A FURTHER STUDY OF THE VARIABILITY IN THE FREQUENCY OF
TYPHOON FORMATION OVER THE WEST PACIFIC OCEAN

MASTER

by

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Abstract

This paper presents a further study of the variability in the frequency of typhoon formation* over the West Pacific ocean, emphasizing the effects of the large-scale sea-air system on the activity of typhoons. Some important relationships between typhoon formation and the climatological aspect of air-sea interaction are pointed out. They include:

(1) During summers and during individual months with many typhoons the polar vortex center moves to the side of the northern hemisphere which is opposite to the North Pacific. At the same time the circum-polar westerlies contract poleward. During months with few typhoons inverse conditions prevail.

(2) A long-wave ridge or blocking high situation often persists over the eastern North Pacific, with a long-wave trough on either side of it. This pattern accompanies frequent typhoon genesis, whereas in summers with few typhoons the trough-ridge pattern over the same regions is entirely reversed.

* The definition of "typhoon" as a cyclone with winds exceeding 17.5 m/sec was adopted according to Chinese custom. It includes systems labelled as "tropical storms" according to American usage.

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(3) During summers or months with many typhoons the circulation over Tibet is characterized by an upper trough or low pressure region, whereas with few typhoons there is a weak high pressure ridge over Tibet.

(4) In summers or months with many typhoons, the monsoon trough at 500 mb and at the surface over the Indian peninsula is relatively weak and is accompanied by higher-than-normal rainfall in the northern part of India along the southern slopes of the Himalayas, whereas in summers or months with few typhoons a well-developed monsoon trough lies further to the south, over the Indian peninsula, producing higher-than-normal rainfall there. With many typhoons the monsoon trough may extend into the West Pacific, whereas with few typhoons it sharply terminates at about 120°E.

(5) In summers or months with many typhoons abnormally warm water is observed over the Central and Eastern Pacific and abnormally cold water over the West Pacific. With few typhoons the opposite is true. It is worth noting that the SST (sea-surface temperature) pattern of the preceding spring has a great resemblance to the SST patterns of the summer typhoon season.

(6) SST's in the region of the warm Kuroshio current and in the latitude belt 30°-40°N are abnormally warm in summers or in months with many typhoons, whereas with few typhoons SST's in the same regions are abnormally cold.

In combining the foregoing relationships with the results obtained in a previous paper (Ding and Reiter, 1980), we are able to obtain a qualitative physical picture of the causes of long-term variability in the frequency of typhoon genesis. On the one hand, thermal forcing of

typhoon activity by abnormally warm water over the Central and Eastern Pacific may cause major tropical circulation systems (tropical upper-tropospheric trough , Tibetan high, intertropical convergence zone, etc.) and the associated zonal Walker circulation and monsoon circulation to move eastward by 20° - 30° longitude. On the other hand, with possible forcing by a contracting polar vortex, many circulation features (tropical easterlies, subtropical high, ITCZ and midlatitude cyclonic activity) and the associated Hadley cell appear to be displaced northward by about 5° latitude. As a result of the combined effects of the above two forcing mechanisms, favorable conditions for typhoon genesis are produced in the region 15° - 20° N, 130° - 170° E.

1. Introduction

In a previous paper (Ding and Reiter, 1980) we focused our discussion on the relationship between the formation of tropical cyclones (typhoons) over the West Pacific and large-scale tropical circulation in the Asian monsoon region and in the Western and Central Pacific. It has been shown that during certain months with different typhoon activity the major characteristics of large-scale circulation features in the tropics are significantly different. We reached the conclusion that large-scale circulation conditions may play a key role in controlling the variability of the typhoon formation frequency in a certain region. If dynamic and thermal conditions favorable for the formation of typhoons could be produced as a result of the evolution or adjustment of large-scale circulation patterns that persist for a long time, a period of above-normal typhoon frequency may be expected. Therefore, in the search for causes and conditions leading to the variability in the frequency of typhoon formation, more attention should be paid to the large-scale circulation features and their changes.

In this paper, we have extended our research on the relationship of large-scale circulation patterns to the variability in typhoon formation to regions in the middle and high latitudes of the northern hemisphere. Such an extension provides a better understanding of changes in the tropical circulation patterns and in typhoon frequency through the interaction between circulation systems in the middle and low latitudes.

We have also studied SST patterns over the North Pacific for the months and years with different typhoon activity. There is an apparent link between SST's and typhoons which influences the variability in the frequency of typhoon formation on a monthly, yearly and longer-term

basis. Several researchers (Namias, 1969, 1973; He, 1979; Brand, 1971; and Ramage, 1974) have also pointed out such SST effects. Others (e.g. Riehl, 1956) dispute such a relationship. Finally, we are attempting to give a tentative physical explanation of the possible causes of the variability in typhoon activity.

It should be pointed out that typhoons form under the influence of the interaction of the atmosphere-ocean system. Such interaction entails very complicated processes and feedback mechanisms (Reiter, 1979). A more detailed understanding of these processes must be achieved before significant improvements in the long-term prediction of typhoon formation can be expected.

2. Data Sources

Monthly upper-air wind and rainfall data for India were taken from the "Monthly Climatic Data Over the World" for the period of 1952-1978 and were supplemented by the mean monthly upper tropospheric circulation over the tropical Pacific during 1954-1959 as published by Joint Task Force Seven (1961). The "Monthly Height Data at 500 mb in the Northern Hemisphere For 1951-1976", compiled by the Department of Geophysics, University of Beijing (Peking) in 1976 (unpublished) provided an invaluable data source. The monthly surface pressure data were received from various sources, mainly from the Division of Long-Term Weather Forecasts of the Central Meteorological Observatory in Beijing. Other monthly and daily data characterizing the state of the general circulation, such as the circulation index at 500 mb and the intensity and position of the subtropical high over the West Pacific and of the polar vortex in the northern hemisphere, were extracted from the Appendix of a paper, "A Survey of Skill and Experiments in the Long-Term Weather Prediction" prepared by the Division of Long-Term Weather Forecasts of the Central Meteorological Observatory in Beijing. Sea-surface temperatures were obtained from the U.S. Navy Fleet Numerical Weather Central in Monterey, California for the period 1962-1976.

3. Long-Term Variations in the Wind Fields of the Tropical Pacific and Their Relationship to Variability in the Frequency of Typhoon Formation.

Figure 1 shows the long-term variability in monthly departures of the frequency of typhoon genesis west of the date line (heavy line) and of the surface trade-wind u-components averaged over the area 5° - 19° N, 128° E- 95° W (thin line). The data were subject to a seven-month running averaging to remove the high-frequency noise. A stronger-than-normal easterly flow is characterized in this diagram by positive signs. We can see an apparent negative correlation between these two departures during the late 1960's, but not during the rest of the sample period. This generally poor correlation suggests that the North Pacific typhoon genesis is not critically dependent on the behavior of the area-averaged northeast trade winds. In the sixties many peaks of the weaker-than-normal east winds were encountered in the North Pacific trade region. In the fifties peaks of stronger-than-normal east winds appeared more frequently. The relatively moderate activity of typhoons in the fifties and the increased activity in the sixties described by Ding and Reiter (1980) might be related to the long-term trade-wind behavior of the North Pacific. Figure 2 compares the trade wind u-component averaged over the area 1° - 15° S, 128° - 75° W to typhoon frequency. A positive correlation between the frequency of typhoon formation over the tropical West Pacific and the South Pacific trade winds still is not statistically significant. It suggests, however, a tendency for an active period of typhoon formation to follow several months after the easterly trade winds strengthen in the southern hemisphere. Li (1956) and Tao and He (1979) pointed out that the outbreak of the cold air in Australia and the subsequent intensification of the cross-equatorial flow and of the

southwest monsoon can stimulate the typhoon activities in the northern hemisphere. Fujita et al. (1969) also showed an excellent example of how the airflow in the southern hemisphere intruded into the tropical region of the northern hemisphere and at last produced an active period of tropical cyclones over the Eastern Pacific which lasted for about two weeks. Recently Ding (1978b) has given a detailed analysis of such interaction between the airflow of both hemispheres and its possible effect on the typhoon formation over the tropical Pacific. He pointed out that in the summer (July-Sept.) of 1967 six such interaction episodes took place. They altogether produced 20 typhoons over the tropical Pacific which accounted for 60% of the total typhoon number (25) in that year. If such interactions, indeed, were important, they do not reveal themselves significantly in Fig. 2. We also are at a loss to explain a mechanism by which impulses of the zonal trade-wind flow originating in the southern hemisphere could influence the typhoon formation over the Western North Pacific on a monthly or seasonal basis.

Figure 3 gives the departures of the monthly v-component in the Pacific trade region 5° - 19° N, 125° E- 95° W (dashed line). Positive values indicate stronger-than-normal flow toward the equator. An excellent positive correlation exists between that curve and the Line Islands precipitation index (dashed-dotted line). A negative correlation between the anomalies of the v-component and the frequency of typhoon formation is somewhat better than the one encountered in Fig. 1, suggesting that active periods of typhoon formation tend to occur when stronger-than-normal south winds or weaker-than-normal north winds prevailed. This conclusion is in agreement with the behavior of the ITCZ and of the attendant southwest monsoon, considering that most of

the typhoons form within or around the ITCZ. In years with many typhoons the ITCZ is very strong and extended and often moves northward to about 20°N . As a consequence, the south wind component increases in the region equatorward of 20°N . On the other hand, when the ITCZ withdraws southward and is found in a near-equatorial position, few typhoons occur. At the same time northeast tradewinds with above-normal flow toward the equator prevail over most of the tropical Pacific. Precipitation trends in the "dry zone" of the equatorial Pacific, exemplified by the time-smoothed precipitation index (PI) for the Line Islands (Reiter, 1978) suggest that above-average precipitation appears in that zone during years with few typhoons and stronger-than-normal flow towards the equator.

We have also considered possible relationships between the trade-wind behavior in the East and West Pacific and Northwest Pacific typhoon frequencies. For this purpose average monthly departures from the long-term monthly mean u - and v -components in the regions 5° - 19°N , 125° - 180° (NW), 1° - 15°S , 125° - 180° (SW), 5° - 19°N , 180° - 95°W (NE) and 1° - 15°S , 180° - 75°W (SE) were calculated and subjected to a 7-month running-mean filter. Comparisons of these data with the aforementioned tropical storm frequencies are summarized in Table 1. None of the listed peak correlations meet the 90% significance level, therefore no consistent interplay between the interannual variability of Pacific trade-wind behavior and that of tropical storm frequency can be deduced.

Figures 4 through 6 show the long-term variability in departures of the 850-mb wind fields from the long-term monthly mean values at five upper air stations over the tropical West Pacific. A negative correlation is indicated between the strength of the easterlies at 850 mb and

Table 1 Maximum lag correlations, R , between trade-wind easterly and equatorward wind components and Northwest Pacific tropical storm frequencies, using 7-month smoothed data sets. (Lags, in months, are positive if peak typhoon activity leads peak wind-component strength.)

	West Pacific		East Pacific	
	R	Months	R	Months
$u_{N.H.}$ (easterlies > 0)	0.16 0.44	0 -12	-0.14	+4
$u_{S.H.}$ (")	0.08	-1	-0.22 0.25	+5 +17
$-v_{N.H.}$	0.34	+2	0.33 -0.38	-3 +17
$v_{S.H.}$	-0.17 0.28	-4 -15	-0.21	-1
$(-v_{S.H.} + v_{S.H.})/2$	-0.23	+2	-0.34	-1

the frequency of typhoon formation with the exception of 1964, when many typhoons formed with strong low-level east winds (and cold SST) over the Pacific. The anomalies in the environmental conditions and in the typhoon formation of that year will be discussed later. Generally, when the westerly component strengthens or the easterly component weakens, typhoon activity becomes more frequent. When east winds prevail over the tropical West Pacific, there is little chance for typhoon formation.

Possible relationships between the v-component at 850 mb and typhoon formation are tested in Fig. 6. Active periods of typhoon formation tend to occur when the southerly wind component reaches maximum values.

4. Some Characteristics of Vertical Cross-Sections of Zonal Wind Fields During Months with Different Frequencies of Typhoon Formation.

Two sets of north-south vertical cross-sections and one set of west-east sections have been constructed to render a three-dimensional picture of the zonal wind fields over the Central and Western Pacific. Zonal components were computed for standard levels up to 100 mb using all available observation stations over the Pacific region, and isopleths were drawn at 2 m/s increments. Preliminary analyses were adjusted for vertical continuity and horizontal consistency by cross-checking with horizontal maps published by Ding and Reiter (1980). For stations such as Tarawa ($1^{\circ}21'N$, $172^{\circ}56'E$) and Marcus ($24^{\circ}17'N$, $153^{\circ}38'E$), which have very short periods of records, the mean zonal wind component was not considered representative. We included them in our analysis only for the purpose of reference. Vertical cross-sections of zonal winds at about $140^{\circ}E$ in summer are shown in Fig. 7 to depict typical conditions over the West Pacific when many typhoons (upper part) and few typhoons (lower part) occur. The months composited in our analysis are listed in Table 2. There are four significant differences between these two cross sections: (1) In summers with many typhoons the equatorial low-level west winds are relatively deep, reaching to 600 mb. They barely reach to 800 mb in summers with few typhoons. The westerlies in the former case are also much stronger than in the latter case. The northern limit of the west winds in summers with many typhoons extends by about 5° latitude farther than in summers with few typhoons. (2) There is an upper easterly jet between 200-mb and 150-mb levels within 10° of the equator, with maximum speeds of 18 m/s, in summers with many typhoons, whereas this feature can not be detected in summers

Table 2. Selected months with many typhoons and few typhoons.

Month	Year	Number of Typhoons	Total for Each Month	Year	Number of Typhoons	Total for Each Month	Average Ratio of the Number of Typhoons Between Months With Many and Few Typhoons
July	1958	7	33	1957	1	11	3:1
	1965	5		1959	2		
	1967	8		1968	3		
	1971	7		1969	3		
	1972	6		1975	2		
August	1960	10	44	1963	3	19	2.3:1
	1966	10		1969	4		
	1967	9		1975	5		
	1968	9		1976	4		
	1974	7		1977	3		
September	1965	7	37	1968	3	17	2.2:1
	1966	9		1970	4		
	1967	9		1973	3		
	1971	6		1974	4		
	1972	6		1975	4		
Total Typhoons for 3 Months			114			47	2.4:1

with few typhoons. (3) With many typhoons the upper westerly jet in midlatitudes is somewhat weaker in intensity, and its southern limit is 3° - 5° farther to the north, than in summers with few typhoons. The north-south movement of the upper westerly jet between periods with different typhoon activity is closely associated with the expansion and contraction of the circumpolar westerly vortex. With few typhoons the strong westerly winds in midlatitudes frequently intrude into tropical regions above the 500-mb level. This fact is reflected by the presence of a tongue of weak east winds in the lower portion of Fig. 7. (4) At low levels, the subtropical east winds are stronger in summers with few typhoons than with many typhoons.

Figure 8 shows vertical cross-section of zonal winds along approximately 160°E , representative of the structure of zonal wind fields over the Central Pacific. A significant feature noted in this figure is the presence of westerlies at all levels between 500 mb and 100 mb over the subtropics to about 5°N in summers with few typhoons. The equatorward penetration of the upper westerlies is mainly caused by the southward and westward movement of the TUTT. With many typhoons there is only a small area of upper westerlies in the subtropics. No easterly jet is evident in either of the two sections shown in Fig. 8. This suggests that in summers with many typhoons the upper easterly jet develops and persists west of 160°E . The jet terminates at about 120° or 130°E in summers with few typhoons. In the lower troposphere of the tropics the easterly winds are better developed with fewer typhoons. In Fig. 9 west-east vertical cross-sections of the zonal wind along about 10°N are shown, giving further support to the above-described major features of the structure of the zonal wind field. For example, the considerable

eastward extension, up to 150°E , of low-level westerlies below 500 mb, a strong upper easterly jet west of 160°E , and the absence of upper westerly winds over the Central Pacific can be noted during summers with many typhoons. The termination of low-level westerlies and of the upper easterly jet at about 130°E , the presence of upper westerly winds near 160°E caused by the southward dipping of the TUTT, and the strong low-level easterly winds underneath that layer of upper westerlies characterize summers with few typhoons.

Figures 7 through 9 give valid indications of the three-dimensional structure of the wind field over the West Pacific. There are five basic flow systems: the upper easterly jet, the low-level westerlies (SW monsoon), the upper westerlies of midlatitudes, the subtropical upper westerlies and the tropical low-level easterlies (NE trade winds). Of them, the low-level westerlies, the upper easterly jet and the subtropical upper westerlies appear to be essential to typhoon formation. In summers with many typhoons the circumpolar westerlies in the middle and high latitudes contract poleward and the upper westerlies associated with the TUTT rarely intrude into the tropical Pacific west of 160°E , so that in the subtropics and tropics deep easterlies are established, with very weak vertical wind shears. At times when the low-level westerlies from the South Asian monsoon region or from the southern hemisphere extend eastward and northward, an extended and well-developed ITCZ may form farther to the north and east than is normally the case. The tropical upper-level easterlies help to strengthen the divergence at upper levels. All these factors, i.e. strong low-level convergence along the ITCZ, weak vertical wind shear in a deep easterly flow regime, and the enhanced upper-level divergence field combine to produce conditions favorable for typhoon formation. In summers with few typhoons the

circumpolar westerlies tend to expand, allowing the troughs associated with them to intrude into low latitudes. Moreover, the subtropical upper westerlies associated with the TUTT also frequently dominate the upper part of the troposphere over the central and western Pacific. Thus, upper westerlies often lie above the low-level easterlies creating a strong vertical wind shear. Owing to the weakness of the low-level westerlies associated with the SW monsoon, the ITCZ is ill-developed and assumes a near-equatorial position. Furthermore, a significant upper-level divergence field cannot develop over the West Pacific due to the absence of an upper-level easterly jet. Therefore, strong vertical wind shears, weak low-level convergence along the ITCZ -- or even an absence of the ITCZ --, and sluggish upper-level divergence constitute a situation unfavorable for typhoon formation.

Figures 10 through 12 show vertical cross-sections of zonal wind for July, August and September. They, and the cross-sections for the whole summer (Figs. 7 to 9) have similar distributions of the above-mentioned five basic airflow patterns. A noteworthy feature is the eastward extension to 170°E of the low-level westerlies in September months with many typhoons (Fig. 12^o). For the individual months of certain summers the same is true. Fitting examples are shown in Figs. 13 and 14, taken from the "Mean Monthly Upper Tropospheric Circulation Over the Tropical Pacific During 1954-1959" (Joint Task Force Seven, 1961). In July of 1957, when typhoon formation was dormant, upper westerlies appear in both of the cross-sections over the subtropical and tropical region. Upper westerlies are absent in the cross-section along 160°E in July of 1958 when typhoon formation was very active. Over the Central Pacific the center of upper westerlies was displaced southward

by 5° in July of 1957 relative to its position in July of 1958. Figures 15 and 16 are the corresponding 200-mb synoptic maps. It can be seen that in July of 1957 the TUTT extended relatively far westward and dominated most of the Western and Central Pacific with upper westerly winds, whereas in July of 1958 closed anticyclonic cells were better developed and the TUTT moved to the region east of 170°W . The 200 mb level circulation patterns in the summer of 1957 were similar to those in the summer of 1959, as pointed out in the data source. Accordingly, only few typhoons formed during both years.

The mean vertical profiles of zonal winds for summer over several stations in the Central and Western Pacific are shown in Fig. 17. Over the central and western Pacific within 15° of the equator and below 500 mb the easterlies in summers with few typhoons are stronger than with many typhoons, whereas the opposite is true above 500 mb. These differences become more obvious the farther west the stations are located. In the subtropics the differences are generally small, summers with few typhoons having slightly stronger west wind in the whole troposphere over the West Pacific.

Based on the above analysis of wind fields, we can reach the conclusion that the prerequisite to an active summer typhoon period is a large-scale tropical general circulation environment well-protected from the effects of disturbances in middle and high latitudes. Under such conditions, and as soon as the SW monsoon advances either from South Asia or from the southern hemisphere into the tropical West Pacific, a sequence of typhoon formation can be initiated.

5. The Characteristic Patterns of Monsoon Rainfall in India During Months with the Different Frequencies of Typhoon Formation.

In our previous paper (Ding and Reiter, 1980), we pointed out that frequent typhoon formation over the West Pacific occurs during periods of monsoon breaks in India, whereas infrequent typhoon formation occurs during active monsoon periods. This findings were based on the analysis of low-level airflow fields. We now have further evidence of this relationship from rainfall data. Twenty-two recording surface stations in India have been selected to construct the distributions of rainfall. Although these stations cover various climates in India, they basically can be grouped into two categories, one being representative of the SW monsoon rainfall in Northern India (about 8 stations), the other representing the monsoon rainfall over the Indian peninsula. Figure 18 shows the departure of monsoon rainfall from the normal for different typhoon activities over the West Pacific in summer. Figures 18a and 18b, reveal almost opposite patterns of monsoon rainfall. In summers with few typhoons there is above-normal monsoon rainfall over the Indian peninsula, especially in the west coast region, whereas with many typhoons the west coast experiences drought conditions. This result supports our previous contention that when the monsoon trough advances into northern India and lies close to the Himalayan foothills (a condition characteristic of monsoon breaks in India) the typhoon activity over the West Pacific is enhanced. Obviously, under such conditions most of the stations in Northern India receive more rainfall than normal, while the rest of the peninsula remains relatively dry. When the monsoon trough withdraws southward and lies over the peninsula, (conditions of active monsoon periods in India), typhoons over the West Pacific are infrequent.

The distributions of monsoon rainfall for July, August and September are similar to the ones for summer just described. As an example, we only give the case for August (Fig. 19).

We have compared rainfall totals and their departures from normal from four stations on the peninsula with those from four stations in Northern India, taking three summers with many typhoons (1967, 1971, 1972) and three summers with few typhoons (1969, 1975, 1977) (Tables 3 and 4). The results are as expected: Stations in Northern India show rainfall amounts and positive departures which are larger in summers with many typhoons than with few typhoons, whereas for the stations on the peninsula inverse conditions are indicated.

Thus, there appears to be a teleconnection between monsoon conditions in India and typhoon activity over the West Pacific Ocean.

Table 3 Rainfall amounts (R) of four surface stations over the northern part of India and their departures (ΔR) from the long-term mean. Unit: mm.

Year Station	Years with Many Typhoons								Years with Few Typhoons							
	Amritsar		Mukteswar		New Delhi		Gauhati		Amritsar		Mukteswar		New Delhi		Gauhati	
Rainfall Month	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR
July	215	40	401	75	247	44	306	2	161	1	253	-79	240	29	442	142
August	267	102	360	68	437	258	358	2	166	-2	293	8	241	69	221	-42
September	131	20	211	11	123	-21	180	-7	102	-4	316	116	200	50	157	-33
Average for July-Sept.	204	54	324	51	269	94	281	25	144	-3	287	15	227	49	274	22

Table 4 Rainfall amounts (R) of four surface stations over the Indian peninsula and their departures (ΔR) from the long-term mean. Unit: mm.

Year Station Rainfall Month	Years with Many Typhoons								Years with Few Typhoons							
	Bombay		Poona		Goa		Banglore		Bombay		Pona		Goa		Banglore	
	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR
July	751	67	224	42	921	-2	152	37	790	81	233	64	1046	123	105	-12
August	359	-38	75	-28	385	-72	123	-20	529	110	148	42	547	91	158	11
September	206	-37	117	-11	260	7	212	60	396	99	121	-6	352	97	269	101
Average for July-Sept.	439	-3	139	1	522	-22	162	26	572	93	167	27	648	104	177	33

6. Relationships Between Large-Scale Circulation Features in the Northern Hemisphere and the Frequency of Typhoon Formation Over the West Pacific Ocean.

In this section we will discuss the characteristics of some large-scale circulation systems in the northern hemisphere which are considered to have important effects on the frequency of typhoon formation over the West Pacific. These include the circulation index, the behavior of the polar vortex and of planetary long-waves, the subtropical high, and the circulation patterns over Tibet. Table 5 shows statistics on some of the circulation features in middle and high latitudes for months with many and with few typhoons.

6.1 Circulation Indices and Typhoon Frequency.

I_M and I_Z are the mean meridional and zonal circulation indices at 500 mb for the region 45° - 65° N, 60° E- 150° E and 65° - 65° N, 120° E- 120° W, respectively. The first was chosen in order to test the assumption frequently made by Chinese forecasters that major general circulation adjustments over Central Asia will have down-stream effects over the Pacific that might influence typhoon formation. The indices I_M and I_Z were computed from isobaric height values at latitude-longitude grid points as follows:

$$I_M = \frac{1}{M \cdot (n-1) \cdot \Delta\lambda} \sum_{j=1}^{N-1} \sum_{i=1}^M \left| \left(\frac{Z_{i,j+1} - Z_{i,j}}{\cos \phi_i} \right) \right| \quad (1)$$

$$I_Z = \frac{1}{(M-1) \cdot N \cdot \Delta\phi} \sum_{i=1}^{M-1} \sum_{j=1}^N (Z_{i,j} - Z_{i+1,j}) \quad (2)$$

M = number of latitude circles whose intersections constitute the grid points under consideration

Table 5 Statistics of the characteristics of some circulation features in the middle and high latitudes.

Circulation Features Month		I_Z^*	I_M^*	Square Index of Sub-tropical High Over the Pacific	Mean Intensity Index of Sub-tropical High Over the Pacific	Western-most Position of Ridge Line of Subtropical High (Long.)	Mean Latitude of Sub-tropical High (Lat.)	Northermost Position of 5880 m Characteristic Line of Sub-tropical High (Lat.)	Intensity of Polar Vortex i.e. Height Values at Center at 500 mb (Decameter)
Many Typhoon Months	July	0.84	0.065	12	21	134°(E)	25°(N)	29°(N)	43
	August	1.05	0.071	18	31	127°	30°	34°	43
	September	1.31	0.101	14	25	133°	25°	28°	26
	Average	1.07	0.079	15	26	131°	27°	30°	37
Few Typhoon Months	July	0.73	0.112	21	37	122°	24°	29°	41
	August	0.93	0.051	20	32	123°	25°	30°	38
	September	1.37	0.089	17	28	108°	24°	28°	25
	Average	1.01	0.084	20	32	118°	24°	29°	35

* Calculated for region 45°-65°N, 120°E-120°W.

N = number of meridians whose intersections constitute the grid points under consideration

$\Delta\lambda, \Delta\phi \cong 555$ km, (equatorial) distance between meridians and latitude circles

ϕ_i = geographic latitude

i, j = counting indices for latitude and longitude

$Z_{i,j}$ = 500-mb height (geopotential meters) at grid point (i, j)

The circulation indices I_M and I_Z were calculated from monthly mean data of the 500-mb surface published by Beijing University (1976). The preliminary results of our analysis, for the region 60°E - 150°E , not shown in Table 5, were disappointing, because we could see no difference in I_M or I_Z between months with many and with few typhoons. According to results obtained by other researchers (Japanese Association of Meteorology, 1973; Chang, 1958) we expected that during periods of low zonal circulation index the typhoon activity would decrease. Figure 20 shows a time series of a similar index computed over East Asia, which suggests the presence of a six-year quasi-periodicity (Japanese Association of Meteorology, 1973; see also Chen and Ding, 1979). This periodicity is reminiscent of the behavior of SST anomalies in the Central North Pacific (Favorite and McLain, 1973; Reiter, 1979). According to Fig. 20 during the second half of the fifties the zonal circulation index was low; so was the frequency of typhoon formation. In the sixties high zonal circulation index values prevailed over Eastern Asia while the typhoon activity increased. Such a relationship coincides with our findings described earlier (Ding and Reiter, 1980). The discrepancy between our computation of circulation index for the westernmost of the two regions and results by other authors could be attributed

to the fact that we included a large area of Central Asia (60°E - 110°E), which may have masked any correlation suggested by Fig. 20. Calculations of I_M and I_Z for the area 45° - 65°N , 120°E - 120°W are presented in Table 5. There is only a slight hint that I_Z is larger during months with many typhoons than with few. A further calculation for I_M and I_Z for different sectors are presently in progress. In addition, we intend to compare indices computed from monthly mean isobaric height values with those derived from daily height observations, then averaged over a month. The latter approach should give an indication of the possible significance of nonstationary wave patterns on the interannual variability of typhoon formation.

We have used five parameters to characterize the behavior of the subtropical high over the West Pacific (110°E - 180 , northward of 10°N). They include the "square index" (the total number of grid points having 500-mb height values of more than 5880 meters), the mean intensity index (the sum of a height index for the same grid points, defined as 5880=1, 5890=2, 5900=3, etc.), the westernmost position of the ridge line of the subtropical high, the mean latitude of the subtropical high, and the northernmost position of the 5880 m contour line of the subtropical high at 500 mb. From Table 5 we can see that in months with many typhoons the subtropical high tends to assume a position approximately 3° farther to the north than in months with few typhoons. The intensity of the high is weaker and the "square index" is smaller with many typhoons than in months with few typhoons. Also with few typhoons the subtropical high obviously extends westward reaching the eastern coast of China's mainland, whereas in months with many typhoons the main body of the subtropical high does not stretch westward beyond 130°E .

6.2 The Behavior of Polar Vortex and its Relationship to Typhoon Activity.

The last column of Table 4 shows the intensity of the polar vortex (expressed in terms of its central geopotential height value at 500 mb) in months with different typhoon activity. With many typhoons the intensity of the vortex tends to be weaker (central pressure is slightly higher) than with few typhoons. The differences are too small, however, to be considered significant.

Figure 21 shows a more detailed comparison between departures of monthly frequencies of typhoon formation and monthly height anomalies in the center of the polar vortex. The weak relationship suggested by the last column of Table 5 is not obvious from the time sequences shown in Fig. 21. As a matter of fact, longer-term trends, such as the below-normal typhoon activity in the fifties and the above-normal activities in the sixties seem to go along with a weaker and stronger polar vortex, respectively. It appears that the central pressure of the polar vortex alone is a poor indicator of the circulation patterns influencing tropical storm formation over the West Pacific.

The search for other parameters describing Pacific general circulation patterns led to the consideration of the latitudinal profiles of the u-component along about 140°E at 200 mb (Fig. 22). In periods with many typhoons the jet stream in the westerlies tends to move northward by 3-4° as compared to periods with few typhoons. Figure 23 gives the locations of centers of the polar vortex at 500 mb for 15 months each with many (black circles) and with few typhoons (triangles). Under the former conditions the centers of the vortex tend to be displaced towards the Atlantic sector, whereas with few typhoons most of the vortex

centers fall into the Pacific sector. Such vortex behavior will entail a poleward shift in the Pacific region of the midlatitude westerlies, the subtropical high, the ITCZ and the southwest monsoon during summers with many typhoons. The observed shifts in the polar vortex position induce to the speculation that at least a weak negative correlation may exist between the frequencies of tropical cyclones over the Atlantic and over the Pacific. It also becomes obvious why the vortex central height value at 500 mb provided a poor correlant: Its effects on atmospheric flow patterns in the Pacific sector are overshadowed by the influence of the vortex position.

Of course, the gross characteristics of the polar vortex which we have considered so far still provide a rather incomplete description of atmospheric teleconnections and their possible impact on typhoon formation. Considerably more detail can be gained by analyzing monthly height departures at 500 mb for summers with many and with few typhoons (Fig. 24). The patterns of height departures are almost opposite, especially in the polar region and in the Gulf of Alaska. The pattern shifts are in agreement with the behavior of the polar vortex described above. For individual summer months similar anomaly distributions could be derived (Figs. 25 through 27).

We should like to place special emphasis on the fact that months with many typhoons are characterized by the tendency of high pressure ridges forming over the Canadian West Coast and the Gulf of Alaska, while low-pressure activity dominates the region south of the Bering Sea. With few typhoons this pressure pattern reverses. Anticipating our discussion of SST anomalies (Fig. 42), a characteristic superposition of high pressure anomalies over relatively warm waters in the Gulf

of Alaska, and low pressure anomalies during summers with cold water is indicated. Such superposition has also been noted by Namias (1978) and others. At times such SST anomaly patterns tend to be long-lived and can influence the subsequent winter weather regimes over the United States. An exaggeration of the height pattern in Fig. 24b -- low pressure in the Gulf of Alaska, a persistent high pressure over the North American west coast, and low pressure over the eastern seaboard -- gave rise to the cold winters of 1976/77 and 1977/78, long to be remembered in the Eastern United States. We note (see e.g. Fig. 21) that during the summers of 1976 and 1977 typhoon activity in the West Pacific reached unusually low values. The long-term "memory" aspects of such persistent 500-mb height anomaly patterns as described in Figs. 24 to 27 might conceivably lie in feedback mechanisms between atmosphere and ocean, involving SST anomaly patterns.

The anomaly patterns of Figs. 24 to 27 imply that a blocking situation over the East Pacific off the west coast of North America is conducive to frequent typhoon formation over the West Pacific. When such is the case the Kamchatka peninsula and the Hudson Bay region experience negative height departures, indicating that upper troughs often develop or deepen there. Negative height departures are encountered over Japan and its neighboring seas in summers with few typhoons. This suggests that there are frequent cold waves in this region during such seasons, leading to cool summer weather in Japan, a fact pointed out by Japanese researchers (Japanese Association of Meteorology, 1973).

Figure 28, displaying mean 500-mb charts, shows the expected similarity with Fig. 24. In summers with many typhoons the well-developed upper trough over the Kamchatka region and a high pressure ridge over

the North American west coast are very obvious. In summers with few typhoons a high pressure ridge east of Kamchatka and a deep upper trough over the East Pacific prevail. Also, in summers with few typhoons the quasi-stationary planetary wave off Eastern Asia is rather long. Figures 29 through 31 are 500-mb mean charts for July, August and September, showing expected similarities with Fig. 28. In September with many typhoons the long wave trough off Eastern Asia extends to lower latitudes (also see Fig. 27a) than with few typhoons. This circulation feature may explain the formation of a small number of typhoons which originate from disturbances in extratropical regions during the transition season.

6.3 Behavior of the Subtropical High Over the West Pacific and Its Relationship to Typhoon Formation.

Figure 32 shows the long-term trend of monthly mean departures, in degrees of latitude, of the ridge-line positions of the subtropical highs (dashed line). There is a positive correlation with typhoon formation, indicating that the position of the ridge line is farther to the north than normal, when increased typhoon frequencies prevail. During the sixties the subtropical high was more persistently displaced northward than in the fifties or seventies, in agreement with the frequent typhoon formation of that decade.

In examining the intensities and positions of subtropical highs over the Pacific, shown in Figs. 24 and 28, we feel confident that the related statistics presented in Table 4 are meaningful. In summers with many typhoons the main body of the subtropical high is situated over the Central Pacific but is relatively weak, whereas with few typhoons it moves to the West Pacific, with a high pressure ridge extending into the

East China Sea and into North America. On the average, the subtropical highs in summers with many typhoons are $3-5^{\circ}$ farther to the north than with few typhoons. This northward shift is closely related to that of the westerlies described earlier.

Many researchers (e.g. Tao et al., 1965) have studied the sudden northward push and southward withdrawal of subtropical highs as the typhoon season progresses. An active period of typhoon formation often follows a sudden northward displacement of subtropical highs (Chen and Ding, 1979). We studied the behavior of the northward push and southward withdrawal of subtropical highs and their relationships to typhoon formation for two years with different typhoon frequencies (Figs. 33 and 34). With many typhoons (1967 and 1964) there were three sudden northward surges, the first (from 15°N to 20°N) commencing around June 10, the second (from 20°N to 25°N) on June 20, and the third (from 25°N to 35°N) on July 20. Typhoons over the West Pacific started forming more frequently after the second surge (around June 20). More typhoons formed when the subtropical high reached its seasonal maximum latitude. Several typhoons were also generated in the relatively stable periods when the subtropical high was in the process of southward withdrawal. On the other hand, in years with few typhoons (1959 and 1969) there were only two sudden northward surges of the subtropical high. In 1959 the position of the subtropical high fluctuated around 18°N until June 30. Up to this time hardly any typhoons formed. On June 30 the subtropical high experienced the first northward shift from 18° to 25°N . After a short stay of about two weeks, the second push occurred on July 13, bringing the subtropical high to 35°N . A number of typhoons formed during the southward withdrawal of the subtropical high. In 1969 a

similar change in the position of the subtropical high took place. Until June 30 it remained nearly stationary at 15°N . Then two northward surges occurred on June 20 and July 10, respectively. In 1959 and 1969 the northward surges took place 2-3 weeks later than in the two summers typical for frequent typhoon formation.

6.4 Patterns of Circulation Over Tibet and Its Neighborhood During the Periods of Different Typhoon Activity Over the West Pacific.

Let us return to Figs. 24 and 28 to examine the region of Tibet and its neighborhood. In summers with many typhoons there exists a negative height anomaly, whereas during summers with few typhoons an area of positive departures is evident. Correspondingly, in the former case, an upper trough is over Tibet, whereas in the latter case an enhanced high pressure region is present. It is interesting to note that these 500-mb patterns for summer look similar to those for spring seasons following winters with much snowfall and little snowfall over Tibet obtained by Chen and Yan (1979). On the 500-mb mean maps for July, August and September similar anomalies can also be seen (Figs. 25 through 27 and Figs. 29 through 31). Again we are faced with the possibility of a long-term memory mechanism underlying the teleconnection between Tibetan winter snow cover and the circulation patterns during the subsequent summer. Reiter and Ding (1980) have pointed out that SST anomalies in the Central North Atlantic might be involved in this teleconnection.

The monsoon trough over India during summers with many typhoons is slightly deeper and larger in area than with few typhoons (see Figs. 24 and 28). The rainfall maps of Fig. 18 indicated that in summers with many typhoons there is a region of negative departures over the Indian peninsula, whereas with few typhoons there is a large area of positive

rainfall anomalies, in agreement with pressure anomalies of opposite sign shown in Fig. 24. From the work by Chen and Yan (1979) and Reiter and Ding (1980) it appears that winters with above-normal snow cover in Tibet tend to be followed by positive pressure anomalies and below-normal summer-monsoon rains over the Indian peninsula. A multi-structured system of teleconnections, thus, emerges which has to contend with ocean-atmosphere feedback mechanisms over the Pacific and Atlantic as mentioned before, but also entails the possibility that interannual changes in the albedo and heat balance of the Plateau of Tibet have a profound effect, not only on regional, but also on large-scale circulation patterns.

Figure 24 also indicates that over the West Pacific a low-pressure regime prevails during summers with many typhoons, whereas with few typhoons positive 500-mb height anomalies are found in this region. The surface pressure fields for summers with many and few typhoons (Figs. 35 through 38) support this conclusion. With many typhoons the monsoon trough at the surface is not as deep as during summers with few typhoons, but it extends eastward into the West Pacific. With few typhoons, there is a region of high pressure instead of a monsoon trough over the West Pacific.

7. Patterns of the Sea-Surface Temperature (SST) Anomalies Over the North Pacific During Periods with Many and Few Typhoons and Their Possible Role in Influencing Typhoon Formation Over the West Pacific.

Figure 39 depicts the long-term variability in the zonally averaged SST anomalies in two latitude belts of the North Pacific. A certain relationship between SST's and typhoon formation appears indicated, with positive correlation before 1971 and with negative correlation after 1971. The relationship is better for the 30° - 40° N latitude belt. Similar, but weaker correlations, including a phase shift, are indicated between the long-term variability in SST of the Kuroshio current (Fig. 40) and of the West Pacific (Fig. 41), and West Pacific typhoon frequency. Prior to 1971 (with the exception of anomalous excursions in the curves of Figs. 40 and 41 during 1964/65) it appears that warm SST anomalies were conducive to frequent typhoon formation. This result coincides with conclusions reached by Namias (1969) and He (1979).

The apparent phase shift between SST trends and typhoon frequency that seems to have occurred in 1971 is bothersome. We have to realize, however, that SST anomalies in Fig. 39 were averaged over too wide a longitude sector to provide a valid picture of oceanic effects on typhoon formation. We proceeded, therefore to correlate horizontal distributions of SST anomalies with tropical storm frequencies. Results of these analyses are presented in Fig. 42.

One of the salient features in this figure is the reversal of the sign of SST anomalies over the tropical Pacific ocean equatorward of 20° N between summers with many and with few typhoons. In the former case there is a large area of positive SST anomalies over the central and eastern equatorial Pacific. In the latter case negative anomalies

of Δ SST predominate in the same region, suggesting enhanced upwelling of cold water in the California current. Over the equatorial West Pacific the pattern of SST anomalies are opposite to those over the Eastern Pacific. Here cold SST's correspond to summers with many typhoons, whereas warm SST's coincide with few typhoons. Another significant feature of Fig. 42a is the warm-water band extending from the area south of Japan into the Kuroshio extension and the North Pacific Drift all the way to the west coast of North America north of 60°N . This pattern lends support to the conclusion that an abnormally warm Kuroshio current in summer produces favorable conditions for typhoon formation over the West Pacific. The center of the subtropical gyre in Fig. 42a shows below-normal SST. As has been mentioned before, the warm-water anomaly off the west coast of North America appears to be related to the development of a blocking long-wave ridge that persists there during summer. With few typhoons (Fig. 42b) there is a cold-water band stretching from the region south of Japan to the western coast of North America, providing an obvious contrast to conditions shown in Fig. 42a. This cold water may be linked to greater extratropical cyclone activity which, by increased cloudiness (diminished insolation), increased wind and enhanced upwelling favors negative SST anomalies (see e.g. Elsberry and Camp, 1978). If we compare Fig. 42b with Fig. 24b there is an obvious agreement in the positions of the cold water pool in the mid-latitude North Pacific and the negative departures of 500-mb heights, the latter indicating frequent cyclone activity. In summers with many typhoons the regional cyclonic activity lies farther north near Kamchatka and the Aleutians, corresponding to the cold-water band there (Fig. 42a). A persistent long-wave trough (Fig. 24b) overlying a cold central North Pacific (Fig. 42b) tends to inhibit typhoon formation.

We have constructed similar charts of SST anomalies for summers with different typhoon activity by compositing three years each with many typhoons and few typhoons (Fig. 43). Comparing Fig. 43 with 42 a great resemblance is found with one major exception, the sea region adjacent to Japan. There is a weak warm-water anomaly present in summers with few typhoons. In Fig. 43b two years after 1971 were used, lending emphasis to the phase shift between SST anomalies and typhoon frequencies which was described in connection with Fig. 40. The "see-saw" in SST patterns between East and West Pacific which is indicated in Figs. 43a and b, seems to be one of the prevalent features of long-term SST variability in that ocean (see e.g. Middleton, 1980).

To explore the evolution of the above SST patterns for summer, the antecedent (spring) SST anomaly charts have been constructed (Fig. 44). The broad features of these spring patterns are similar to those of summer: the warm water bands in the North Pacific Drift and in the equatorial East Pacific straddle a cold water band in the subtropics during years with many typhoons; cold water over the eastern equatorial Pacific, warm water over the western equatorial Pacific, and a cold-water region northward of 40°N characterize years with few typhoons. It thus appears that the SST anomaly patterns over the Pacific characterizing different levels of typhoon activity are already in existence in spring before the typhoon season is established. This conclusion might lend itself to improvements in the long-term prediction of typhoon formation over the West Pacific.

We finally show the SST anomaly pattern for the summer of 1964 which was characterized by frequent typhoon formation (Fig. 45). Contrary to the general features shown in Fig. 42a for summers with many

typhoons, a region of negative Δ SST covered almost the whole tropical Pacific, but a prominent warm-water region appeared in the Central North Pacific, providing a hint of the expected warm-water band along the North Pacific Drift, and a cold-water band to the south of it. The low-level wind field was quite different during this season from that for summers with many typhoons. This example serves to show, that not every typhoon season will cooperate by clearly matching SST patterns of either Fig. 42a or 42b.

8. Conclusion.

The foregoing discussion pointed out the possible existence of some relationships between typhoon formation and the large-scale aspects of the sea-air system. These relationships are summarized in Table 6. In our view the greatest impact on typhoon frequency comes from the behavior of the polar vortex and from patterns of SST anomalies especially over the East Pacific. The following tentative mechanisms are offered for an explanation of the interannual variability in the frequency of typhoon formation. If in spring and summer of a given year the SST over the tropical Central and Eastern Pacific is abnormally warm and the areal extent of the cold water in the California current shrinks, the low latitude zonal Walker circulation weakens and also moves eastward. Chen (1977) pointed out such changes in the Walker circulation during spring. As a consequence of changes in the thermal forcing the subsiding branch and the region of upward motion of the Walker circulation will shift eastward (Reiter and Ding, 1980). The zonal circulation over South Asia and the West Pacific will also be displaced eastward. The low-level westerly winds and upper-level easterly winds over the West Pacific will be able to intensify, a favorable condition for typhoon formation, as pointed out earlier (Ding and Reiter, 1980). In this case, accompanying the eastward displacement of the common region of upward motion of the Walker and monsoon circulations, the ITCZ and its associated region of preferred typhoon formation will be found farther to the east than normal. At the same time, the TUTT also moves eastward. Therefore, as a consequence of abnormally warm SST over the Central and Eastern Pacific, almost all tropical circulation systems at lower and upper tropospheric levels tend to be displaced eastward by as

Table 6. Comparison of various components of the sea-air system for the periods with many typhoons and few typhoons.

Sea-Air System	Components of Sea-Air System	Period with Many Typhoons	Period with Few Typhoons
Large Scale Atmospheric Systems	Polar vortex	Weak and/or shifted towards the Atlantic sector.	Deep and/or shifted towards the Pacific sector.
	Long wave patterns	Long wave ridge or blocking high over the eastern Pacific with deep long wave trough and cyclonic activity on either side of this ridge, i.e. over Kamchatka and Canada.	Long wave trough over the eastern Pacific with long wave ridges on either side of it. Cyclonic activity off the eastern coast of Asia moves southward.
	Circumpolar westerlies	Expand and move southward.	Contract and move northward.
	Subtropical high over the West Pacific	Position farther north than normal (30°N). Weak. Main body situated over the Central Pacific.	Position farther south than normal (25-27°N). Strong. Remarkable westward extension of the main body into the West Pacific.
	Circulation features at 500 mb over Tibet	Upper trough or low-pressure region.	Reduction of low pressure or enhancement of high pressure region.

Table 6. (Continued)

Sea-Air System	Components of Sea-Air System	Period with Many Typhoons	Period with Few Typhoons
	Monsoon circulation systems over India	Weak monsoon troughs at 500 mb and at surface over the Indian peninsula. Higher-than-normal monsoon rainfall over northern India but drought over most of peninsula. Monsoon trough extends into the West Pacific	Strong monsoon trough at 500 mb and at surface over the Indian peninsula. Higher-than-normal monsoon rainfall over the peninsula. Monsoon trough confined to the region west of 120°E.
SST Anomaly Patterns	Central and eastern Pacific	Abnormally warm water, especially over the equatorial East Pacific.	Abnormally cold water.
	Western Pacific	Abnormally cold water.	Abnormally warm water.
	Kuroshio current	Abnormally warm water.	Abnormally cold water, with some noted exceptions.
	Region from Japan to the western coast of North America north of 30°N.	Warm water band. Cold water band is in subtropics between two warm water regions.	Cold water band. Warm water band is in subtropics between two cold water regions.
	Antecedent season	Similar to the patterns for summer.	Similar to the patterns for summer

much as 20° - 30° in longitude. This shift enables the area favorable for typhoon formation to be located over a warm sea region and far away from the Asian continent. Under such conditions more tropical disturbances from the Eastern Pacific will have the potential to develop into strong typhoons due to their longer travel distance over a warm ocean, a fact pointed out by Ding (1978a).

Furthermore, as the polar vortex weakens, the circumpolar westerlies will contract and move northward. Coincident with this northward displacement, cyclonic activity, subtropical high and ITCZ will also tend to shift northward from their normal positions by about 5° of latitude. As a result the region of typhoon formation will be able to move to a higher-than-normal latitude belt. Such a general northward movement favors the formation and development of typhoons. As a result of this shift the Hadley cell will also move northward and intensify in response to the placements of the subtropical high and the ITCZ.

Possibly the SST patterns in the latitude belts of 30° - 50° N also contribute to the above-described displacement of circulation features. As pointed out by Namias (1978), a pool of cold water in midlatitudes could help to displace the westerlies farther south than normal by influencing the preferred position of troughs in the mid-troposphere. A pool of warm water in midlatitudes would have the opposite effect. A southward shift of a band of cold water, as shown in Fig. 42b, will force the westerlies and the accompanying cyclonic activity southward, inhibiting tropical storm formation.

In summary, relatively small variations in the ocean-atmosphere system of the northern hemisphere, (eastward displacements of 20° - 30° longitude and northward displacements of 5° latitude), can lead to

considerable changes in typhoon activity. We still have to identify and quantify the primary feedback mechanisms within the ocean-atmosphere-continent system which satisfy the teleconnection described in the present study. So far we have focussed our attention on atmospheric and oceanic conditions in the northern hemisphere that seem to influence West Pacific typhoon formation north of the equator. This emphasis, however, should not rule out the possibility that impulses from the southern hemisphere could also play an active role.

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Acknowledgments

The research reported in this paper was supported by DOE Grant DE-AS02-76EV01340 and by NSF Grant ATM78-17835.

Special thanks are due to Will Spangler of NCAR for his help in printing the monthly climate data over the tropical Indian and Pacific oceans. Mr. Dan Westhoff's assistance in calculating and programming the various analysis steps is also gratefully acknowledged. Finally, the authors thank Ms. Bonnie Grantham for typing the manuscript.

Fig. 1 Long-term variability in the monthly departures of the frequency of typhoon genesis west of the date line (heavy line) and surface trade-wind u-component averaged over the area 5° - 19° N, 125° E- 95° W (thin line) (taken from Reiter, 1979). The data were subject to seven-month running averaging.

Fig. 2 Similar to Fig. 1, but for the trade-wind u-component averaged over the area 1° - 15° S, 125° E- 75° W.

Fig. 3 Long-term variability in the departures of the monthly v-component in the Pacific trade region 5° - 19° N, 125° E- 95° W (dashed line). Positive values indicate the stronger-than-normal flow towards the equator. The lower, dashed-dotted curve shows the Line Islands precipitation index.

Fig. 4 Long-term variabilities in the departures of 850-mb zonal wind component at the stations: Koror, Yap and Guam. Positive values indicate easterly component. Bottom curve NW-Pacific typhoon frequency anomalies. A seven-month running average was applied to the data.

Fig. 5 Similar to Fig. 4, but for the stations Truk and Ponape.

Fig. 6 Similar to Fig. 4, but for the v-component at all the 5 stations.

Fig. 7 Vertical cross-sections of zonal winds along 140°E in summer, (a) for months with many typhoons (upper part), (b) for months with few typhoons (lower part). (The months used in our analysis are listed in Table 2.) The easterly component is denoted by dashed lines and the westerly component by thin full lines. Isopleths are drawn for each 2 m/s.

Fig. 8 Similar to Fig. 7, but for about 160°E .

Fig. 9 The west-east vertical cross-sections of zonal wind along about 10°N .

a

b

Fig. 10 Similar to Figs. 7 through 9, but for July only.

Fig. 10 (Continued)

a

b

Fig. 11 Similar to Figs. 7 through 9, but for August only.

Fig. 11 (Continued)

Fig. 12 Similar to Figs. 7 through 9, but for September only.

Fig. 12 (Continued)

Fig. 13 Similar to Fig. 7 and Fig. 8, but for July of 1957. (Taken from the "Mean Monthly Upper Tropospheric Circulation Over the Tropical Pacific during 1954-1959".)

Fig. 14 Similar to Fig. 7 and Fig. 8, but for July of 1958. (Same data source as Fig. 16.)

Fig. 15 Mean streamlines at 200 mb in July of 1957. (Same data source as Fig. 13.)

Fig. 16 Mean streamlines at 200 mb in July of 1958. (Same data source as Fig. 13.)

Fig. 17 Mean vertical profiles of zonal winds for several stations over the central and western Pacific. Full lines denote conditions with many typhoons, dashed lines with few typhoons.

Fig. 18 Departures of monsoon rainfall amount in India, (a) for summers with many typhoons and (b) for summers with few typhoons. Negative departures are denoted by dashed lines, positive departures by full lines.

a

b

Fig. 19 Similar to Fig. 18, but for August.

Fig. 20 Relationship between the typhoon number over the West Pacific in July-October (dashed lines) and zonal circulation index at 500 mb over East Asia (full lines). [From Japanese Association of Meteorology (1973)].

Fig. 21 Relationship between the departures in the monthly frequencies of typhoon formation (full line, ordinate labelling from +2 to -2 cases) and monthly height departures of center of polar vortex (dashed line, ordinate labelling from +4 to -4 dm).

Fig. 22 The latitudinal profiles of u-component at 200 mb along about 140°E. (a) is typical for summer, (b) for August only. Dashed lines indicate cases with few typhoons, full lines with many typhoons.

Fig. 23 Location of the centers of polar vortex at 500 mb for 15 months with many (black circles) and 15 months with few typhoons (triangles).

Fig. 24 Monthly height departures at 500 mb for summer, (a) for many, (b) for few typhoons. Negative departures are denoted by dashed lines. Units: geopotential decameter.

Fig. 25 Similar to Fig. 24, but for July.

Fig. 26 Similar to Fig. 24, but for August.

a

b

Fig. 27 Similar to Fig. 24, but for September.

Fig. 28 Mean charts at 500 mb for summer, (a) for many typhoons, (b) for few typhoons.

Fig. 29 Similar to Fig. 28, but for July.

Fig. 30 Similar to Fig. 28, but for August.

Fig. 31 Similar to Fig. 28, but for September.

Fig. 32 The long-term trend of monthly mean departures of the ridge line position (in degrees of latitude) of the subtropical high over the West Pacific (dashed line).

Fig. 33 The northward push and southward withdrawal of subtropical high over the West Pacific as the season progresses for two years with many typhoons.

Fig. 34 Similar to Fig. 33, but for two years with few typhoons.

Fig. 35 The mean surface pressure fields for summers (a) with many typhoons, (b) with few typhoons.

Fig. 36 Similar to Fig. 35, but for July.

Fig. 37 Similar to Fig. 35, but for August.

Fig. 38 Similar to Fig. 35, but for September.

Fig. 39 The long-term variability in the zonally averaged Δ SST at 20° - 30° N (dashed lines), 30° - 40° N (dashed-dotted line) latitude belts of the North Pacific and anomalies of typhoon frequency (full line) in the West Pacific.

Fig. 40 The long-term variability in Δ SST over the Kuroshio warm current (dashed line), and West Pacific typhoon frequency (full line).

Fig. 41 Similar to Fig. 39, but for the West Pacific (west of date line).

Fig. 42 The horizontal distributions of SST anomalies over the North Pacific. Positive anomalies are denoted by full lines and negative anomalies by dashed lines; (a) summers with many typhoons, (b) summers with few typhoons. Unit: $^{\circ}\text{C}$.

Fig. 43 Similar to Fig. 42, but for three years with many typhoons (1966, 1967, 1972) and three years with few typhoons (1969, 1973, 1975).

Fig. 44 Similar to Fig. 43, but for the antecedent season (spring).

Fig. 45 The pattern of SST anomalies for the summer of 1964.