfall events over 15 were identified and related to El Nino/ La Nina activity (Table 5). Seven out of twelve years coincided with either years of El Nino onset or the years following its onset. This finding was similar to the previous rainfall study in Hong Kong. Chang (1999) found that 1982 (3247. 5 mm) and 1997 (3343. 0 mm) were the wettest years that coincided with the years of the two strongest El Nino onsets. However, it is interesting to note that 1963, the driest year (901. 1 mm) with the least number of heavy rain days also happened in an El Nino onset year. Results of the present study indicated the non-uniqueness of the atmospheric response to El Nino and difficulty in linking impacts of ENSO events on weather at a local scale.

IV. CONCLUSION

A total of 627 heavy rainfall days happened in the period of 1951 — 2000. Non-significant increasing trends for annual precipitation and number of heavy rain days were detected. About 53. 27% of the heavy rainfall events occurred in summer. Also 27. 7% of summer rain was contributed by the severe rainstorms. It is obvious that summer is the season with the greatest amount of rainfall due to the warmer atmosphere. Tropical cyclone was the prominent mechanism inducing the heavy precipitation, followed by low pressure, southwesterly, frontal, tropical disturbance and easterly. Tropical cyclone and tropical disturbance events were confined to the typhoon season (May to November). Frontal passages were frequent in spring and fall when frontal systems developed over China and migrated southward. The influence of the Southwest Monsoon, warm moist air mass from western Pacific, coupled with atmospheric instability contributed to rainstorm occurrence.

Seven out of twelve years with number of heavy rain days more than 15 coincided with El Nino events. However, the driest year, 1963, also happened in an El Nino onset year. Minimal negative correlation between SOI and frequency of heavy rain days was found. These findings revealed that atmospheric responses to El Nino could be varied, and further investigations are required.

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