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Original Article

Tropical cyclone disasters in the Gulf of Thailand

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Abstract

The origin of tropical cyclones in the South China Sea is over a vast deep sea, southeast of the Philippines. The severe tropical cyclones in summer with northerly tracks attack the Philippines, China, Korea and Japan, while the moderate ones in the rainy season with northwesterly tracks pass Vietnam, Laos and northern Thailand. In October, November and December, the tropical cyclones are weakened and tracks shift to a lower latitude passing the Gulf of Thailand. Tropical cyclone disasters in the Gulf of Thailand due to strong winds causing storm surges and big waves or heavy rainfall over high mountains in causing floods and land slides result in moderate damages and casualties.

Analyses are made of six decades of data of tropical cyclones from 1951-2006 having averaged numbers of 3 and 13 in Thailand and the South China Sea respectively. Detailed calculation of surges and wave heights of the 5 disastrous tropical cyclones in the Gulf of Thailand reveal that the Upper Gulf of Thailand with a limited fetch length of about 100 km in north/south direction and about 100 km width in the east/west direction, resulted in a limited maximum wave height of 2.3-2.5 m and maximum storm surge height of 1.2 m generated by Typhoon Vae (1952), while the east coast, with longer fetch length but still limited by the existence of its shoreline, resulted in an increased maximum wave height of 4 m and maximum storm surge height of 0.6 m in the Upper Gulf of Thailand generated by Typhoon Linda (1997). These are the Probable Maximum Cyclones here.

The southern shoreline, with unlimited fetch length on the east by tropical cyclones approaching from the South China Sea, generated maximum wave height of 6-11 m by Typhoon Gay (1989), resulting in more casualties and damages. Note that storm surges on the southern shorelines with steep slopes are small due to the short distance of shallow shorelines in receiving wind stresses for piling up sea levels. These disasters can be alleviated from known characteristics of tropical cyclones and through proper warning before coming to the Gulf of Thailand.

Keywords: tropical cyclone, disaster, Gulf of Thailand, storm surge, wave

1. Tropical cyclones in the South China Sea and the Andaman Sea

In summer air over a vast deep sea surface near the equator, southeast of the Philippines, which is overheated will become lighter and rise, creating a low pressure center defined as tropical cyclone. The outer cooler air blows towards the center in counterclockwise direction over the northern hemisphere due to the Coriolis effect, and clockwise in the southern hemisphere. This results in a system of cloud which precipitates when it passes over a mountainous areas and thus produces flood.

Tracks of tropical cyclones over the South China Sea presented by Crutcher and Quayle (1974) is shown in Figure 1, northerly in summer passing the Philippines, China, Korea and Japan, northwesterly in rainy season passing Vietnam, Laos and northern Thailand, while in October, November and December the tropical cyclones are weaker and northwesterly tracks shift to a lower latitude passing the Gulf of Thailand. The severe tropical cyclone in summer or

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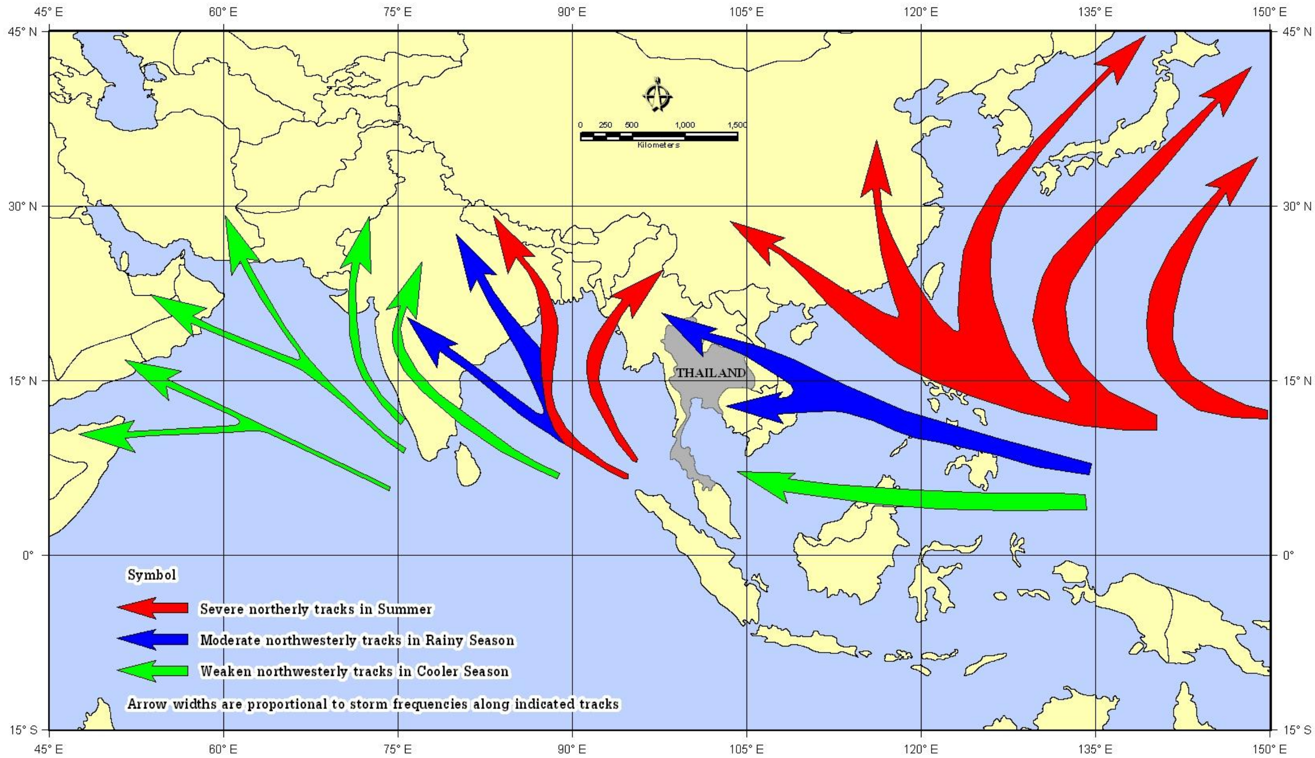

Figure 1. Tropical cyclone tracks in the South China Sea and Andaman Sea. (Crutcher and Quayle, 1974)

typhoon having its usual northerly track and frequency for August in the western North Pacific (the Philippines, China, Korea and Japan) is presented in Figure 2 by Jamison (1956) with only 1 typhoon over an 11-year period passing Vietnam, Laos and northern Thailand.

The origin of tropical cyclones in the Andaman Sea is over a vast deep sea, east of Sri Lanka, Figure 1. The severe tropical cyclones in April, May and June with northerly tracks attacked Bangladesh, Myanmar and Thailand, while the moderate ones in July, August and September with northwesterly tracks passing India and Pakistan and those weaker ones in October, November and December shift to lower latitude passing the Arabian Sea and die out at the end of the year when the sun is past the equator. Appendix A showed seventy severe tropical cyclones and resulting Probable Maximum Cyclones as well as the casualties in Bangladesh. Appendix B showed typhoon Nargis's track and satellite image on May 2, 2008.

1.1 Designation of tropical cyclones

Tropical cyclone is a cyclone that originates over tropical oceans and is driven principally by heat transfer from the ocean. A tropical cyclone is characterized by four parameters, namely, its forward speed V_F radius of the eye R, the minimum pressure at its center p_0 and the maximum wind speed at the radius of the eye U_{max}.

Tropical cyclones in the Pacific Ocean and the South China Sea are designated according to the magnitudes of U_{max} >35 knots by the World Meteorological Organization as follows:

Tropical depression	$26 < U_{max} < 34$ knots
Tropical storm	$35 < U_{max} < 47$ knots
Severe tropical storm	$48 < U_{max} < 63$ knots
Typhoon	$U_{max} > 64$ knots

1.2 Physics of tropical cyclones

Distribution of absolute angular momentum, per unit mass, around the axis of the storm, defined as $M = rV_t + \frac{1}{2} fr^2$ where r is the radius from the storm center; V_t is the tangential velocity; and f is the Coriolis parameter, which is just twice the projection of the earth's angular velocity vector onto the local vertical plane. The second term on the right of the equation is the contribution of the earth's rotation to the angular momentum, whereas the first is the contribution from the rotating wind field. In the absence of frictional torque, M is conserved following axis symmetric displacements of fluid rings.

The function of temperature, pressure, and water concentration defined approximately as $s \approx C_P\, In(T) - R_d\, In(p) + \frac{L_v q}{T} - qR_v\, In(H)$ where T is the absolute temperature, p the pressure, q the concentration of water vapor, and H the relative humidity. The thermodynamic parameters in the

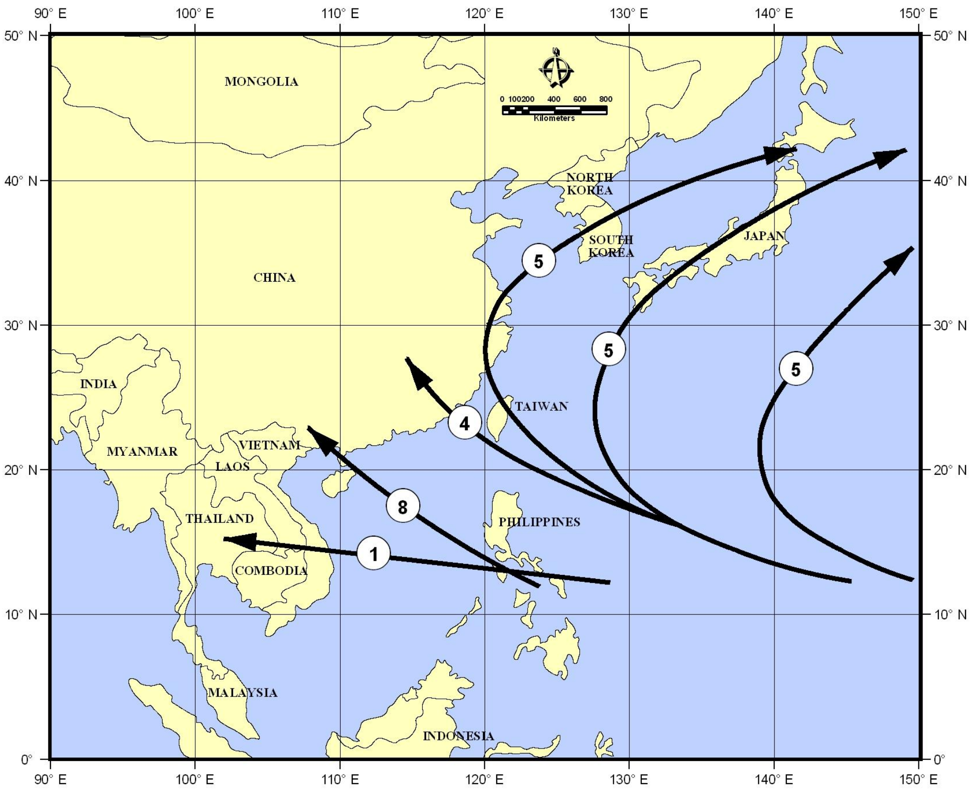

Figure 2. Mean typhoon tracks and frequency (over an 11-yr period) for August in the western North Pacific. (Jamison 1956)

equation are the heat capacity at constant pressure, C_p, the gas constants for dry air and water vapor, R_d and R_v, and the latent heat of vaporization, L_V.

The flux of momentum into the sea and the flux of enthalpy from the sea are usually quantified using bulk formulae of the form $F_m = -C_d^\rho |V|V|$ and $F_k = C_k \rho |v|(k_0^* - k)$ where V is some near-surface wind speed, ρ is the air density, k is the specific enthalpy of air near the surface, and k_0^* is the enthalpy of air in contact with the ocean, assumed to be saturated with water vapor at ocean temperature. The dimensionless transfer coefficients of momentum and enthalpy are C_d and C_k .

2. Tropical cyclones in the Gulf of Thailand

Five tropical cyclone disasters in the Gulf of Thailand due to strong winds and surges are reported by Vongvisessomjai (2007), namely (i) in 1952 when typhoon Vae attacked the Upper Gulf, (ii) in 1962 when tropical storm Harriet caused disaster at Laem Talumpuk of Nakorn Si Thammarat province due to its devastation winds and surges causing 800 deaths, (iii) in 1970 when tropical cyclone Ruth attacked Ko Samui and coastline of Surat Thani and Chumphon, (iv) in 1989 when typhoon Gay caused disasters at Patiew and Tha Sae of Chumphon province due to strong winds and surges, 580 deaths mostly of fishermen, 620 boats sunk, 40,000 houses destroyed and about 11 billion Baht damage, and (v) in 1997 when typhoon Linda attacked Thupsake of Prachuap Khiri Khan province resulting in 30 deaths, 102 missing and more than 400,000 rai of agricultural land destroyed. Before coming to Thailand typhoon Linda caused worst calamity of the century in Vietnam with 594 deaths, 30,000 displaced and 472 million US Dollars damages. This paper presents the characteristics of these 5 disastrous tropical cyclones in the Gulf of Thailand as shown in Figure 3.

2.1 Pressure distribution

The pressure distribution of a cyclone p increases as a function of the radial distance r from its center from p_o to the atmospheric pressure p_n, as proposed by Myers (1954):

$$p - p_o = (p_n - p_o) \exp(-R/r) \quad for \quad 0 < r < \infty \quad (1)$$

2.2 Velocity distribution

The wind velocity distribution of a cyclone v varies as a function of the radial distance r, as proposed by Jelenianski (1965) and given below.

$$v = v_o (r/R) \quad \text{for} \quad r \le R \quad (2)$$

and $$v = v_o (r/R) \quad \text{for} \quad r \le R \quad (3)$$

Figure 3. Tracks of 5 most disastrous tropical cyclones over Thailand.

where v_o = the maximum sustained wind in a cyclone;
R = the radius of maximum sustained speed;
r = distance from center of the cyclone and the point where v is desired.

Tracks of 5 disastrous tropical cyclones over the South China Sea affecting Thailand are shown in Figure 3. Characteristics of the first three tropical cyclones affecting Thailand are shown for their variations of pressure and wind speed versus radial distance r by Vongvisessomjai (2007). These tropical cyclones can be seen clearly from weather satellite in the form of huge clouds as shown in Appendix B. These clouds cause heavy rainfall and floods while strong winds cause destruction of houses, i.e. typhoon Vae attacking the Upper Gulf of Thailand in October 1952, tropical storm Harriet attacking Laem Talumpuk of Nakhon Si Thammarat province in October 1962 and tropical cyclone Ruth causing damages to Ko Samui, Surat Thani, Chumphon and Prachuap Khiri Khan in November 1970. In 1989 typhoon Gay caused disaster at Patiew and Tha Sae of Chumphon province where 580 people were killed.

2.3 Storm surge

A storm surge is an abnormal rise of sea level at a coastline caused by the driving forces in terms of a very high horizontal atmospheric pressure gradient and very strong surface wind. These driving forces produce normal and tangential stresses along the sea surface and introduce the movement of seawater as well as inclination of the sea surface. The rise of sea level caused by the pressure drop over the sea surface and the strong wind drift of seawater towards the downwind becomes a kind of forced progression of waves in the unbound seawater region when it is accompanied by the progression of low pressure front, therefore, the storm surge height was expressed as a function of wind velocity and inclination of shoreline to the wind direction and pressure drop as follows.

$$S = AV^2 \cos\theta + B(\Delta p) + C \quad (4)$$

Absan (1994) used storm surge height S of seventy severe tropical cyclones in the Bay of Bengal listed in Table A.1 of Appendix A for analysis by a multiple regression to obtain A = 0.0262, B = 0.000089 and C = 3.92 m. Which revealed very high value of storm surge height of 10 m due to very high maximum wind velocity of 220 km/h, very high pressure drop Δp of 46 mb and very mild slope of shoreline. The storm surge heights in the Gulf of Thailand are much smaller due to lower maximum wind velocity and pressure drop.

2.4 Cyclonic wave

The stress of surface winds produces waves in bodies of water depending upon wind velocity V and fetch length. For a slowly moving cyclone, the following formulas given by CERC (1984) can be used to obtain a good estimate of the deepwater (deeper than 25 m) significant wave height and period in the lower Gulf of Thailand which is an open sea since the Upper Gulf of Thailand is shallow and enclosed sea which should use Wilson's numerical method in the next section.

$$H_o = 5.03\, exp\left[\frac{R\,\Delta p}{4700}\right]\left[1+\frac{0.29\alpha.V_F}{\sqrt{U_R}}\right] \quad (5)$$

and

$$T_S = 8.6\, exp\left[\frac{R\,\Delta p}{9400}\right]\left[1+\frac{0.145\alpha.V_F}{\sqrt{U_R}}\right] \quad (6)$$

Where

H_o = deepwater significant wave height in meters

T_S = the corresponding significant wave period in seconds

R = radius of maximum wind in kilometers

Δp = p_n - p_o where p_n is the normal pressure of 760 mm of mercury, and in mm of mercury.

V_F = the forward speed of the cyclone in knots

p_o = the central pressure of the cyclone in mm of mercury.

U_R = the maximum sustained wind speed in knots, calculated for 10 meters above the mean sea surface at radius (R):

$$U_R = 0.865\ U_{max} \quad \textit{(for stationary cyclone)} \quad (7)$$

$$U_R = 0.865\ U_{max} + 0.5\ V_F \textit{(for moving cyclone)} \quad (8)$$

U_{max} = maximum gradient wind speed in knots 10 meters above the water surface

$$U_{max} = 0.447\left[14.5\left(p_n - p_o\right)^{1/2} - R\left(0.31 f\right)\right] \quad (9)$$

f = Coriolis parameter (2w sin ϕ) in radians per hr

Latitude (ϕ)	5°	10°	15°	20°
f	0.046	0.091	0.135	0.179

α = is a coefficient depending on the forward speed of the cyclone, V_F, and the increase in effective fetch length because the cyclone is moving. It is suggested that for a slowly moving cyclone α = 1.0

The approximate wave period may be obtained from

$$T_S = 12.1\sqrt{\frac{H_o}{g}} \quad (10)$$

Equations 5-10 are used to provide approximate values of cyclonic waves while accurate calculations are presented in the following sections. It is these large waves and surges induced by the strong winds of the tropical cyclones that cause casualties of people living along the shorelines.

3. Cyclonic surge and wave at Ao Phai

Planning and design of a power plant at Ao Phai require knowledge on probable maximum and minimum sea levels as well as surge and wave generated by tropical cyclones from the South China Sea.

3.1 Cyclonic surge analysis

In determining the Probable Maximum Cyclone (PMC) and the 250 year cyclone (Cyclone associated with value of central pressure index of once in 250 years) for further computation of cyclonic surges and waves, several tracks as known (Figure 3) are tried and the most severe cyclonic effect is 35 nautical miles (radius of the eye) north of Ao Phai with movement of the storms center east to west by Vongvissessomjai *et al.* (1977). It is generally assumed that the Central Pressure Index (CPI) or the minimum central pressure (p_o) values of storms belong to a normal distribution which can be well approximated by Weibull and Gamma distributions. This permits the extrapolation of the CPI to theoretically high recurrence interval so as to get the corresponding values of the CPI for PMC. The inherent parameters adopted for PMC and the 250 year cyclone from Figure 4 are given in Table 1. The typhoon Vae (1952), tropical storm Harriet (1962), tropical storm Ruth (1970), typhoon

Table 1. Historical typhoon (cyclone) characteristics from Vongvisessomjai (2007).

No.	Year, Month, Date	Name	CPI or p_o (mb)	Δp = p_n - p_o (mb)	Max. Velocity U_{max} (km/h)	Max. Velocity U_{max} (mph)	Forward Speed, V_F (mph)	Radius, R (nautical miles)
1	1952 Oct 21-22	VAE	992	21	134	84	14.97	76
2	Oct 24-25	TRIX	998	15	70	44	17.27	60
3	1960 Oct 03-04	-	992	21	83	52	3.45	8.4
4	1962 Oct 25-26	HARRIET	997	16	110	69	18.45	76
5	1966 Jun 17-18	-	-	-	-	-	12.67	-
6	Oct 25-26	-	990	23	77	48	9.21	49
7	1967 Jun 17-18	-	978	35	99	62	12.67	140
8	Oct 05-06	-	996	17	78	49	11.52	16
9	Oct 09-10	-	998	15	70	44	17.27	90
10	Nov 10-11	-	-	-	-	-	12.67	-
11	1968 Sep 05-06	BESS	992	21	70	44	2.30	115
12	Oct 21-22	HESTER	998	15	74	46	11.52	10
13	1967 Jun 24-25	-	998	15	74	46	6.91	7.5
14	Sep 20-21	-	992	21	82	51	12.67	57
15	Nov 10-11	-	1000	13	72	45	16.12	10
16	1970 Sep 20-21	-	994	19	83	52	13.82	20
17	Oct 25-26	KATE	1000	13	43	27	13.82	314
18	Nov 29-30	RUTH	1000	13	67	42	11.52	43
19	1972 Jun 03-04	NAMIE	990	23	77	48	6.91	123
20	Sep 06-07	-	990	23	78	49	4.61	16
21	Sep 18-19	-	-	-	-	-	-	-
22	Dec 04-05	SALLY	994	19	80	50	5.76	5
23	1973 Nov 12-13	-	1002	11	61	38	5.76	4
24	Nov 17-18	THELMA	998	15	72	45	5.76	39
25	1974 Oct 09-10	-	1002	11	54	34	6.91	15
26	Nov 05-06	-	998	15	72	45	13.82	60
27	1989 Nov. 01-04	GAY	989	24	186	116	12.00	-
28	1997 Nov. 01-05	LINDA	976	37	102	64	30.00	-

Gay (1989) and typhoon Linda (1997) occurred once every 8-10 or 9 years, which is the recurrence interval of El Nino (Trenberth, 1992).

The surge computation was performed using the storm surge model of Bodine (1971) for the PMC and 250-year cyclone by Vongvisessomjai (2007) for a span of 46 hours of high wind velocity.

3.2 Cyclonic waves analysis

The waves generated by cyclones, known as “cyclonic waves” are important aspects of tropical cyclones occurring in the nearshore zone and in the immediate neighborhood of coastal front structures. They can be prominently superposed on the surge levels. Quantitative estimates of the waves associated with tropical cyclones are forecasted and included here.

A procedure for present computation of cyclonic waves is developed from Wilson’s numerical method (Day, 1977). Two design cyclones, the PMC and the 250-year cyclone as used for the surge computation, are adopted. The wave computation was performed by Vongvisessomjai (2007) for a span of 46 hours which covered the whole period of high wind velocity. The severest cyclonic wave were found to be 2.3 m in height and 5.9 s in period at PMC condition. For the condition of the 250-year cyclone, the severest cyclonic wave characteristics were found to be 1.9 m and 5.1 s. No cyclonic waves have been actually recorded to permit comparisons when this study was made in 1977 for Ao Phai nuclear power plant. However, this cyclonic wave model has been successfully applied to tropical cyclones in Hong Kong and Taiwan (Day, 1977), and the computed order of magnitudes obtained above are within this expectation

4. Tropical cyclone in the East Coast

Pornpinatepong *et al.* (1999) used the WAM Model in predicting wind waves in the Gulf of Thailand and Andaman

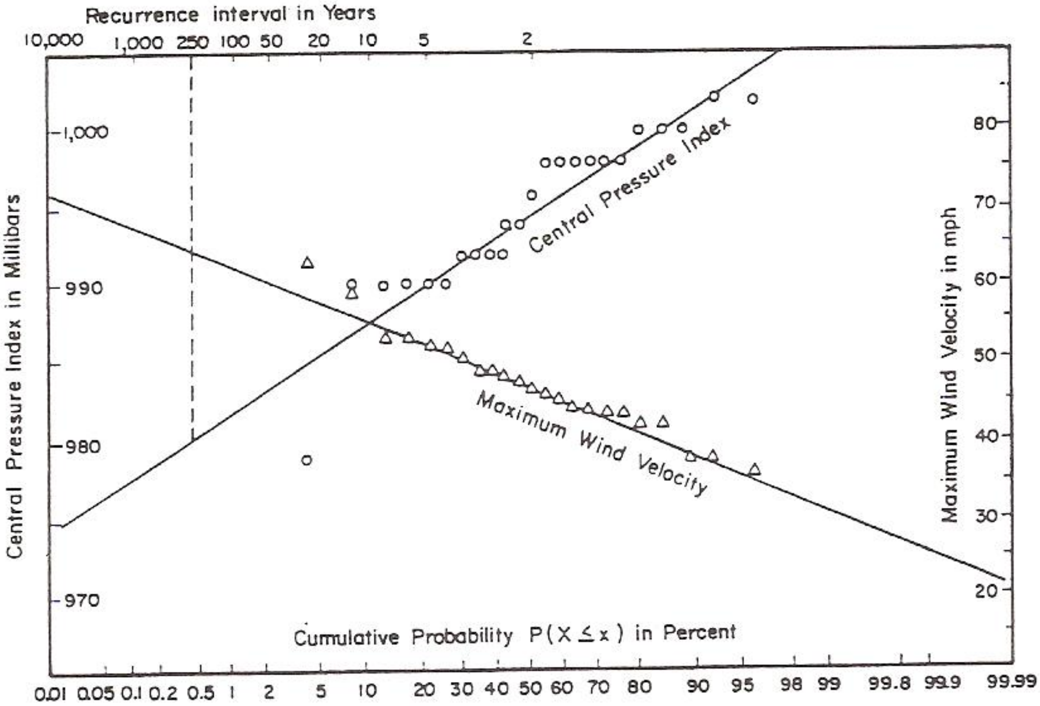

Figure 4. Recurrence intervals of tropical cyclone characteristics for the Gulf of Thailand.

Sea under a joint project of Thai and US Government agencies with financial support from Thai Research Fund from 1996-1999.Wave data used in calibrating the wave model were taken initially from satellites ERS-2 and TOPEX and later from 9 buoys in the Gulf of Thailand and 2 buoys in the Andaman Sea operated by the National Research Council of Thailand (NRCT). The WAM Model, which was the third generation of the WAM group (1988), was originally developed over 10 years by the Max Planck Institute for Meteorology in Germany. This wave model has been used to forecast ocean wave height in conjunction with an input forecast wind data, 110-km resolution, provided by the Master Environmental Library (MEL), US Department of Defense. The model developed from this project has been used operationally at the Weather Forecast Department of the Royal Thai Navy. The forecast data are shown daily on the Royal Thai Navy Website (Wirattipong *et al.*, 1999).

The most important results of the WAM Model are the wind waves generated by typhoon Linda, which was formed on October 26, 1997, as a tropical disturbance within an area of convection east of the Philippines islands near latitude 10^{o}N and longitude 130^{o}E , and then moved westward under the subtropical ridge to the north. When entering the South China Sea, it transformed into a tropical storm and moved westward to the southern tip of Cape Camau of Vietnam at 00Z on November 2 with the intensity of 55 knots (28m/s) as shown in Figure 3. It approached the Gulf of Thailand around 00Z on November 3 with typhoon intensity and turned north westward following steering from the subtropical ridge. Its strength weakened as it encountered mountains (Prachuap Khiri Khan province). After crossing over the Andaman Sea, it reconsolidated and became a typhoon once again at 00Z on November 6. Six hourly waves on November 2 and 3, 1997, are shown in Figures 5 and 6 respectively. The wave heights increased is 0.3 m (1 foot) internal using blue colours from 0.3-1.5 m, green colours from 1.5-2.7 m, and yellow colours from 2.7-3.9m. The black arrows show wave directions and the white arrows show directions of cyclonic winds which rotate counterclockwise around the center of cyclone. It can be seen that very big waves are located at the eye of the cyclone near to its center due to its maximum wind speed here. Figure 7 shows three-hourly waves of oceanographic buoys at Ko Chang with the maximum wave height of 2.2 m at noon on November 3, at Rayong with the maximum wave height of 2.5 m, and at Huahin with the maximum wave height of 2.7 m around midnight on November 3, 1997. Note that the maximum wave heights at the eye of the tropical cyclone shown in Figures 5 and 6 are about 4.0 m, which are bigger than those waves recorded at the three buoys shown in Figure 7.

The increased fetch length of the east coast but still limited by the existence of its shoreline resulted in an increase of wave height of 2.5 m at Rayong and 2.7m at Huahin while the maximum significant wave height at the eye of the tropical cyclone is about 4.0 m. It is to be noted that in the study of the deep sea port at Map Ta Phut, JICA (1983) estimated the design wave height of 3.67 m for a return period of 50 years and 3.85 m for a return period of 100 years.

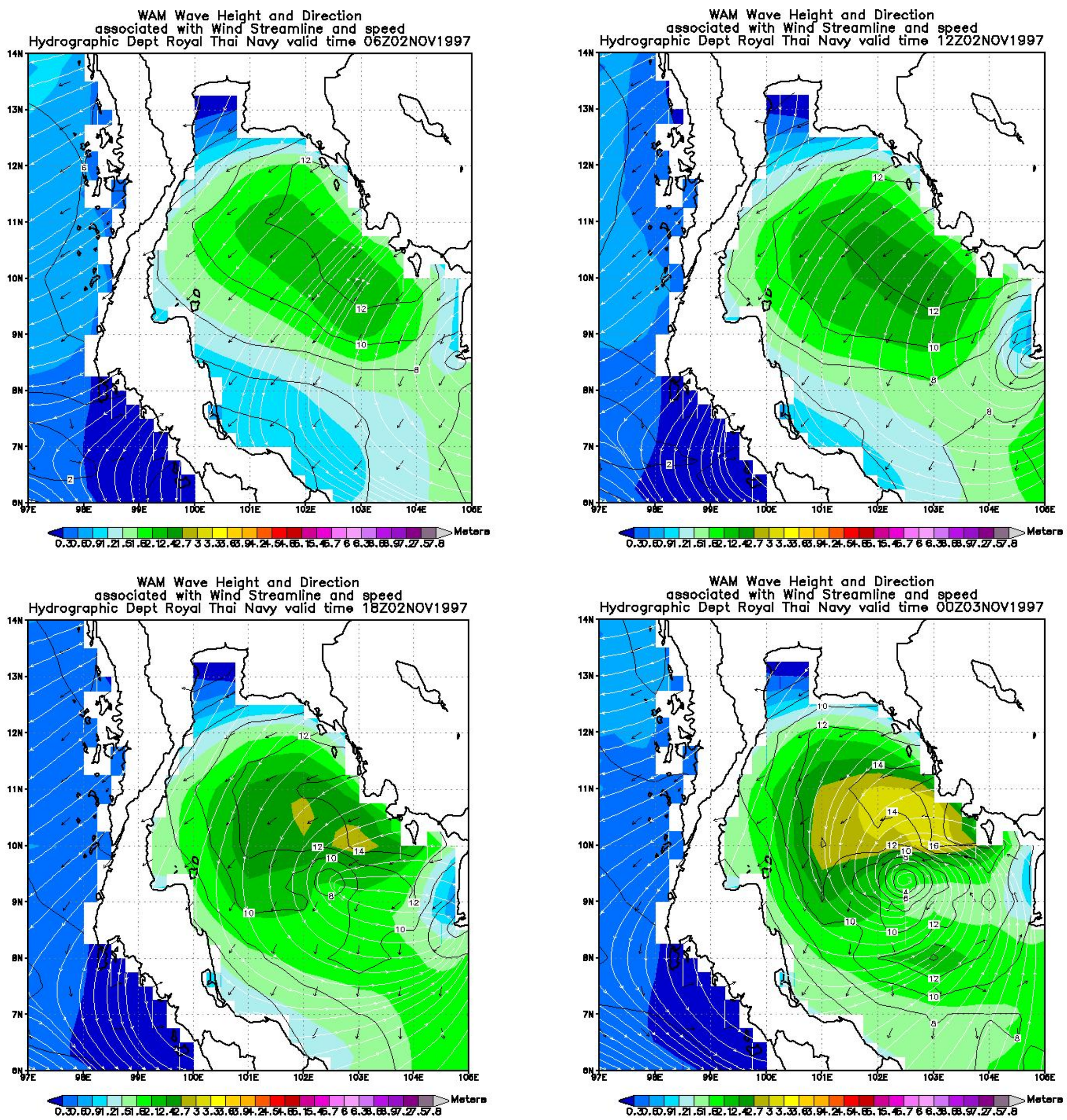

Figure 5. Six-hourly waves on November 2, 1997.

5. Tropical cyclones in the Southern Coast

The tropical cyclones in the southern coast coming from the South China Sea, which is open sea with unlimited fetch length, the resulting waves are much larger than in the Upper Gulf of Thailand and the east coast. However, the storm surges on the southern shoreline with steep slope are small due to short distance of shallow section in receiving wind stress in piling up sea level.

When tropical storm Harriet (1962) caused disaster at Laem Talumpuk in Nakhon Si Thammarat province due to its devastating winds causing 800 deaths, 252 injured, and left over 10,000 homeless while typhoon Gay (1989) with its eye apparently passing directly over the Seacrest, the Unocal oil drilling ship moored in the Gulf of Thailand, caused the ship to capsize shortly after the eye passage with estimated wave heights of 6-11 m, killed 91 seamen with only 2 survivers rescued. During the landfall in southern Thailand typhoon Gay claimed at least 580 lives, also more than 620 fishermen were reported missing, and 200 fishing vessels were lost.

Retrieved from http://en.wikipedia.org/wiki/Typhoon_Gay (1989).

6. Six decades of cyclone data

The Thai Meteorological Department (TMD) reported that the average numbers of tropical cyclone passing Thailand and the South China Sea from 1951-2006 as shown in Figure 8 are about 3 and 13 per year respectively and their

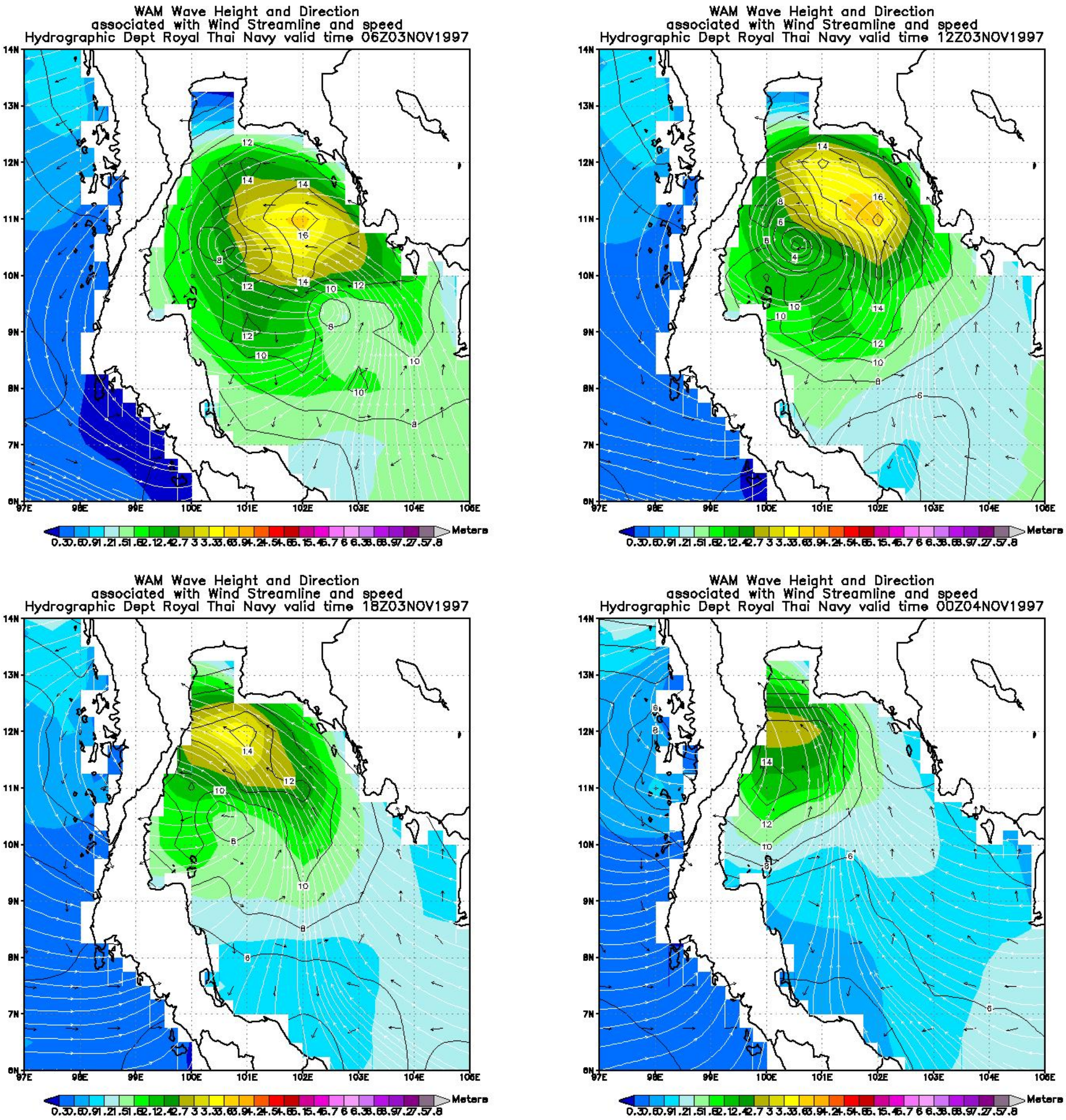

Figure 6. Six-hourly waves on November 3, 1997.

severity is the same which is consistent with Figures 1 and 2 that lower numbers of tropical cyclone pass Thailand and they are the weaker ones. This paper presented 5 disastrous tropical cyclones listed in Table 1 which are weaker tropical cyclones having lower values of the maximum wind velocity U_{max} and pressure drop Δp as compared with the severe tropical cyclones or typhoon in the western North Pacific (the Philippines, China, Korea and Japan) as shown in Figure 2, or the severe tropical cyclones in the Andaman Sea in Appendix A as listed in Tables A.1 and A.2 with the very high values of maximum wind velocity U_{max} and pressure drop caused high casualties listed in Table A.3.

7. Conclusion

1. Severe tropical cyclones in summer months of April, May and June caused severe damages to the Philippines, China, Korea and Japan in the South China Sea as shown in Figures 1 and 2 or Bangladesh and Myanmar in the Andaman Sea as shown in Appendix A.

2. Moderate tropical cyclones in rainy months of July, August and September caused moderate damages to Hong Kong, Vietnam, Laos and northern Thailand in terms of heavy rainfalls and floods.

3. Weaker tropical cyclones in the cooler months of

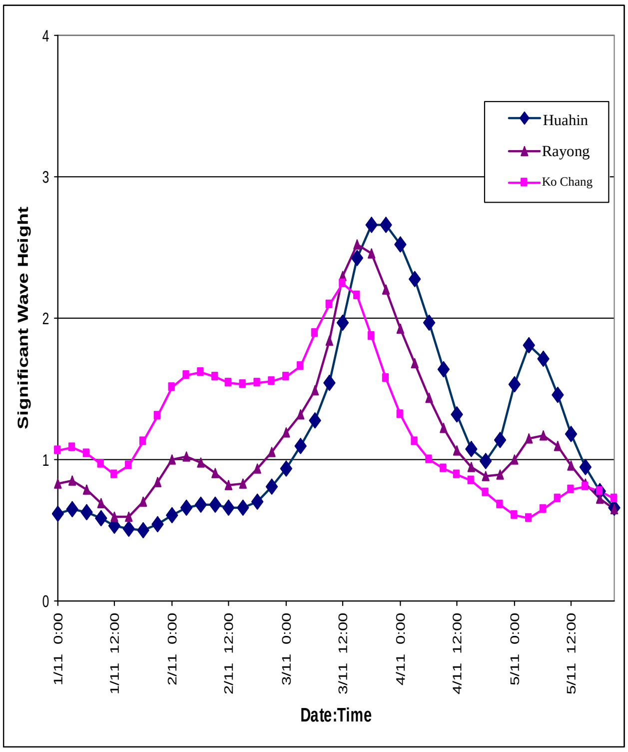

Figure 7. Three-hourly waves of buoys at Ko Chang, Rayong and Huahin November 1-5, 1997.

October, November and December shifted to a lower latitude, passing the Gulf of Thailand, which was relatively shallow (maximum depth of 85 m) and small in size compared with the vast deep sea (depths of 3,000-4,000 m) and caused less damages in terms of storm surges and wave heights. The five disastrous tropical cyclones in the Gulf of Thailand in six decades (Figure 3 and Table 1) were almost the Probable Maximum Cyclones here but could not compare with those tropical severe cyclones in summer (Figures 1, 2 and Tables A.1, A.2 and A.3).

4. These disasters could be alleviated from known characteristics of tropical cyclones and through proper warning.

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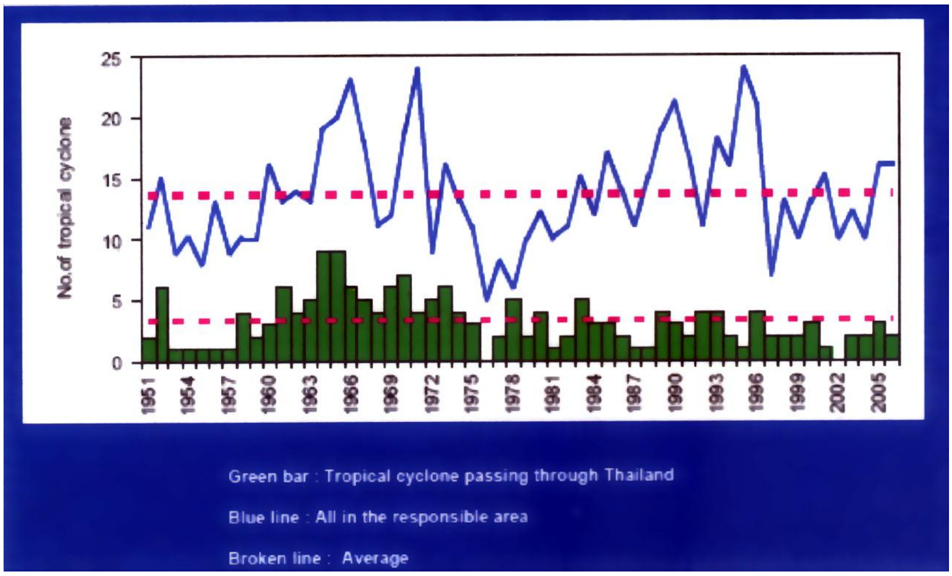

Figure 8. Numbers of tropical cyclone passing Thailand and the area between latitude 15^{0}S- 45^{0}N and longitude 65^0 - 150^{0}E. (www.tmd.go.th).

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Appendix A

Severe Tropical Cyclones and Casulties in Bangladesh

Table A.1. Seventy Severe Cyclones in the Andaman Sea.

Date, Month, Year	Type	U_{max}(km/h)	p_o(mb)	Δp (mb)	S(m)
27 Oct - 1 Nov 1876	SCS (H)	220		46	3.0-10.0
26 Jun - 4 Jul 1883	SCS	117		16	
2 Oct 1897	SCS	100		41	
21-24 Oct 1897	SCS	102		41	
4-7 Nov 1915	CS	74		13	
18-22 Nov 1922	SCS	102		21	
10-17 May 1925	CS	87		41	
19-23 May 1926	CS	81		18	
21-26 Apr 1936	SCS	117		20	
22-29 May 1936	SCS	113		21	
7 May 1941	CS	87		17	1.5-3.0
21-27 May 1941	CS	87		17	
14-18 Oct 1942	SCS	109		16	
19-20 Sep 1945	D	46		8	
10-18 Oct 1945	SCS	107		20	
23 Oct 1947	SCS	113		15	
8 Aug 1954	DD	56		8	
2-3 Sep 1954	D	46		10	
21-22 Sep 1954	D	37		8	
7-9 Sep 1958	DD	56		10	
21-24 Oct 1958	SCS	91		17	1.8
9-10 Jul 1959	DD	56		10	
17-18 Jul 1959	D	46		10	
12-15 Aug 1960	D	37		8	
23-25 Sep 1960	DD	56		10	
7-10 Oct 1960	SCS(H)	161	951	16	3.0-6.1
30-31 Oct 1960	SCS(H)	209	974	35	3.5-9.1
6-9 May 1961	SCS(H)	151	950	29	2.4-8.8
27-30 May 1961	SCS(H)	145		16	1.8-9.0
25-29 May 1963	SCS(H)	202		55	2.4-9.1
6-7 Jun 1963	D	46		7	
9-10 Aug 1963	D	46		7	
9-15 Sep 1963	D	46		8	
26-29 Sep 1963	D	46		8	
4-6 Oct 1963	SCS(H)	124		22	
17-28 Oct 1963	CS	74	968	10	
10-12 May 1965	SCS(H)	161		38	3.5-5.8
31 May - 1 Jun 1965					6.0-7.6
5 Nov 1965	SCS(H)	160	953		2.4-3.7
14-15 Dec 1965	SCS(H)	210	979	64	2.4-6.9
1 Oct 1966	SCS (H)	146		31	4.5-9.1
1 Nov 1966	SCS (H)	120			6.1-6.7
27 Sep-1 Oct 1967	SCS (H)	145			9.6
10-11 Oct 1967	SCS (H)	145			1.8-8.8
22-24 Oct 1967					1.5-7.6
8-10 May 1968					2.5-4.6
10 Oct 1969					2.4-7.3

Table A.1. (Continued)

Date, Month, Year	Type	U_{max}(km/h)	p_o(mb)	Δp (mb)	S(m)
5-7 May 1970					3.0-5.0
23 Oct 1970	SCS (H)	163			
12-13 Nov 1970	SCS (H)	223	944	69	3.0-9.1
8 May 1971					2.4-4.3
30 Sep 1971					2.4-4.3
6 Nov 1971					2.4-5.5
18 Nov 1973					2.4-4.0
9 Dec 1973	SCS (H)	122			1.5-7.5
15 Aug 1974	SCS	97			1.5-6.7
28 Nov 1974	SCS (H)	162	977	38	0.4-5.2
21 Oct 1976	SCS	105			2.0-5.0
12-13 May 1977	SCS (H)	124			4.5
2-4 Oct 1978	CS	83			2.0
10 Dec 1981	SCS	110	989	27	1.8-4.6
14-16 Oct 1983	SCS	98	995		4.0
8-10 Nov 1983	SCS (H)	127	986		1.5
3 Jun 1984	CS	89			
23-25 May 1985	SCS (H)	154	982	26	2.1-4.6
8-10 Nov 1986	SCS	96	993	17	2.0-4.0
28-30 Nov 1988	SCS (H)	162	983	30	0.1-4.4
18 Dec 1990	SCS	115	995		1.5-2.1
29-30 Apr 1991	SCS (H)	225	940	74	3.6-7.6
2 Jun 1991	SCS	100			1.8-2.0

Note: U_{max} = Maximum wind speed
p_o = Central pressure
Δp = Pressure drop
S = Surge height
SCS (H) = Severe cyclonic storm with hurricane wind
CS = Cyclonic storm
DD = Deep depression
D = Depression

Table A.2. Probable Maximum Cyclones in the Andaman Sea.

Parameter \ Return Period (yr)	100	250	500	1,000
Max.Wind Vel. U_{max} (km/h)	286	320	354	382
Pressure drop Δp (mb)	84	96	108	118

Table A.3. Casualties of Severe Cyclones in Bangladesh.

Date, Month, Year			Dead
	Jun	1822	40,000
	Oct	1876	100,000
	Oct	1895	14,000
		1897	175,000
19-23	May	1926	2,700
21-24	May	1941	5,000
8-11	Oct	1960	6,000
30	Oct	1960	5,119
9	May	1961	11,166
28	May	1963	11,520
11	May	1965	19,279
12	Nov	1970	500,000
20-24	Oct	1976	1,000
4	Apr	1978	1,000
25	May	1985	11,069
29	Nov	1988	2,000
29	Apr	1991	138,000

Appendix B

Typhoon Nargis' s Track and Satellite Image on May 2, 2008