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STORM SURGE STATISTICS

BY

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Introduction

Descriptions of Storm Surges in Hong Kong caused by tropical cyclones are contained in Royal Observatory Technical Memoir No. 8 and in Royal Observatory Technical Note No. 26. No further description is therefore included in this note.

ROTN No. 26 analyses surges and meteorological data but is not concerned with water level which is an engineering problem. However, in recent years, numerous consultants' reports have been printed assuming that the normal tide will be high for every storm surge or ignoring the problem altogether. The Observatory has usually been expected to comment on a time scale that gave no opportunity for making precise calculations. From a practical viewpoint, the effect of a storm surge depends very much on the state of the normal astronomical tide at the time that the surge occurs. The purpose of this note is to present updated statistics and additional data on storm surges and also to use a statistical method to determine the probabilities of co-incidence of storm surges and astronomical tides and hence, estimate the return periods of flooding at different levels. It is intended that a more precise dynamical method will follow in due course.

Tidal Data Available

Tidal measurements are made by the Port Works Division of the Public Works Department.

Early observations were made by observing tide poles but a recording tide gauge was installed in Arsenal Yard in January 1950 and moved to North Point Pier in October 1952. Others were installed in Chi Ma Wan in 1961, Tai Po Kau in 1963 and Tsim Bei Tsui in 1974.

For the sake of completeness Table III contains data on all tropical cyclones for which any tide reports are available but only the data between 1954 - 1973 for Tolo Harbour and between 1950 - 1974 for Hong Kong Harbour has been used in the computations.

On the Cause of Storm Surges

Isozaki (3) states that storm surges are caused by two factors; the sea-level rise in response to atmospheric pressure fall and also to the effects of wind. It is quoted that the pressure effect is greater over the open ocean and the wind effect is greater in bays and inlets less than about 120 metres deep.

The dome of water under a low pressure area has its own natural speed of propagation as a gravity wave. In deep water this speed is higher than the speed of movement of most typhoons but in shallow water fast moving typhoons may cause amplification due to resonance effects.

Wind effects are even more complicated. In the open sea, due to the Coriolis force, surface water tends to move somewhat to the right of downwind. Winds spiral into a typhoon anticlockwise so that the Coriolis force causes the surface water to move away from the centre resulting in up-welling near the centre. On a smaller scale in shallow bays and inlets water piles up at the downwind end. Again it is possible for resonance effects to develop if, as a storm passes, winds reverse their direction after an interval comparable with the natural period of oscillation of the bay.

The effect of waves is also important. In deep water waves consist mainly of a rotation, the surface water moves foreward but this is compensated by the water underneath moving backwards. In shallow water the return flow underneath is reduced or cut off and the waves cause a massive transport of water downwind. Hurricane force northeasterly winds blowing down the shallow Tolo Channel must be held largely responsible for the destructive surges in Tolo Harbour.

The track of the typhoon is also a significant factor. Fig. 1 shows that the five typhoons that caused the biggest surges in Hong Kong all followed very similar tracks, passing very close to the northwestern tip of Luzon Island. Fig. 2 shows the tracks of the ten typhoons which caused the largest surges at North Point without coming within 100 miles of Hong Kong. Most of these typhoons were above average in size but their tracks are surprisingly dissimilar. The only thing that they appear to have in common is that they passed somewhere near the northwestern tip of Luzon. Two of them: T. Freda in 1975 and T. Bess in 1974 produced surges of more than 1 metre at North Point.

When a large typhoon is centred near the northwestern tip of Luzon (see Figs. 3 and 4) there are usually very strong easterly winds in the Luzon straits, northeasterlies in the Taiwan Straits and sometimes southwesterlies over the southern part of the South China Sea. All these winds could help to propagate the storm surge into the northern part of the South China Sea. The Luzon Straits are mostly more than 1 km deep but the Taiwan Straits shelve to about 50 metres so that large scale wind stress there may be a significant factor. Six out of these ten typhoons occurred in October when the northeasterlies in the Taiwan Straits were reinforced by the winter monsoon.

The Statistical Method

The relative importance of the various factors can only be determined by a full scale dynamical study. This paper is intended as an interim study to make better statistical use of the available data.

It is possible to estimate the return periods of various water levels by plotting the annual maximum water levels directly onto extreme probability paper. However, when this is done (see Table I), surge data from many typhoons that arrived at times of low tide are hidden and make little or no contribution to the results. This means that insufficient data is used for much confidence to be placed in the results.

A better method is to extract all the surge levels (the amounts by which the actual levels exceed the predicted values) and obtain their return periods. In this way, data from all the most intense tropical cyclones can be used. The effect of all possible astronomical tides on the return periods can then be computed (4).

A computer analysis of the 1975 tide tables was made listing the predicted heights at every hour. By counting the hours at each level and dividing by the total number of hours Table II was obtained. This shows the percentage of time during which the sea level should normally be above each level.* Table II is based on the three months, July, August and September, 1975 as these are typically the months with the highest occurrence of tropical cyclones. However, it should be borne in mind that in October and November, although typhoons are usually less frequent, predicted water levels are about 0.2 m higher than during the months used for this study.

Only those storm surges available for consecutive years in Table III were used in order to apply Gumbels method (2). The highest surge in each year was extracted and the results arranged in order. These data were then processed on the Observatory's computer and the following regression lines were obtained relating the surge heights H to the reduced variates ZZ:

Tolo Harbour	H = 115.61 + 70.56 ZZ	centimetres
Victoria Harbour	H = 73.43 + 35.81 ZZ	centimetres

From Gumbel's tables, the reduced variates were converted to probabilities PP shown in Table IV. These probabilities are the probabilities of surges above the specified levels. In order to obtain the probabilities of a surge occuring in a particular (1 decimetre) height range, each PP was substracted from its successor to produce the column ∇ PP also in Table IV.

The probability of coincidence of two events is the product of their separate probabilities. Tables II and IV were therefore combined to produce tables like Table V. Table V shows the various combinations of surge and astronomical tide, with their probabilities, that can combine to produce a water level of 4 metres in Tolo Harbour and Victoria Harbour.

*All heights refer to Chart Level (C.D.) as used in the Tide Tables and not to Principal Datum (PD) which is 0.15 m higher.

Results

By adding the probabilities of all the combinations one arrives at the probability of a 4 metre water level. Since one is only considering one event per year the reciprocal of the probability is the return period in years.

Seven tables similar to Table V were computed for other levels but they are not reproduced here. Only the end results of this analysis are given in Table VI.

The results found in Tables VI use more data than the results in Table I because each storm surge is combined with all possible states of the astronomical tide. However, only the worst storm surge each year is considered. This probably leads to an underestimate of the frequency of small surges (waterlevels of 3 or 3.5 m) which may be caused by monsoon winds or other phenomena. At these levels, it is possible that Table I may be more accurate.

Verification

The main purpose of this note was to demonstrate a statistical method of combining storm surges with astronomical tides. The approximate agreement between Tables I and VI suggests that the method works quite well on the data used. However, these data cover a relatively short period and are not intended to substitute for a full dynamical treatment which will model a wide variety of storms. However, it is encouraging that using Table VI the 5 metre water level in Tolo Harbour due to Typhoon 'Wanda' should have a return period of about 30 years, whereas in fact there were similar surges in 1874, 1906 and 1937. Unfortunately the data for North Point do not fit nearly so well, as the 1937 typhoon would have a return period of about 100 years.

LIMITATIONS OF THE METHOD

There are still many uncertainties. It has been tacitly assumed that storm surges and astronomical tides are independent. However, a surge from a particular size of typhoon should be smaller at high tide than at low tide. This is partly because the surface area is greater at high tide and more water is needed to produce the same rise in level (i.e. the same surge) and partly because wind and waves are more efficient at transporting volumes of water when the depth is low.

No account has been taken of the surge profile. This does not matter if the peak of the surge only lasts for a short time and the profile is similar to that of the normal tide. However, if the surge stays near its peak for a long time and does not fall as fast as the astronomical tide rises then the highest water level will not coincide with the highest point of the surge.

There are many other factors that could be taken into account including rainfall and runoff and differences both in timing and amplitude of astronomical tides in different parts of Hong Kong. It is of interest that the tides at the new station at Tsim Bei Tsui seem to lag behind the tides at other stations in Hong Kong by one or two hours, while the amplitude of some recent surges there has been greater than at North Point.

Another complication is that Plover Cove Reservoir was built in 1965-66 and this may have caused a discontinuity in the tidal data for Tolo Harbour. A similar discontinuity may have arisen from the effects of the reclamation of Kowloon Bay.

Finally on a smaller scale, no allowance has been made for the slope of the water surface inside Victoria Harbour caused by wind stress. Since the tidegauge is not in the middle of the Harbour some readings may not be representative. Watts(5) showed that differences between Kowloon Docks and Hong Kong were very small in the 1937 typhoon but reached about 0.3 m in typhoon Gloria in 1957. Similar considerations apply to Tolo Harbour. The full dynamical treatment should resolve this problem.

I am grateful to Mr. H.C. Leong and Mr. W.P. Kwong for assistance in preparing the tables.

References

1) Storm Surges in Hong Kong by T.T. Cheng ROTN 26. 1967

2) Statistical Theory of Extreme Values and Some Practical Applications Emil J. Gumbel 1954

3) Storm Surges on the Coast of Kanto & Tokai Districts. Papers in Met & Geophysics April 1970. Ichiro Isozaki 1970

4) Storm Tide Frequences on the South Carolina Coast.NOAA Tech Report NWS 16 Vance A Myers 1975

5) The effect of Meteorological Conditions on Tide Height at Hong Kong,by IEM Watts ROTM 8 1959

Table I Return Periods of Water Levels in Hong Kong using Gumbel's Method directly on the highest annual water levels.

Location	Tolo Harbour (1954-1973)	North Point (1950-1974)
Water Level	Return Period	Return Period
3.0 m		3 years
3.5 m		91 years
4.0 m	7 years	323 years
5.0 m	33 years	
6.0 m	180 years	
7.0 m	800 years	

Table II **Predicted Water Levels - Occurrence and Probabilities**

Range **Metres**	Number of Hours of Occurrence July, August, Sept. 1975	Probability	Probability that Water is above the Predicted Level
0.00- 0.09	0	0.0000	1.0000
0.10- 0.19	2	0.0009	1.0000
0.20- 0.29	7	0.0032	0.9991
0.30- 0.39	15	0.0068	0.9959
0.40- 0.49	30	0.0136	0.9891
0.50- 0.59	28	0.0127	0.9755
0.60- 0.69	48	0.0217	0.9628
0.70- 0.79	51	0.0231	0.9411
0.80- 0.89	92	0.0417	0.9180
0.90- 0.99	137	0.0620	0.8763
1.00- 1.09	184	0.0833	0.8143
1.10- 1.19	236	0.1069	0.7310
1.20- 1.29	197	0.0892	0.6241
1.30- 1.39	180	0.0815	0.5349 ← MSL
1.40- 1.49	165	0.0747	0.4534
1.50- 1.59	151	0.0684	0.3787
1.60- 1.69	124	0.0562	0.3103
1.70- 1.79	116	0.0525	0.2541
1.80- 1.89	109	0.0494	0.2016
1.90- 1.99	106	0.0480	0.1522
2.00- 2.09	91	0.0412	0.1042
2.10- 2.19	69	0.0313	0.0630
2.20- 2.29	42	0.0190	0.0317
2.30- 2.39	23	0.0104	0.0127
2.40- 2.49	5	0.0023	0.0023
2.50- 2.59	0	0.0000	0.0000

TABLE III LIST OF TYPHOONS FOR WHICH SOME TIDAL INFORMATION IS AVAILABLE

YEAR	MONTH	TROPICAL CYCLONE	R.O. OBSERVATION				MAX STORM SURGE (m)			MAX SEA LEVEL (m)			NEAREST APPROACH TO HONG KONG						
			MIN M.S.L. PRESSURE (mbar)	MAX WIND (kn) GUST	MAX WIND (kn) 10-MIN	MAX WIND (kn) 60-MIN	NORTH POINT	TAI PO	CHI MA WAN	NORTH POINT	TAI PO	CHI MA WAN	DAY	TIME (GMT)	DIR. (°)	DIST. (n. mile)	CENTRAL M.S.L. PRESSURE (mbar)	MOVEMENT DIR. (°)	MOVEMENT SPEED (kn)
1906	SEP		986.2			49	1.83	6.10		3.35			17	2300	180	5	985	270	9
1923	AUG		970.0	113*		67	1.68	4.57		3.20			17	2200	360	5	970	270	16
1929	AUG		980.9	102		57	0.85			2.38			22	0600	200	25	980	290	8
1936	AUG		979.4	115	69	63	1.92	4.27		3.81			16	1900	200	50	964*	290	16
1937	SEP		958.3	130*	74	59	1.98	3.81		4.05	6.25		01	1900	206	7	949*	296	15
1949	SEP		990.8	81	61	56	1.49			2.90			07	1900	170	37	988	260	8
1951	JUN		1001.6	63	39	36	0.52			2.74			19	0300	205	200		295	8
	AUG		990.1	76	46	44	0.73			2.44			01	1300	216	82	986	306	8
	SEP		1002.4	59	37	36	0.52			2.44			21	0300	240	100		330	8
1953	SEP	SUSAN	994.7	75	44	42	0.64			2.44			18	0900	201	32	992	291	6
1954	AUG	IDA	992.4	87	50	48	1.68			3.20			29	0700	198	76	988	288	16
	OCT	NANCY	1012.7	33	21	18	0.61			2.77			09	1700	177	246		267	7
	NOV	PAMELA	997.1	84	53	50	1.16			2.83			06	0600	205	30	995	295	14
	NOV	RUBY*	1001.8	47	28	25	0.67			3.11			11	0900	080	50	998	350	6
1955	JUN	BILLIE	1005.0	48	31	27	0.61			2.62			04	2000	200	95	1000	290	7
	SEP	KATE	1007.5	61	37	33	0.70			2.74			24	1400	186	266		276	16
1956	JUL	VERA	1005.5	46	29	26	0.46			2.77			07	0900	180	260	990	270	18
	AUG	CHARLOTTE	1003.5	45	30	27	0.73			2.44			29	1900	170	286	990	260	13
	OCT	JEAN	1008.3	41	25	23	0.64			2.83			23	1500	177	156	995	267	1
1957	JUL		999.0	45	28	26	0.49			2.32			02	2100	173	242	980	263	7
	JUL	WENDY	987.7	71	38	32	0.76			2.22			16	1800	020	30	985	290	10
	SEP	GLORIA	984.3	101	64	62	1.34			3.08			22	0800	208	30	970*	298	8
	OCT		1004.2	53	31	30	0.46			2.41			15	0300	250	80	1000	340	11
1958	MAY		1001.9	59	36	34	0.67			2.44			31	0000	227	115		317	3
	AUG		1004.0	62	34	29	0.49			2.01			07	0300	197	82	990	287	4
	AUG		1003.9	36	20	17	0.34			2.29			26	1500	180	156		270	6
1959	JUL	WILDA*	995.7				0.37			2.22			06	0000	086	84	990	356	13
	SEP	NORA*	996.2	47	27	25	0.24			2.22			10	1200	110	51	992	020	6
1960	JUN	MARY	973.8	103	54	52	1.10			2.77			08	2100	285	5	966*	015	12
	JUN	OLIVE	997.0	66	35	32	0.60			2.44			29	0200	185	127	980	275	13
	OCT	KIT	1005.0	51	27	25	0.70			2.71			10	2100	211	197	985	301	6
1961	MAY	ALICE	981.1	89	47	45	0.55			2.59			19	0400	0	0	980*	010	12
	JUL	ELSIE*	995.4	42	20	14	0.30			2.29			15	0300	040	110	990	310	9
	SEP	OLGA*	986.1	64	36	35	0.58			2.53			09	1700	045	30	982	315	7
	SEP	SALLY	993.4	50	29	27	0.43			2.35			29	0400	341	19	993*	251	14
1962	SEP	WANDA	953.2	140	78	72	1.77**	3.20		3.96	5.03		01	0300	235	10	944*	325	12

TABLE III (Cont'd)

			R.O. OBSERVATION				MAX STORM SURGE (m)			MAX SEA LEVEL (m)			NEAREST APPROACH TO HONG KONG						
				MAX WIND (kn)														MOVEMENT	
YEAR	MONTH	TROPICAL CYCLONE	MIN M.S.L. PRESSURE (mbar)	GUST	10-MIN	60-MIN	NORTH POINT	TAI PO	CHI MA WAN	NORTH POINT	TAI PO	CHI MA WAN	DAY	TIME (GMT)	DIR. (°)	DIST. (n. mile)	CENTRAL M.S.L. PRESSURE (mbar)	DIR. (°)	SPEED (kn)
1963	JUL	AGNES	1002.1	50	25	24	0.55	0.67	0.58	2.83	2.83	2.93	21	2000	200	103	998	290	10
	AUG	CARMEN	1001.4	56	27	26	0.21	0.58	0.30	2.44	2.65	2.47	15	0900	180	222	985	270	12
	SEP	FAYE	996.5	70	29	27	0.85	0.98	0.76	2.83	2.77	2.77	16	0900	168	122	990	258	10
1964	MAY	VIOLA	991.9	82	38	36	0.94	1.40		2.90	3.20		28	0000	245	55	998	335	8
	JUL	WINNIE	997.1	70	29	28	0.61	0.85	0.73	2.38	2.59	2.59	01	1500	212	261	960	302	9
	AUG	IDA	972.0	112	47	45	1.31	2.16	1.43	2.86	3.63	2.96	08	1500	211	32	965*	301	16
	SEP	RUBY	968.2	122	60	59	1.49	2.96	2.32	3.14	3.54	3.20	05	0500	213	17	954*	303	11
	SEP	SALLY'	989.1	56	37	35	0.55	1.04	0.49	2.41	3.02	2.44	10	1300	031	32	985	301	14
	OCT	DOT'	977.3	94	51	48	0.58	1.43	0.82	2.65	3.23	2.95	12	2200	090	18	973*	360	10
1965	JUL	FREDA	995.8	61	28	27	1.01	1.01	1.01	2.99	2.90	2.86	14	1500	190	134	988	280	15
	SEP	ROSE	1000.1	46	21	20	0.21	0.27		2.41	2.19		04	1600	201	129	996	291	10
	SEP	AGNES	1004.7	52	26	24	0.30	0.70	0.61	2.32	2.59	2.44	27	0500	230	135	996	320	9
	NOV	ELAINE	1010.0	46	16	13	0.46	0.67	0.94	2.90	3.05	3.08	12	2100	240	185	1000	330	5
1966	MAY	JUDY	1002.5	29	14	13	0.34		0.55	2.07		2.22	28	2200	129	171	998	039	7
	JUL	LOLA	989.5	82	40	35	0.55	1.09	0.79	1.95	2.22	2.10	13	1400	255	13	987*	345	9
	JUL	MAMIE	1003.5	48	21	20	0.37	0.46	0.52	2.38	2.44	2.65	17	0800	185	55	995	275	17
	JUL	ORA	1000.1	49	21	18	0.34	0.58	0.58	2.07	1.95	2.22	25	1800	235	220	988	325	10
1967	AUG	IRIS	999.9	57	25	24	0.43		0.94	2.53		2.65	15	1100	189	109	995	279	7
	AUG	KATE	989.6	80	34	33	0.71	1.11	1.22	2.77	2.83	2.91	21	0900	243	50	985	333	9
	NOV	EMMA	1008.9	51	24	23	0.52	0.73		2.83	2.99		07	1200	216	172	1000	306	7
1968	JUL	NADINE	991.8	34	15	14	0.69	0.79	0.76	2.77	2.77	2.90	26	1900	102	165	985	012	5
	AUG	ROSE	1001.9	42	18	17	0.30		0.46	2.38		2.56	11	1500	190	238	995	280	12
	AUG	SHIRLEY	968.6	72	40	37	1.09	1.78	1.65	2.79	2.85	2.90	21	1100	0	0	966*	360	10
	SEP	BESS	1002.5	50	20	21	0.46	0.55	0.58	2.56	2.62	2.71	01	1400	169	159	995	259	3
	SEP	WENDY	999.5	44	20	19	0.40	0.67	0.55	2.59	2.56	2.71	08	1600	196	87	983	286	13
	SEP	ELAINE'	1003.5	39	17	16	0.76		0.82	2.77		2.80	01	0600	68	129	995	338	7
1969	JUL	VIOLA'	981.9	67	35	28	0.70	0.98	0.82	3.11	3.26	3.14	26	1200	06	54	975	276	10
	SEP	ELSIE'	996.4	25	11	10	0.15	0.46	0.30	2.26	2.32	2.41	27	1800	33	200	980	303	13
1970	JUL	RUBY'	993.6	69	29	28	0.30	0.32	0.40	2.36	2.30	2.50	16	0200	90	40	990	360	10
	AUG	T.D.'	994.7	64	24	22	0.20	0.44	0.37	2.26	2.41	2.42	02	2130	360	50	990	270	12
	AUG	VIOLET	1002.6	48	21	20	0.12	0.30	0.30	1.86	1.86	2.04	08	2100	204	59	998	294	14
	SEP	GEORGIA'	995.0	56	25	23	0.58	1.11		2.61	2.89		13	2200	95	66	990	005	9
	OCT	IRIS	1007.4	35	15	14	0.21	0.34	0.52	2.41	2.41	2.53	07	0800	155	99	1000	065	5
	OCT	JOAN	1002.7	55	25	23	0.58	0.82	0.67	2.62	2.83	2.74	16	1800	223	246	980	313	5
1971	JUN	FREDA	984.3	79	38	35	0.85	1.37	1.01	2.35	2.61	2.50	17	1640	230	22	984	320	9
	JUN	IDLA	1004.1	46	18	17	0.34	0.82	0.55	2.29	2.19	2.47	27	1200	225	260	990	315	12
	JUL	HARRIET	1005.9	31	14	13	0.21	0.21	0.37	2.32	2.32	2.50	05	0700	197	400	970	287	14
	JUL	LUCY'	977.9	68	35	34	0.97	1.40		2.91	2.82		22	0340	15	25	977*	285	14
	JUL	NADINE'	992.0	50	23	21	0.21	0.34		2.16	2.22		26	1500	45	240	975	315	11
	AUG	ROSE	982.8	121	58	55	0.64	0.98	1.23	2.56	3.00	2.98	16	1730	270	13	982	360	8
	SEP	DELLA	1008.1	49	22	20	0.45	0.48	0.61	2.49	2.46	2.71	28	1500	190	195	990	280	12
	OCT	ELAINE	1005.6	34	17	14	0.78	0.89	1.01	3.21	3.35	3.35	07	1600	185	300	985	275	12

TABLE III (Cont'd)

YEAR	MONTH	TROPICAL CYCLONE	R.O. OBSERVATION				MAX STORM SURGE (m)			MAX SEA LEVEL (m)			NEAREST APPROACH TO HONG KONG						
			MIN M.S.L. PRESSURE (mbar)	MAX WIND (kn)			NORTH POINT	TAI PO	CHI MA WAN	NORTH POINT	TAI PO	CHI MA WAN	DAY	TIME (GMT)	DIR. (°)	DIST. (n. mile)	CENTRAL M.S.L. PRESSURE (mbar)	MOVEMENT	
				GUST	10-MIN	60-MIN												DIR. (°)	SPEED (kn)
1972	JUN	T.D.	999.7	40	18	16	0.34	0.76		2.38	2.53		10	2100	145	120	992	055	8
	JUN	ORA	1003.0	42	18	15	0.27	0.49		2.38	2.38		26	1500	220	210	990	315	15
	JUL	SUSAN	990.2	37	15	13	0.40			2.65			13	0600	95	80	986	185	7
	NOV	PAMELA	1007.5	59	27	26	0.56	1.30		2.88	3.06		08	2000	310	120	998	040	17
1973	JUL	WILDA	1002.0	22	11	08	0.43	1.04	0.91	2.65	2.59	3.17	02	1200	100	200	990	010	7
	JUL	ANITA	1004.4	52	21	18	0.34	0.46	0.82	1.83	1.86	2.32	07	2000	225	420	975	315	10
	JUL	DOT	978.0	77	38	35	0.67	1.31	1.22	2.62	2.74	3.08	16	2100	90	12	976*	360	10
	AUG	GEORGIA	1002.8	51	23	19	0.43	0.88		2.50	2.71		12	0900	250	195	990	340	8
	AUG	JOAN	998.4	50	22	20	0.49	0.70		2.41	2.47		20	2200	180	60	995	270	15
	AUG	KATE	1001.1	47	20	18	0.37	0.64		2.53	2.62		22	1800	160	180	986	250	15
	SEP	LOUISE	1006.9	43	18	17	0.12	0.18	0.79	2.10	2.13	2.74	05	1100	180	150	990	270	9
	SEP	MARGE	1007.6	33	14	10	0.21	0.27		2.10	2.22		13	0200	185	210	992	275	12
	OCT	NORA	1002.3	38	16	14	0.67	0.88	0.70	2.50	2.59	2.59	10	0800	50	265	990	320	10
	OCT	RUTH	1010.5	35	16	15	0.55	0.70	0.64	2.77	2.93	2.90	19	1500	270	320	990	360	12
1974	JUN	T.D.	1003.3	43	19	16	0.42	0.60	0.70	2.46	2.50	2.70	07	1800	240	125	998	330	7
	JUN	DINAH	996.2	64	25	22	0.66	1.10	0.90	2.36	2.50	2.60	12	1400	205	240	980	295	11
	JUL	IVY	1002.7	61	26	23	0.56	0.70	1.00	2.66	2.60	3.10	22	0700	230	130	994	320	10
	SEP	TRIX	1001.3	46	18	16	0.39	0.40	0.60	2.18	2.20	2.40	05	1800	200	100	995	290	8
	SEP	WENDY	1005.2	20	6	6	0.25			2.16			26	1800	105	350	980	015	6
	OCT	BESS	1001.8	50	20	18	1.23	1.45	1.48	3.32	3.43	3.56	12	2300	180	190	990	270	15
	OCT	CARMEN	994.1	70	29	25	0.82	1.09	1.00	2.87	3.17	3.06	19	0000	200	70	990	290	7
	OCT	DELLA	1010.1	40	15	12	0.41	0.59	0.66	2.19	2.31	2.34	25	1300	200	240	992	290	10
	OCT	ELAINE	1000.0	52	20	17	0.73	1.02	0.87	2.82	2.97	2.97	30	0110	180	80	994	270	6
	NOV	GLORIA	1001.7	27	10	8	0.34	0.63	0.54	2.34	2.48	2.51	09	1500	105	105	995	195	4
	DEC	IRMA	1004.8	38	18	18	0.25	0.65	0.40	2.50	2.49	2.73	02	0900	325	30	1000	055	11
1975	JUN	T.D.	1003.7	33	15	14	0.44	0.53	0.47	2.03	2.09	2.15	16	1300	215	180	998	305	8
	AUG	T.D.	990.2	45	20	19	0.32	1.00	0.67	2.40	2.64	2.50	13	1800	0	0	990	350	8
	SEP	ALICE	1006.1	41	23	16	0.23	0.47	0.57	2.14	2.19	2.40	19	0300	205	270	995	295	14
	SEP	BETTY	1000.0	36	15	14	0.19	0.39		2.28	2.20		24	0200	05	95	995	275	9
	OCT	DORIS	1001.8	52	27	20	0.37			2.30			06	0000	290	85	997	020	15
	OCT	ELSIE	996.2	76	32	31	0.64	1.23		2.30	2.35		14	0530	180	27	994	270	11
	OCT	FLOSSIE	1003.0	67	28	26	0.67			2.90			23	0100	235	140	995	325	13

* Estimated

\+ Tropical cyclone landed east of Hong Kong

** Data from C.M. Guilford's unpublished report

Maximum readings of the year are underlined.

Data in years prior to 1954 were obtained from Ref. 1.

Table IV Probabilities of Surge Heights

Location	Tolo Harbour			North Point		
Surge Height H (m)	ZZ	PP	∇ PP	ZZ	PP	∇ PP
0.5				−0.6544	0.85	0.08
0.6				−0.3751	0.77	0.10
0.7				−0.0958	0.67	0.11
0.8				0.1835	0.56	0.09
0.9				0.4627	0.47	0.09
1.0	−0.2213	0.71	0.05	0.7420	0.38	0.08
1.1	−0.0796	0.66	0.05	1.0213	0.30	0.06
1.2	0.0622	0.61	0.05	1.3005	0.24	0.05
1.3	0.2039	0.56	0.05	1.5798	0.19	0.05
1.4	0.3456	0.51	0.05	1.8591	0.14	0.03
1.5	0.4873	0.46	0.05	2.1384	0.11	0.025
1.6	0.6290	0.41	0.04	2.4176	0.085	0.020
1.7	0.7708	0.37	0.04	2.6969	0.065	0.015
1.8	0.9125	0.33	0.04	2.9761	0.050	0.012
1.9	1.0542	0.29	0.03	3.2554	0.038	0.010
2.0	1.1959	0.26	0.03	3.5347	0.028	0.006
2.1	1.3376	0.23	0.03	3.8140	0.022	0.005
2.2	1.4794	0.20	0.02	4.0932	0.017	0.004
2.3	1.6211	0.18	0.02	4.3725	0.013	0.0035
2.4	1.7628	0.16	0.02	4.6518	0.0095	0.0023
2.5	1.9045	0.14	0.02	4.9310	0.0072	0.0018
2.6	2.0462	0.12	0.015	5.2103	0.0054	0.0013
2.7	2.1880	0.105	0.013	5.4896	0.0041	0.0009
2.8	2.3297	0.092	0.012	5.7688	0.0032	0.0007
2.9	2.4714	0.080	0.010	6.0481	0.0025	0.0006
3.0	2.6131	0.070	0.010	6.3274	0.0019	0.0005
3.1	2.7548	0.060	0.007	6.6066	0.0014	0.0004
3.2	2.8966	0.053	0.007	6.8859	0.0010	0.00025
3.3	3.0383	0.046	0.006	7.652	0.00075	0.00017

Table IV Probabilities of Surge Heights (Cont'd)

Location	Tolo Harbour			North Point		
Surge Height H (m)	ZZ	PP	∇ PP	ZZ	PP	∇ PP
3.4	3.1800	0.040		7.4445	0.00058	
3.5	3.3217	0.035	0.005	7.7237	0.00044	0.00014
3.6	3.4634	0.031	0.004	8.0030	0.00034	0.00010
3.7	3.6052	0.027	0.004	8.2823	0.00026	0.00008
3.8	3.7469	0.023	0.004	8.5615	0.00020	0.00006
3.9	3.8886	0.020	0.003	8.8408	0.00015	0.00005
4.0	4.0303	0.017	0.003	9.1201	0.00011	0.00004
4.1	4.1720	0.015	0.002	9.3993	0.00008	0.00003
4.2	4.3138	0.013	0.002	9.6786	0.00006	0.00002
4.3	4.4555	0.011	0.002	9.9579	0.00004	0.00002
4.4	4.5972	0.010	0.001	10.2371	0.00003	0.00001
4.5	4.7389	0.009	0.001	10.5164	0.00002	0.00001
4.6	4.8806	0.008	0.001	10.7957	0.000015	0.000005
4.7	5.0224	0.007	0.001	11.0750	0.000012	0.000003
4.8	5.1641	0.006	0.001	11.3542	0.000010	0.000002
4.9	5.3058	0.005	0.001	11.6335	0.000008	0.000002
5.0	5.4475	0.0043	0.0007	11.9128	0.000007	0.000001
5.1	5.5892	0.0038	0.0005			
5.2	5.7310	0.0033	0.0005			
5.3	5.8727	0.0029	0.0004			
5.4	6.0144	0.0025	0.0004			
5.5	6.1561	0.0021	0.0004			
5.6	6.2978	0.0018	0.0003			
5.7	6.4396	0.0015	0.0003			
5.8	6.5813	0.0013	0.0002			
5.9	6.7230	0.0011	0.0002			
6.0	6.8647	0.0010	0.0001			
6.1	7.0064	0.0009	0.0001			
6.2	7.1482	0.0008	0.0001			
6.3	7.2899	0.0007	0.0001			
6.4	7.4316	0.0006	0.0001			
6.5	7.5733	0.0005	0.0001			

Table V Various Combinations of Surge and Astronomical Tide, with Their Probabilities That Can Be Combined to Produce a Water Level of 4 Metres in Tolo Harbour and at North Point

Location		Tolo Harbour			North Point		
Surge (A) Height	Normal Tide(B)	Prob. of (A)	Prob. of (B)	Combined Prob.	Prob. of (A)	Prob. of (B)	Combined Prob.
(m)	(m)						
4.0	any tide	0.017	1.0000	0.0170	0.00011	1.0000	0.00011
3.9 - 4.0	tide > 0.1	0.003	1.0000	0.0030	0.00004	1.0000	0.00004
3.8 - 3.9	> 0.2	0.003	0.9991	0.0030	0.00005	0.9991	0.00005
3.7 - 3.8	> 0.3	0.004	0.9959	0.0040	0.00006	0.9959	0.00006
3.6 - 3.7	> 0.4	0.004	0.9891	0.0040	0.00008	0.9891	0.00008
3.5 - 3.6	> 0.5	0.004	0.9755	0.0039	0.00010	0.9755	0.00010
3.4 - 3.5	> 0.6	0.005	0.9628	0.0048	0.00014	0.9628	0.00013
3.3 - 3.4	> 0.7	0.006	0.9411	0.0056	0.00017	0.9411	0.00016
3.2 - 3.3	> 0.8	0.007	0.9180	0.0064	0.00025	0.9180	0.00023
3.1 - 3.2	> 0.9	0.007	0.8763	0.0061	0.0004	0.8763	0.00035
3.0 - 3.1	>1.0	0.010	0.8143	0.0081	0.0005	0.8143	0.00041
2.9 - 3.0	>1.1	0.010	0.7310	0.0073	0.0006	0.7310	0.00044
2.8 - 2.9	>1.2	0.012	0.6241	0.0075	0.0007	0.6241	0.00044
2.7 - 2.8	>1.3	0.013	0.5349	0.0070	0.0009	0.5349	0.00048
2.6 - 2.7	>1.4	0.015	0.4534	0.0068	0.0013	0.4534	0.00059
2.5 - 2.6	>1.5	0.02	0.3787	0.0075	0.0018	0.3787	0.00068
2.4 - 2.5	>1.6	0.02	0.3103	0.0062	0.0023	0.3103	0.00071
2.3 - 2.4	>1.7	0.02	0.2541	0.0051	0.0035	0.2541	0.00089
2.2 - 2.3	>1.8	0.02	0.2016	0.0040	0.004	0.2016	0.00081
2.1 - 2.2	>1.9	0.03	0.1522	0.0046	0.005	0.1522	0.00076
2.0 - 2.1	> 2.0	0.03	0.1042	0.0031	0.006	0.1042	0.00063
1.9 - 2.0	>2.1	0.03	0.0630	0.0019	0.010	0.0630	0.00063
1.8 - 1.9	>2.2	0.04	0.0317	0.0013	0.012	0.0317	0.00038
1.7 - 1.8	>2.3	0.04	0.0127	0.0005	0.015	0.0127	0.00019
1.6 - 1.7	>2.4	0.04	0.0023	0.0001	0.020	0.0023	0.00005
1.5 - 1.6	>2.5	0.05	0.0000	0.0000	0.025	0.0000	0.00000
TOTAL PROBABILITY				0.1288			0.00940
RETURN PERIOD				7.8 years			106 years

Table VI (a) Return Periods for Different Water Levels above Chart Datum Using the Method Described in the Text

Location	Tolo Harbour	North Point
Water Level (m)	Return Period	Return Period
3.0		8 years
3.5		28
4.0	8 years	106
4.5	15	423
5.0	30	1700
5.5	56	
6.0	120	
6.5	230	

(b) Water Levels Having Specified Return Periods - Metres above Chart Datum

Return Period	Tolo Harbour	North Point
20 years	4.7 metres	3.37 metres
50 years	5.39 "	3.7 "
100 years	5.9 "	3.97 "
150 years	6.2 "	4.12 "
200 years	6.4 "	4.22 "

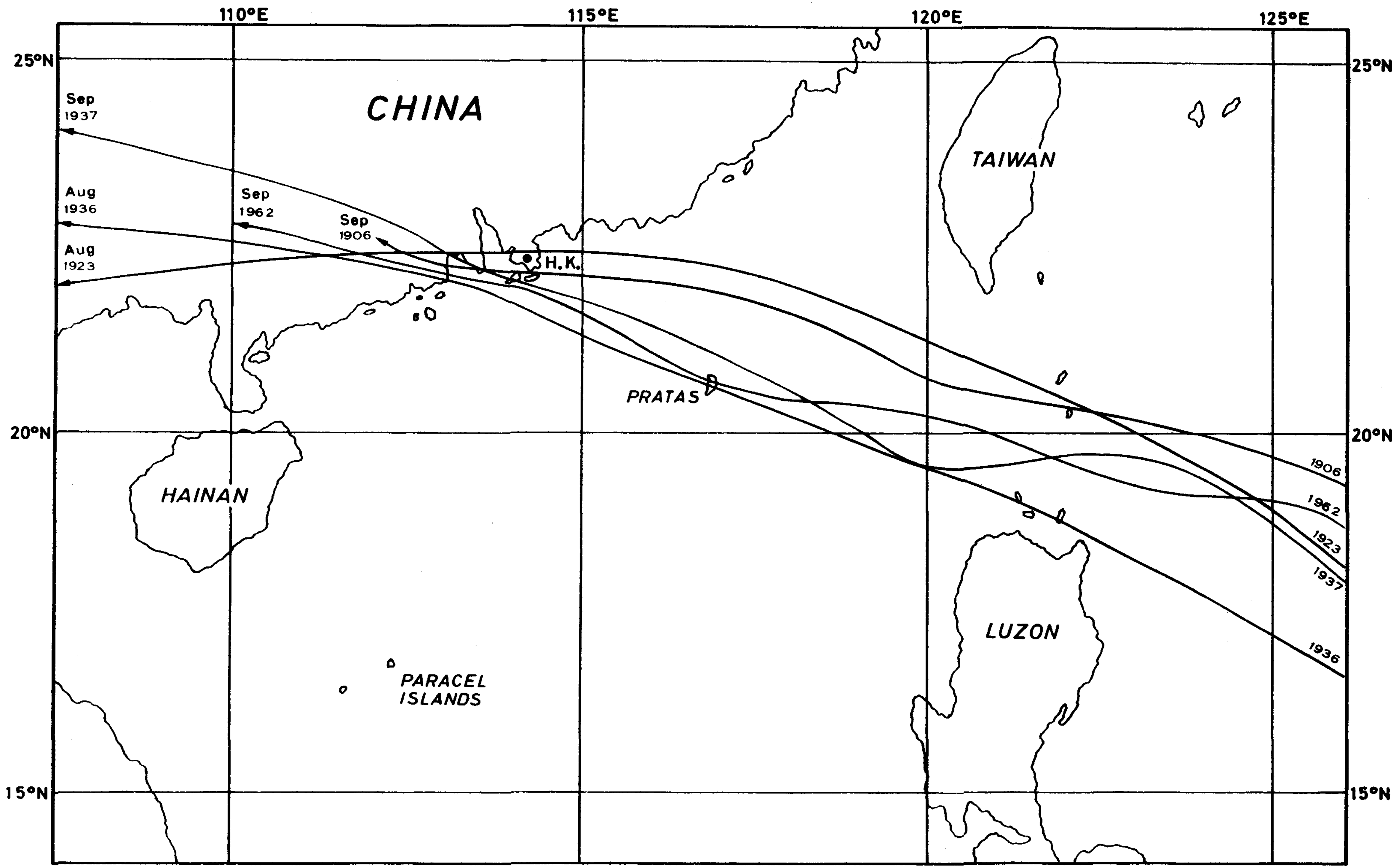

Fig. 1 TRACKS OF TYPHOONS THAT CAUSED THE GREATEST SURGES IN HONG KONG.

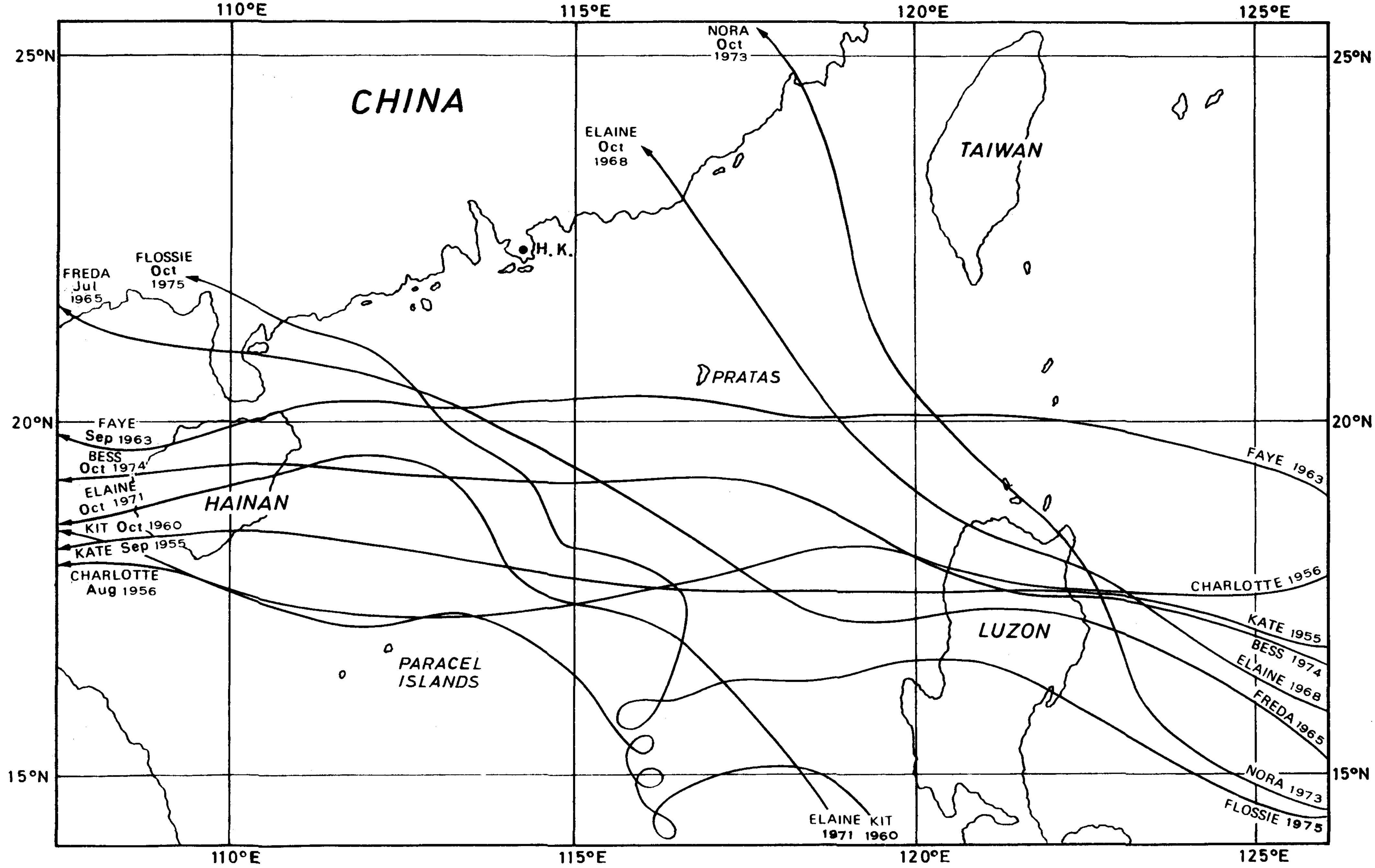

Fig. 2 TRACKS OF TYPHOONS THAT CAUSED THE LARGEST SURGES IN HONG KONG WITHOUT COMING WITHIN 100 MILES OF HONG KONG.

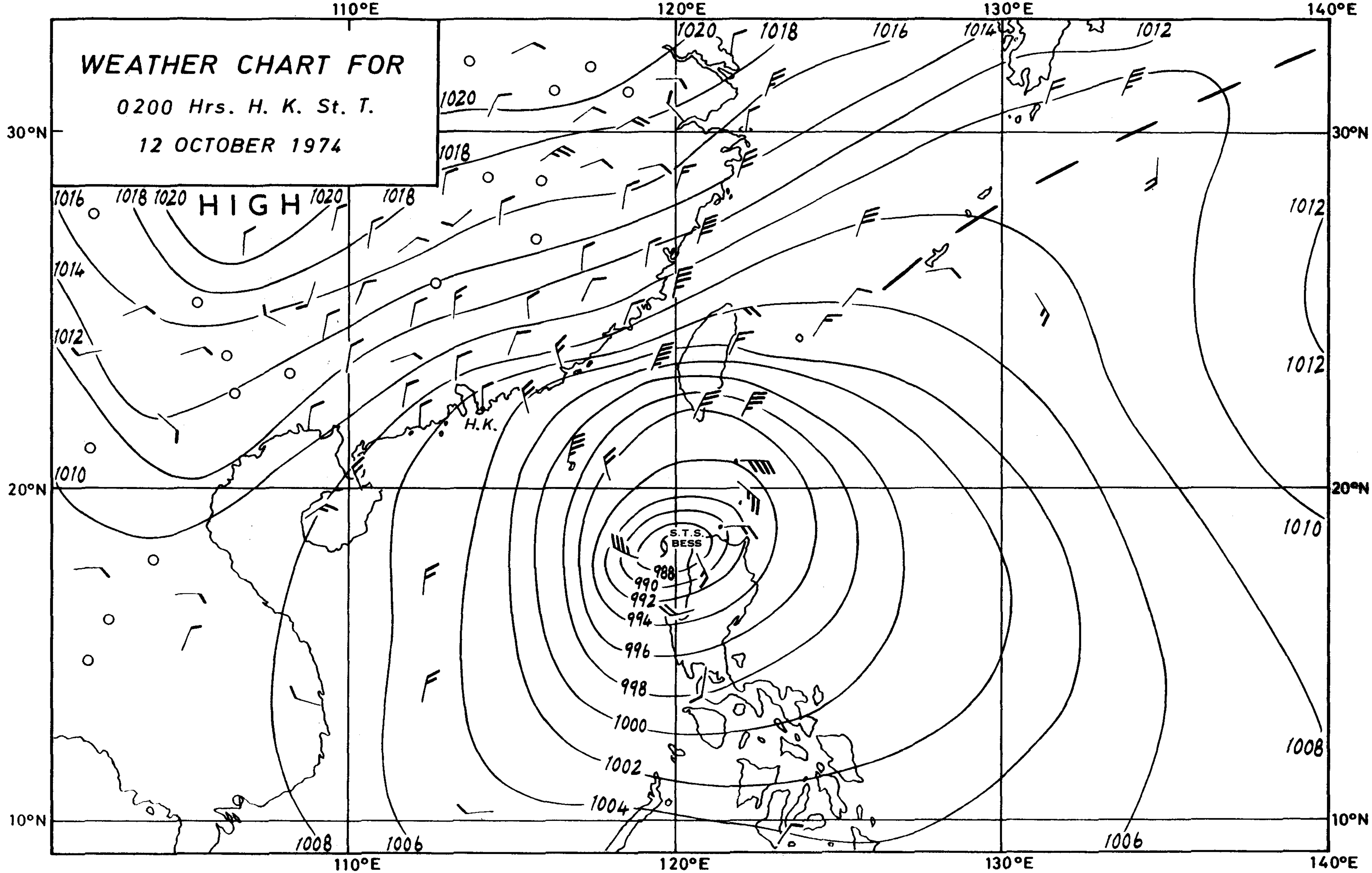

Fig. 3 WEATHER MAP FOR 0200 HRS.

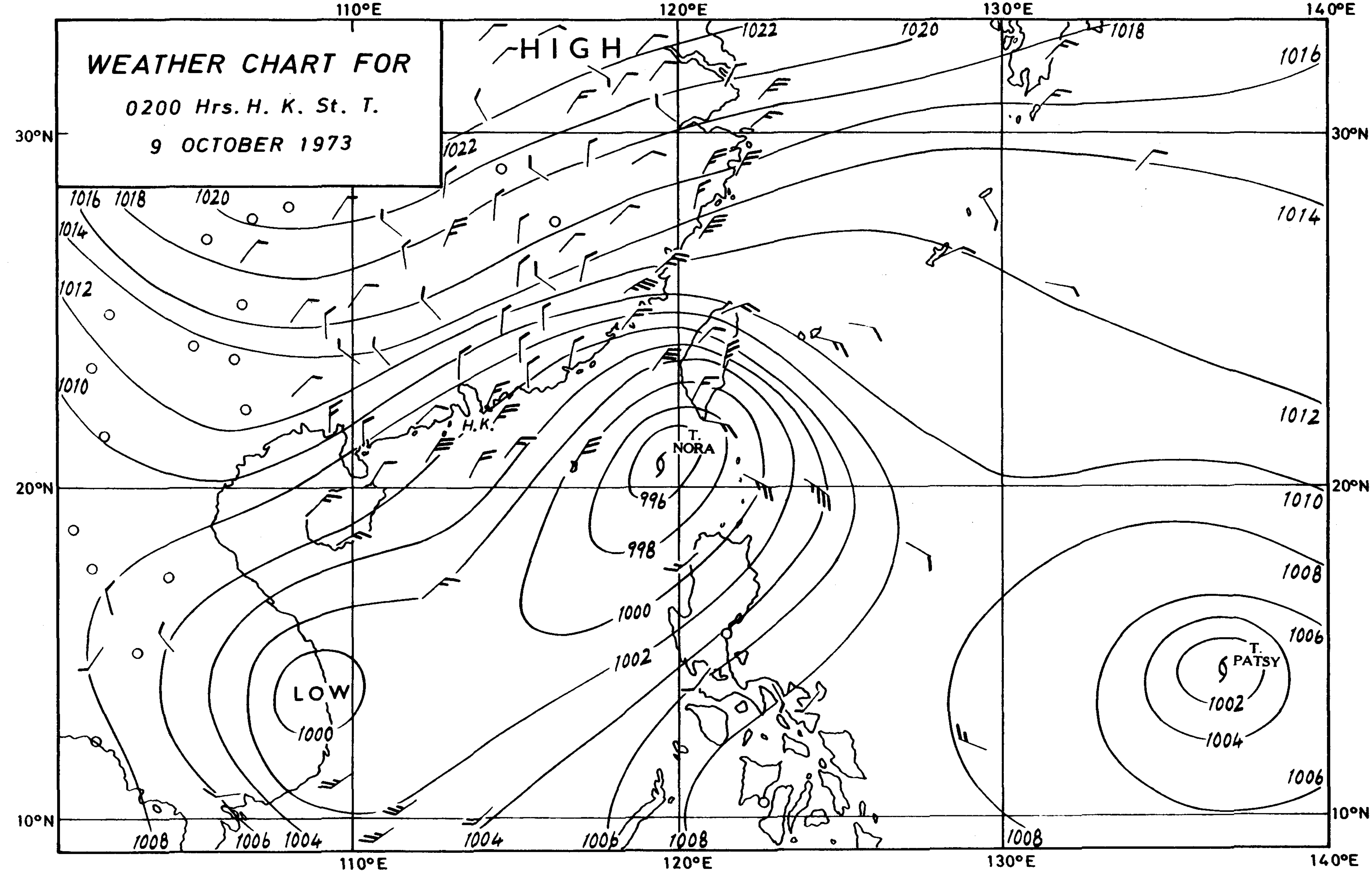

Fig. 4 WEATHER MAP FOR 0200 HRS.