CHAPTER 2
PROTECTION FROM CYCLONES

Thematic paper: Role of forests and trees in protecting coastal areas against cyclones

Hermann M. Fritz[1] and Chris Blount[1]

On 26 December 2004, a major earthquake and subsequent tsunami severely damaged coastal communities in countries along the Indian Ocean. Although tsunamis and cyclones are completely different natural disasters in their generation mechanisms, through inundation they both cause primary damage and mortality in coastal areas; in this context the importance of the multi-hazard approach in coastal protection is raised. However, coastal vulnerability is site- and hazard-dependent. The duration of the cyclone storm surge lasts from several hours up to a day and is significantly longer than the tsunami wave period. Narrow coastal forest belts and mangroves are inefficient in reducing storm surge. Kilometres of coastal wetlands or forests are required to significantly attenuate massive inland inundation caused by cyclones. However, mangroves and other coastal forests can reduce wind and storm wave impact as well as current velocities. The additional benefits of these forests include protection from coastal erosion and preservation of wetlands.

1 INTRODUCTION

The Indian Ocean tsunami of December 2004, which killed over 200 000 people and affected livelihoods and coastal resources in 14 Asian and African countries, highlighted the need for coastal protection against tsunamis and other hazards, including cyclones and storm surges. A number of countries have called for the restoration of coastal forests to improve protection of coastal areas. It is difficult, however, to provide specific parametres for protection forests (i.e. width, density and biological characteristics) for effective dissipation of the energy of storm waves and cyclone-force winds because the potential for damage depends on many variables related to the particular site and cyclone. Anecdotal evidence needs to be analysed carefully as reduced impact behind mangrove forests can be attributable to the specific location and setting and not just the forest.

This paper is based on a scientific review of field, experimental and numerical modeling investigations and provides an objective analysis of the roles coastal forests play in protecting lives, natural resources and infrastructure, as well as valuable information for use in coastal area planning and management. An initial overview provides insight into the frequency, strength and location of tropical cyclones in conjunction with natural vegetation types, land-use patterns and coastal vulnerabilities. The effectiveness of coastal forests and trees in protecting population, infrastructure and natural resources from cyclones is discussed.

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[1] Civil & Environmental Engineering, Georgia Institute of Technology, Savannah, GA 31407, United States. fritz@gatech.edu

2 TROPICAL CYCLONES

2.1 GENERATION

In tropical and some subtropical areas, organized cloud clusters form in response to perturbations in the atmosphere. If a cloud cluster forms in an area sufficiently removed from the Equator, then Coriolis accelerations are not negligible and an organized, closed circulation can form. A tropical system with a developed circulation, but with windspeeds of less than 17.4 metres/second (i.e. 63 kilometres/hour or 39 mph), is termed a tropical depression. Given that conditions are favourable for continued development (basically warm surface waters, little or no wind shear and a high pressure area aloft), this circulation can intensify to the point where sustained windspeeds exceed 17.4 metres/second, at which time it is termed a tropical storm. If development continues to the point where the maximum sustained windspeed equals or exceeds 33.5 metres/second (121 kilometres/hour or 75 mph), the storm is termed a cyclone (Indian Ocean), typhoon (Western Pacific) or hurricane (Atlantic and Eastern Pacific).

2.2 SAFFIR–SIMPSON SCALE AND ASSOCIATED CYCLONE HAZARDS

The Saffir–Simpson Scale is a guideline for the damage potential of a tropical cyclone based solely on sustained windspeed (Saffir and Simpson, 1969). Potential cyclone damages due to storm winds, storm surges and storm waves associated with the five Saffir–Simpson categories are shown in Figure 2.1, Table 2.1 and 2.2.

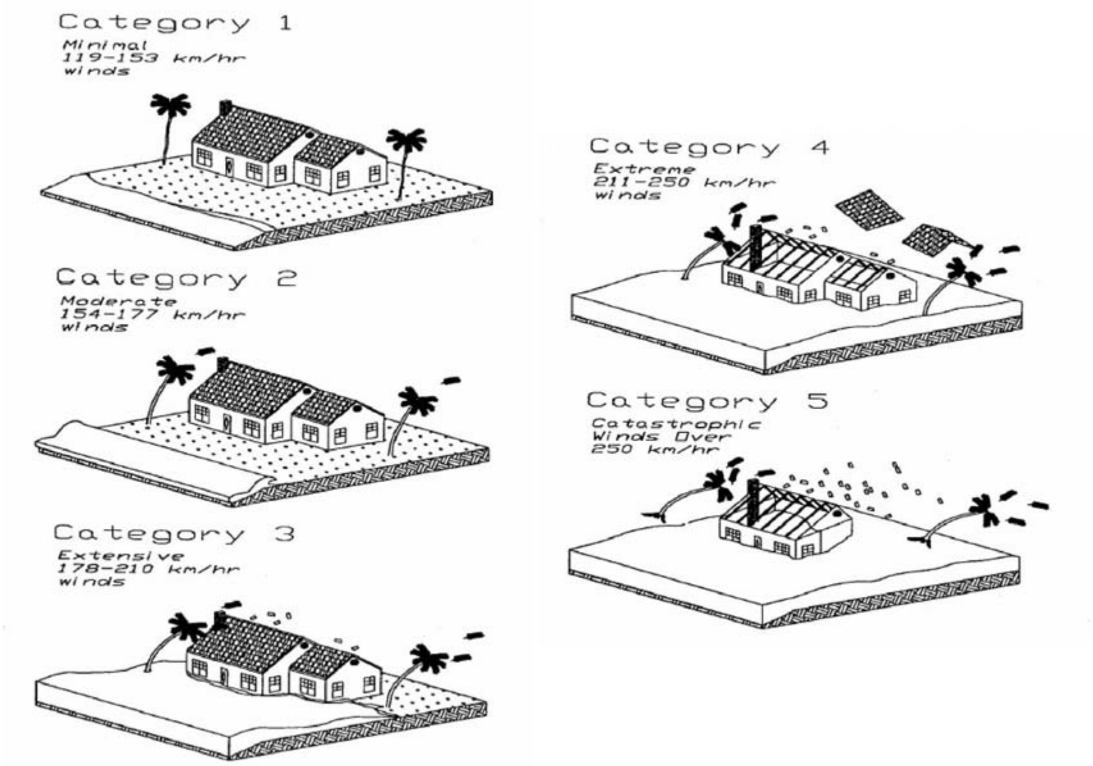
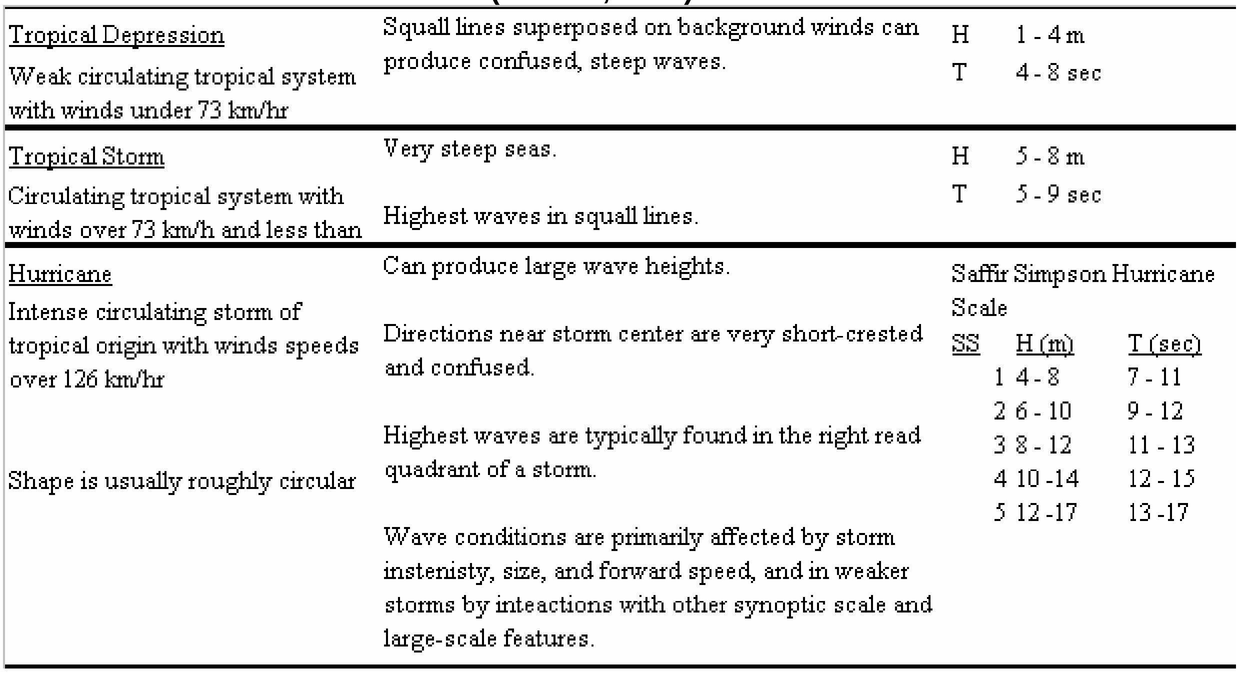


Figure 2.1 Windspeed based on the Saffir–Simpson Scale and associated cyclone damage levels (USACE, 2002)

Table 2.1 Amended Saffir–Simpson cyclone damage potential scale based on windspeed, storm surge heights and beach erosion volumes modified after Basillie (1998)

Cat	Central pressure [mb]	Wind speed [km/h]	Peak storm surge elevation above MSL [m]	Cyclone centre forward speed [km/h]	Storm surge rise time [hr]	Average beach erosion volume [m^3/m shoreline]	Max. beach erosion volume [m^3/m shoreline]	Damage potential
1	>980	119–153	1.2–1.7	50–88	2.5–4.5	3.0–8.3	6.3–17.6	Minimal
2	965–979	154–177	1.7–2.6	29–50	4.5–7.5	8.3–25	17.6–53	Moderate
3	945–964	178–210	2.6–3.8	19–29	7.5–11	25–63	53–133	Extensive
4	920–944	211–250	3.8–5.5	10–19	11–21	63–190	133–400	Extreme
5	<920	>250	>5.5	<10	>21	>190	>400	Catastrophic

Table 2.2 Local sea states with characteristic wave heights (H) and wave periods (T) generated by cyclones for the Saffir–Simpson categories (USACE, 2002)



Tropical Depression Weak circulating tropical system with winds under 73 km/hr	Squall lines superposed on background winds can produce confused, steep waves.	H 1 - 4 m T 4 - 8 sec
Tropical Storm Circulating tropical system with winds over 73 km/h and less than	Very steep seas. Highest waves in squall lines.	H 5 - 8 m T 5 - 9 sec
Hurricane Intense circulating storm of tropical origin with winds speeds over 126 km/hr Shape is usually roughly circular	Can produce large wave heights. Directions near storm center are very short-crested and confused. Highest waves are typically found in the right read quadrant of a storm. Wave conditions are primarily affected by storm instenisty, size, and forward speed, and in weaker storms by inteactions with other synoptic scale and large-scale features.	Saffir Simpson Hurricane Scale SS H (m) T (sec) 1 4 - 8 7 - 11 2 6 - 10 9 - 12 3 8 - 12 11 - 13 4 10 -14 12 - 15 5 12 -17 13 -17

2.3 CYCLONE-AFFECTED AREAS AROUND THE WORLD

Tropical cyclones develop in the following ocean basins: North Atlantic (NATL: 90° to 20°west, 5° to 25° north), western North Pacific (WPAC: 120° to 180° east, 5° to 20° north), eastern North Pacific (EPAC: 90° to 120° west, 5° to 20° north), South Indian (SIO: 50° to 115° east, 5° to 20° south), North Indian (NIO: 55° to 90° east, 5° to 20° north) and Southwest Pacific (SPAC: 155° to 180° east, 5° to 20° south). Figure 2.2 shows the relative worldwide distribution of cyclones over these basins (Abbott, 2006). While cyclones occur within 15°-wide bands in the northern and southern hemisphere, a few areas account for the bulk of the casualties and damage including: the Bay of Bengal, the Gulf of Mexico, the South China Sea and the Mozambique Channel. Cyclone impacts are particularly catastrophic on these coasts due to the typically perpendicular cyclone tracks, converging bays and shallow bathymetries.

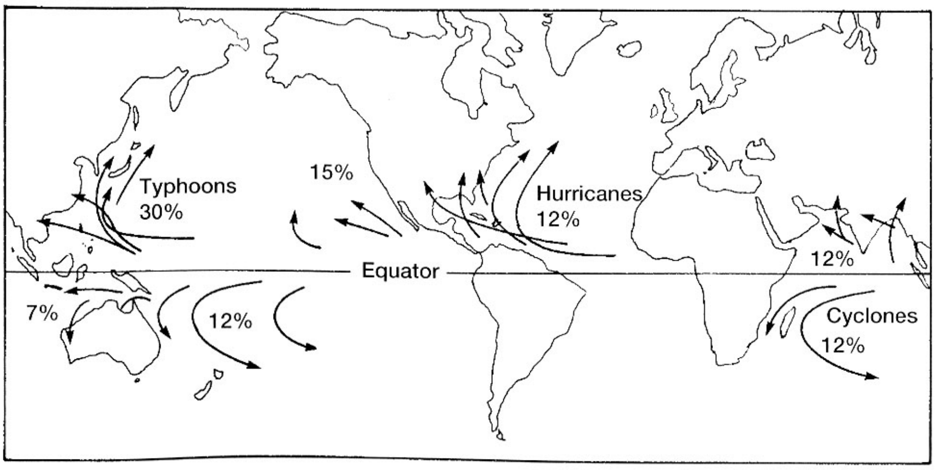


Figure 2.2 Typical tropical cyclone tracks with global distribution and local names (Abbott, 2006)

Webster *et al.* (2005) investigated the relationship between rising sea surface temperature (SST) and the frequency and intensity of tropical cyclones in each ocean basin. There has been much controversy over this issue, but the article outlines the relevant relationships between SST and tropical cyclones. Over the period of record from 1970 to 2004, the tropical ocean SST rose 0.5°C. The article indicates that there is no statistically significant trend in the total number of storms and the total number of storm days over that period with respect to the SST. There are apparent decadal-scale variations on the global scale that are similar to those in individual basins (Figure 2.3).

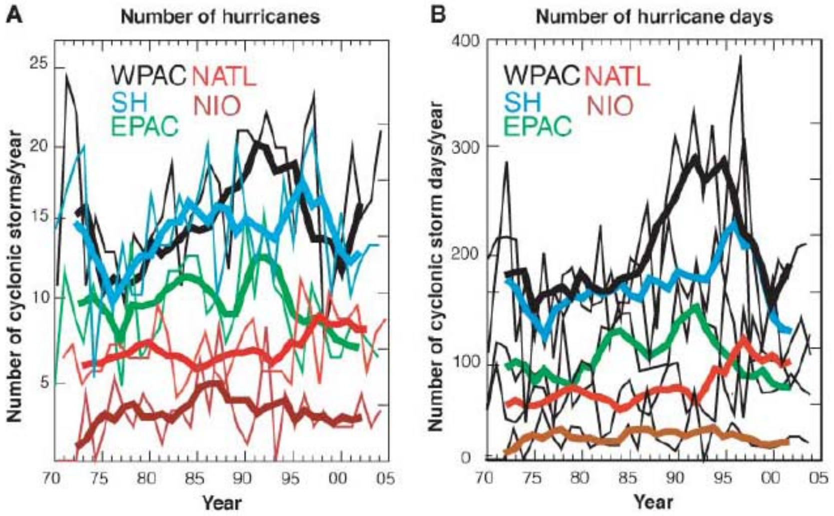


Figure 2.3 Regional time series for 1970 to 2004 for the NATL, WPAC, EPAC, NIO, and Southern Hemisphere (SIO plus SPAC) for (A) total number of cyclones and (B) total number of cyclone days. Thin lines indicate the year-by-year statistics. Heavy lines show the 5-year running averages (Webster *et al.*, 2005)

Except for the North Atlantic, all of the basins have seen a decrease in the number of cyclones and cyclone days over the past decade; however, there has been a significant increase in the number and percentage of very intense (category 4 and 5) storms as shown in Figure 2.4. This increase in most hazardous and damaging cyclones occurs in all of the basins with the largest increases in the Indian, North Pacific and Southwest Pacific oceans and the smallest increase in the North Atlantic. The increase in category 4 and 5 cyclones is most disturbing with regard to the protective role of mangrove and coastal forests as their effectiveness in protecting coastlines declines with increasing storm intensity.

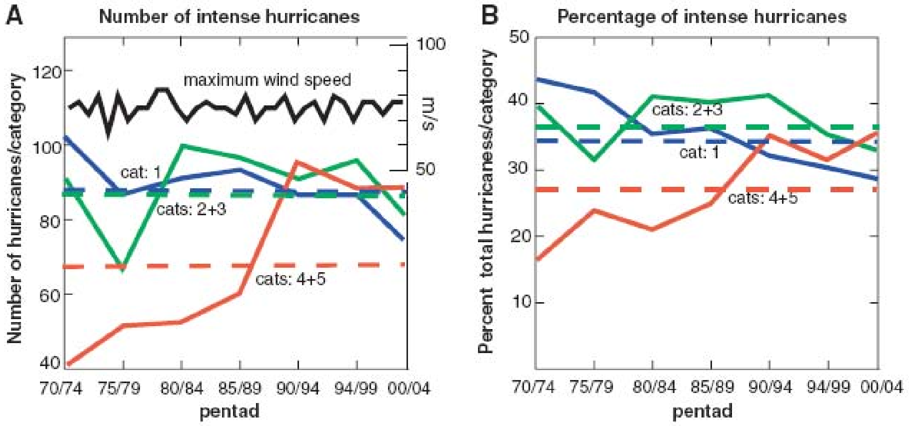


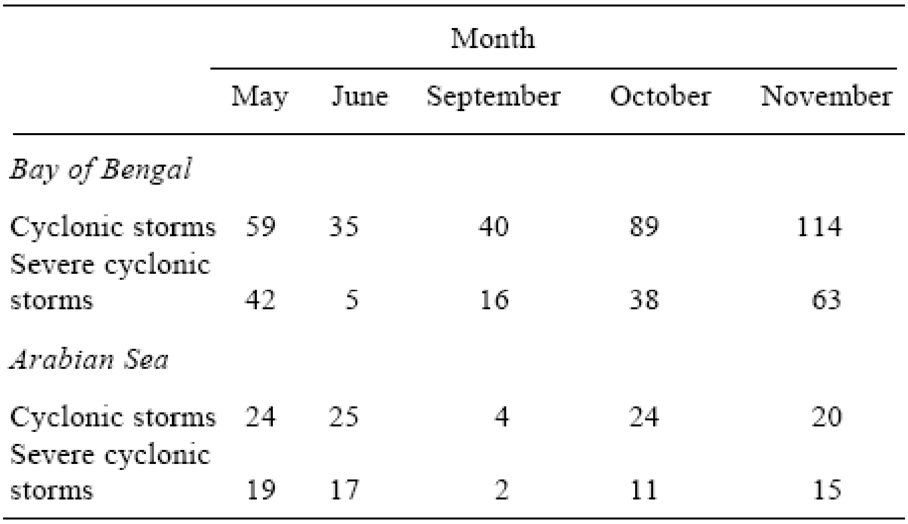
Figure 2.4 The number and percentage of intense cyclones from 1970 to 2004

These data correspond to the work done by Emanuel (2005), who created a power dissipation index (PDI) to measure the intensity and potential destructiveness of a cyclone. There is evidence that the SST is a major (but not the only) controlling factor of the PDI, and the report indicates there has been a near doubling of the PDI over the period of record. While Webster *et al.* (2005) reported stable upper bound limits on actual maximum intensity in the past, Emanuel proposed that potential and actual maximum intensities could increase with a continued increase in global warming.

2.4 NORTH INDIAN OCEAN TROPICAL CYCLONES

Singh *et al.* (2000) analysed 122 years (1877–1998) of tropical cyclone frequency in the North Indian Ocean. Approximately four times as many tropical cyclones occur in the Bay of Bengal compared to the Arabian Sea. Cyclones occur most often in May, October and November (Table 2.3), with an average of five to six tropical cyclones every year.

Table 2.3 Breakdown of cyclones by month, severity and sea in the North Indian Ocean



	Month				
	May	June	September	October	November
Bay of Bengal					
Cyclonic storms	59	35	40	89	114
Severe cyclonic storms	42	5	16	38	63
Arabian Sea					
Cyclonic storms	24	25	4	24	20
Severe cyclonic storms	19	17	2	11	15

Because of the heavy socio-economic impact suffered along the Bay of Bengal annually due to cyclones, it is important to track any change in frequencies. The highest number of severe cyclones occurs in November with an average of one per year. These cyclones usually hit the Andhra Pradesh or Tamil Nadu regions of the Indian coast, but the cyclones sometimes affect Bangladesh or Myanmar. Over the 122 years studied, the frequency of tropical cyclones in the Bay of Bengal during November has doubled. The second highest number of severe tropical cyclones occurs in May, and most of these cyclones strike Bangladesh or Myanmar.

Singh *et al.* (2000) concluded that cyclone frequency significantly increased in November and May (primarily in the Bay of Bengal), significantly decreased in June and September, and changed minimally during October. The overall frequency of tropical cyclones in the Bay of Bengal has a decreasing trend of 15 percent per hundred years, but November shows a 20 percent increase per 100 years *vis-à-vis* the rate of cyclones that reached severe cyclone stage.

Table 2.4 (De *et al.*, 2005) lists the most destructive cyclones to hit India and the surrounding area. Karim (2006) compiled a comprehensive list of cyclones to hit Bangladesh since 1960 (Table 2.5).

Table 2.4 Most destructive cyclones to hit India (modified after De *et al.* 2005)

Year	Name of Country	No. of Deaths	Storm surge (m)
1737	Hoogli, West Bengal (India)	300 000	12.2
1876	Bakerganj (Bangladesh)	25 000	3.0 - 12.2
1885	False point (Orissa)	5 000	6.7
1960	Bangladesh	5 490	5.8
1961	Bangladesh	11 468	4.9
1970	Bangladesh	200 000	4.0 - 5.2
1971	Paradeep, Orissa (India)	10 000	2.1 - 6.1
1977	Chirala, Andhra Pradesh (India)	10 000	4.9 - 5.5
1990	Andhra Pradesh (India)	990	4.0 - 5.2
1991	Bangladesh	138 000	2.1 - 6.1
1998	Porbander cyclone	1 173	
1999	Paradeep, Orissa (India)	9 885	9.1

Table 2.5 Most destructive cyclones to hit Bangladesh (modified after Karim, 2006)

Date	Year	Max. wind speed (km/hr)	Storm Surge (m)	Deaths		Date	Year	Max. wind speed (km/hr)	Storm Surge (m)	Deaths
9-Oct	1960	162	3.0	3 000		06-Nov	1971		2.4 - 5.5	-
30-Oct	1960	210	4.6 - 6.1	5 149		18-Nov	1971		2.4 - 4.0	-
09-May	1961	146	2.4 -3.0	11 466		09-Dec	1973	122	1.5 - 4.6	183
30-May	1961	146	6.1 - 8.8	-		15-Aug	1973	97	1.5 - 6.7	-
28-May	1963	203	4.3 - 5.2	11 520		28-Nov	1974	162	2.1 - 4.9	a few
11-Apr	1964	-	-	196		21-Oct	1976	105	2.4 - 4.9	-
11-May	1965	162	3.7	19 279		13-May	1977	122	-	-
31-May	1965	-	6.1 - 7.6	-		10-Dec	1981	97	1.8	2
14-Dec	1965	210	4.6 - 6.1	873		15-Oct	1983	97	-	-
01-Oct	1966	146	4.6 - 9.1	850		09-Nov	1983	122	-	-
11-Oct	1967	-	1.8 - 8.5	-		03-Jun	1984	89	-	-
24-Oct	1967	-	1.5 - 7.6	-		25-May	1985	154	3.0 - 4.6	11 069
10-May	1968	-	2.7 - 4.6	-		29-Nov	1988	162	1.5 - 3.0	2 000
17-Apr	1969	-	-	75		29-Apr	1991	225	6.1 - 7.6	138 000
10-Oct	1969	-	2.4 - 7.3	-		02-Jun	1991	100	1.8	-
07-May	1970	-	3.0 - 4.9	-		02-May	1994	200	-	170
23-Oct	1970	-	-	300		25-Nov	1995	100	-	6
12-Nov	1970	223	6.1 - 9.1	500 000		19-May	1997	225	4.6	126
08-May	1971	-	2.4 - 4.3	-		26-May	1997	150	3.0	70
30-Sep	1971	-	2.4 - 4.3	-						

The damage and destruction generated by these cyclones have not decreased. Loss of life, however, tends to show a decrease because of better weather forecasts and warnings, their dissemination, and disaster management strategies put in place by national weather services in conjunction with the significant role played by the World Meteorological Organization (WMO) through its regional meteorological centres (RMCs) that deal especially with tropical cyclones.

2.5 WESTERN PACIFIC OCEAN TROPICAL CYCLONES

Imamura and To (1997) compiled and summarized typhoon and flood data for 40 years and collected site information about the coastal problems by conducting field investigations along the coast of Viet Nam. Viet Nam continues to suffer from multiple human, economic and social damage owing to cyclones and flooding, even though an extensive flood control system has been developed. An increasing population with concentrations in hazardous coastal areas and the lack of funding for construction and maintenance of dykes and rivers are two of reasons for the continuing problem. Figure 2.6 shows the tracks of the two 1985 typhoons that successively devastated Viet Nam. Figure 2.7 shows the damage from human-induced and natural disasters in Viet Nam.

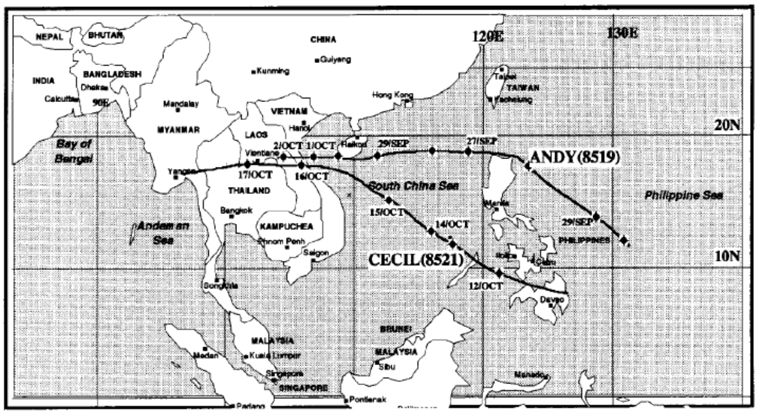


Figure 2.1 The tracks of typhoons Andy and Cecil that devastated central Viet Nam in 1985

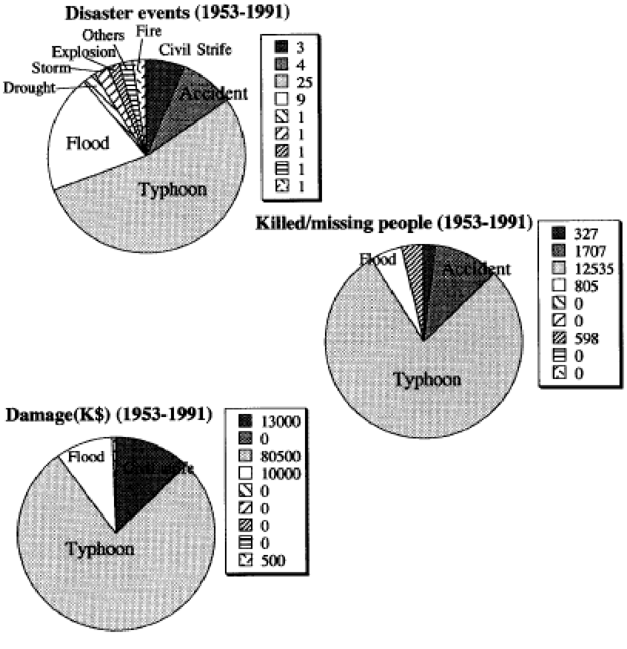


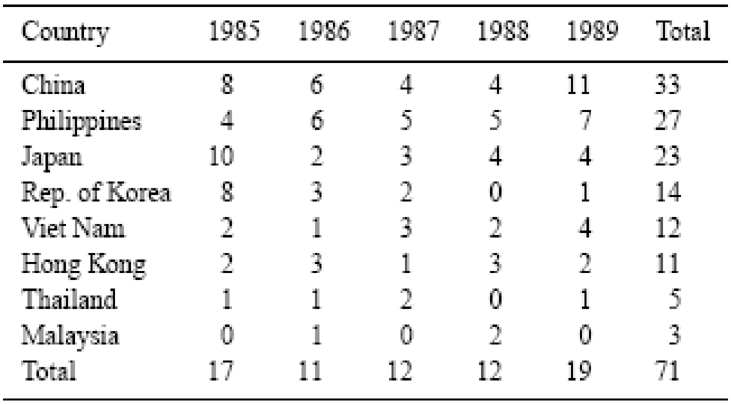
Figure 2.2 Estimated damage caused by human-induced and natural disasters in Viet Nam (1953–1991)

Statistical data for yearly frequency from 1954 to 1991, as well as numbers for submerged rice fields, deaths and calculations of losses from 1970 to 1990 (General Bureau of Hydro-Meteorology

[1980] and UN/DHA [1994]) indicate that during the 1960s and 1970s there were five years with more than eight typhoons, whereas only one occurred in the 1980s; this suggests that there was high typhoon activity from 1960 to 1980, which corresponds to the tendency recorded elsewhere in Southeast Asia, including Japan (Ohnishi, 1994). Typhoons start in March, peak in October and finally decrease at the end of the year. The period between June and November is considered to be the storm season.

Approximately one-third of the cyclones generated in the world occur in the Western North Pacific Ocean; consequently, Southeast Asia is always vulnerable. Table 2.6 summarizes 71 typhoons that caused damage to Southeast Asian countries from 1985 to 1989. Note that the totals each year do not add up, because each typhoon usually affected more than one country. China had the highest frequency at 46.5 percent; the Philippines and Japan were second (35.2 percent); the Republic of Korea, Viet Nam and Hong Kong Special Administrative Region were third (17.3 percent); and Thailand and Malaysia were fourth (5.6 percent). The number of typhoons hitting Viet Nam was almost half that of the Philippines, but higher than Thailand. The occurrence of typhoons decreases from the open sea to the coast. The report expected that Viet Nam would not be third but second in terms of losses because damage in Viet Nam has increased in spite of lower typhoon frequency. Financial losses in Japan and the Republic of Korea have decreased rapidly.

Table 2.6 Frequency of typhoons in Southeast Asian countries (1985–1989)



Country	1985	1986	1987	1988	1989	Total
China	8	6	4	4	11	33
Philippines	4	6	5	5	7	27
Japan	10	2	3	4	4	23
Rep. of Korea	8	3	2	0	1	14
Viet Nam	2	1	3	2	4	12
Hong Kong	2	3	1	3	2	11
Thailand	1	1	2	0	1	5
Malaysia	0	1	0	2	0	3
Total	17	11	12	12	19	71

3 CYCLONE IMPACT CHARACTERISTICS

3.1 RETURN PERIOD CALCULATIONS

The Indian state of Orissa on the Bay of Bengal coast has been hit by many tropical cyclones in the past 200 years. Chittibabu *et al.* (2004) compiled a comprehensive list of 128 tropical cyclones that struck Orissa from 1804 to 1999. Included in these strikes was the supercyclone of 29 to 30 October 1999, which killed approximately 10 000 people and had a 7.5-metre storm surge. Cyclonic flooding in the Bay of Bengal is associated with storm surges, high tides and high water levels due to the heavy rainfall. Chittibabu *et al.* (2004) calculated that the 1999 cyclone had a return period of approximately 50 years. Cyclones in 1831, 1885 and 1895 were also possible supercyclones. A location map of Orissa and an inundation map of Orissa districts caused by the aforementioned supercyclone in 1999 are given in Figure 2.8. Table 2.7 shows the India Meteorological Department (IMD) cyclone classification system.

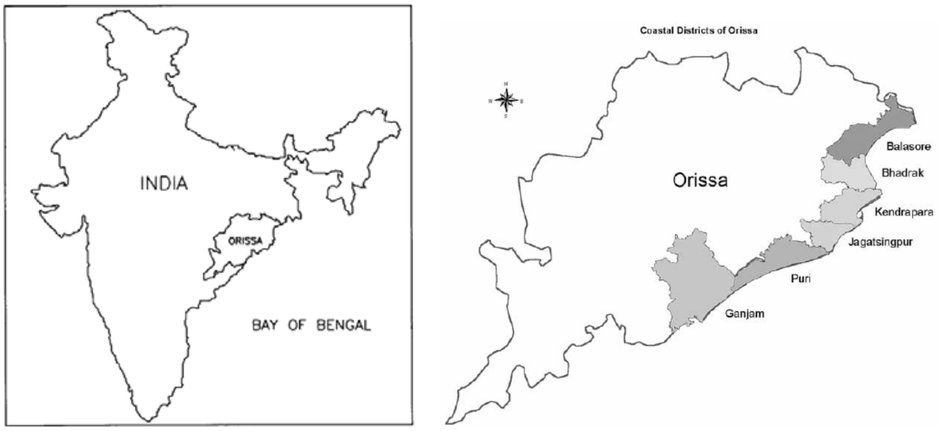


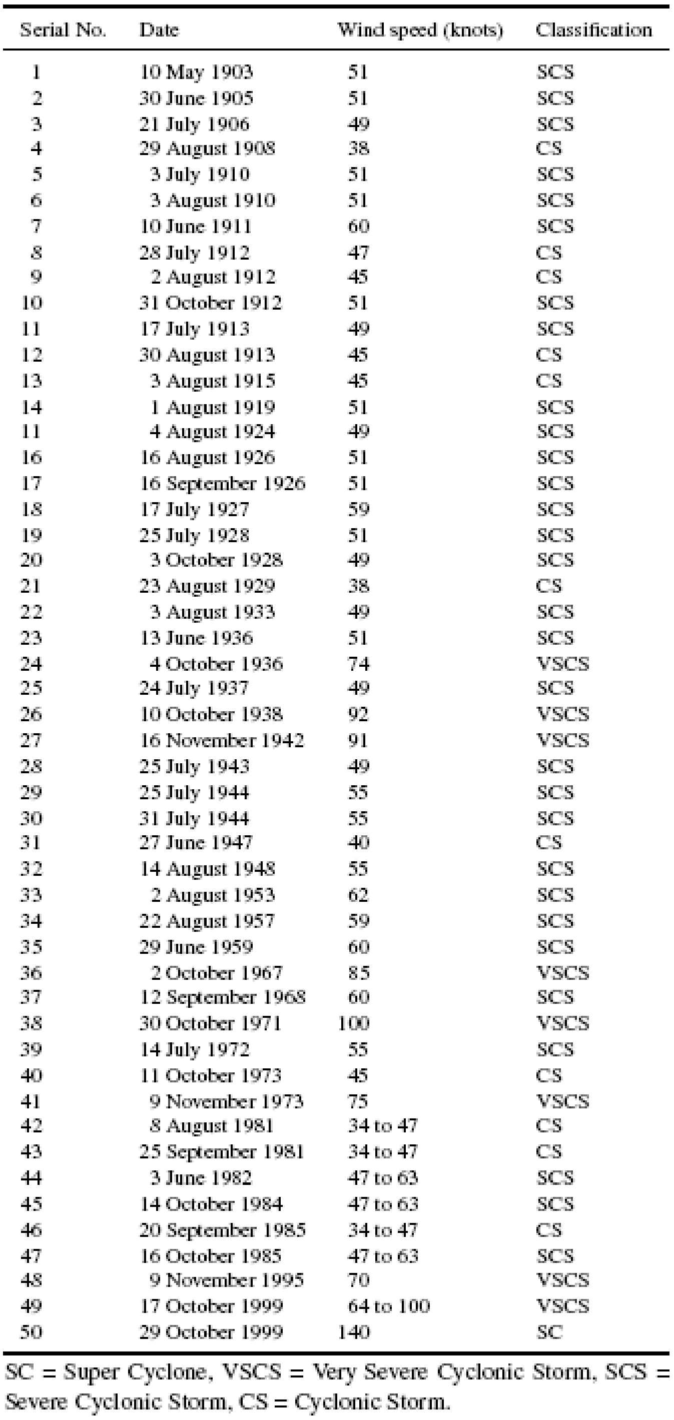
Figure 2.3 Location map of Orissa and the inundated areas of Orissa after the 1999 supercyclone

Table 2.7 IMD cyclone classification by sustained windspeed

Storm category	Abb.	Wind speed (knots)	Wind speed (kph)
Super cyclone	SC	> 120	> 221
Very severe cyclonic storm	VSCS	64 to 119	119 to 221
Severe cyclonic storm	SCS	48 to 63	88 to 118
Cyclonic storm	CS	34 to 47	63 to 87
Cyclonic depression	CDP	33 or less	62 or less
Cyclonic disturbance during monsoon	CD	(Not specified)	(Not specified)

Table 2.8 shows the individual tropical cyclones in Orissa as reported by the IMD. By sorting the historical data, the report shows the return periods for flooding in the nineteenth and twentieth centuries (Table 2.9). The report notes that minor events were eliminated in the twentieth century due to the construction of river embankments.

Table 2.8 Twentieth century cyclones in Orissa, India



Serial No.	Date	Wind speed (knots)	Classification
1	10 May 1903	51	SCS
2	30 June 1905	51	SCS
3	21 July 1906	49	SCS
4	29 August 1908	38	CS
5	3 July 1910	51	SCS
6	3 August 1910	51	SCS
7	10 June 1911	60	SCS
8	28 July 1912	47	CS
9	2 August 1912	45	CS
10	31 October 1912	51	SCS
11	17 July 1913	49	SCS
12	30 August 1913	45	CS
13	3 August 1915	45	CS
14	1 August 1919	51	SCS
11	4 August 1924	49	SCS
16	16 August 1926	51	SCS
17	16 September 1926	51	SCS
18	17 July 1927	59	SCS
19	25 July 1928	51	SCS
20	3 October 1928	49	SCS
21	23 August 1929	38	CS
22	3 August 1933	49	SCS
23	13 June 1936	51	SCS
24	4 October 1936	74	VSCS
25	24 July 1937	49	SCS
26	10 October 1938	92	VSCS
27	16 November 1942	91	VSCS
28	25 July 1943	49	SCS
29	25 July 1944	55	SCS
30	31 July 1944	55	SCS
31	27 June 1947	40	CS
32	14 August 1948	55	SCS
33	2 August 1953	62	SCS
34	22 August 1957	59	SCS
35	29 June 1959	60	SCS
36	2 October 1967	85	VSCS
37	12 September 1968	60	SCS
38	30 October 1971	100	VSCS
39	14 July 1972	55	SCS
40	11 October 1973	45	CS
41	9 November 1973	75	VSCS
42	8 August 1981	34 to 47	CS
43	25 September 1981	34 to 47	CS
44	3 June 1982	47 to 63	SCS
45	14 October 1984	47 to 63	SCS
46	20 September 1985	34 to 47	CS
47	16 October 1985	47 to 63	SCS
48	9 November 1995	70	VSCS
49	17 October 1999	64 to 100	VSCS
50	29 October 1999	140	SC

SC = Super Cyclone, VSCS = Very Severe Cyclonic Storm, SCS = Severe Cyclonic Storm, CS = Cyclonic Storm.

**Table 2.9 Return periods for flooding in Orissa:
(a) nineteenth century, (b) twentieth century**

(a)

Event	Flood depth (m)	Return period (years)
Minor	<1.5	1.5
Moderate	1.5 to 3.0	3.5
Severe	>3.0	9

(a)

(b)

Event	Flood depth (m)	Return period (years)
Moderate	1.5 to 3.0	4
Severe	>3.0	10

Accurate methods to determine the maximum windspeed (and therefore intensity) have only been available since 1971. Hence, the 16 moderate to severe storms from 1971 to 2000 were used for the computer simulations by Chittibabu *et al.* (2004). These tracks were used to synthesize six tracks (one intersecting each coastal district) to provide more complete geographical coverage of the coastal area (Figure 2.9).

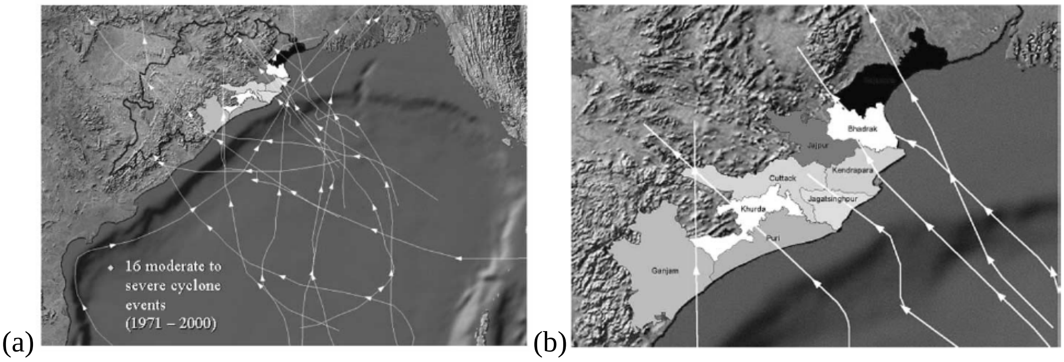


**Figure 2.4 (a) Cyclone tracks impacting the coast of Orissa from 1971 to 2000
(b) six synthesized generic cyclone tracks (Chittibabu *et al.*, 2004)**

These tracks were used with the Indian Institute of Technology (ITT-D) numerical storm surge model to calculate the storm surges along the Orissa coast. It should be noted that the surge values in the southern part of Orissa are almost half of those in the northern part due to the nearshore topography and orientation of the coastline with respect to the storm track. Combining these storm surge data with a tidal prediction model (WXTide) and wave setup, Chittibabu *et al.* predicted the total water level for a 50-year return period (Figure 2.10).

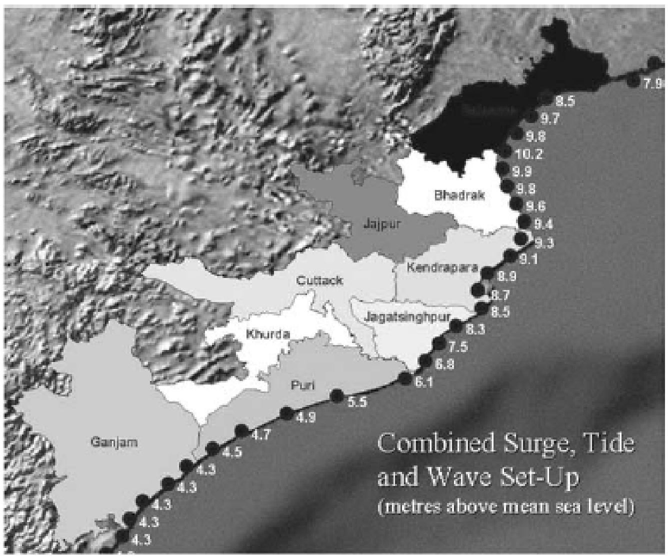


Figure 2.5 Total water level on a 50-year return basis (Chittibabu *et al.*, 2004)

A similar study was conducted for Bangladesh (Kabir *et al.*, 2006). The report discussed the creation, calibration and validation of hydrodynamic, cyclone and storm surge models using 17 major cyclones in Bangladesh from 1960 to 2000. Using a statistical analysis of the models, surge levels were calculated for the 10-, 20-, 50- and 100-year return periods. Figure 2.11b shows the calculated surges for the 100-year return periods. The analysis indicated that the areas around Sandwip Island and the Meghna River mouth have the highest storm surges. The computed storm surge levels match the areas affected by 1970, 1985 and 1991 cyclones (Figure 2.11a). The Sundarbans mangrove forests to the west of the Ganges River Delta are the largest in the world extending up to 80 kilometres into the Bay of Bengal; they reduce cyclone impacts significantly. This is the prime example of natural cyclone impact mitigation.

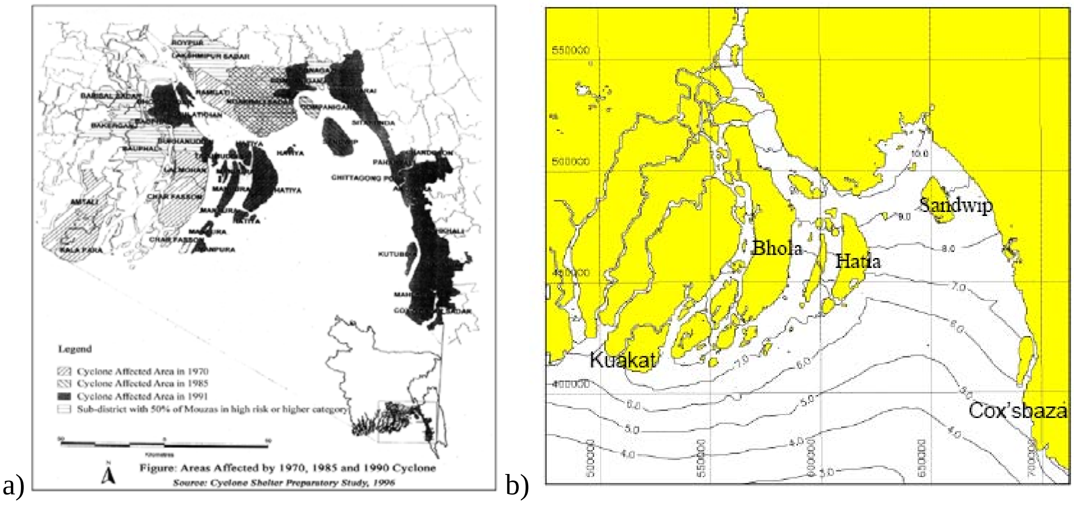


Figure 2.6 Bangladesh storm surges:
(a) Areas most affected by historic cyclones (Karim 2006)
(b) computed 100-year return period surge levels (Kabir *et al.*, 2006)

3.2 VULNERABILITY TO CYCLONES

Dube *et al.* (2004) created models to simulate the storm surgesfrom past cyclones in the head of the Bay of Bengal (Orissa, West Bengal and Bangladesh) and discussed how each of the storms that were modeled formed and how the storms affected the specific areas. Dube *et al.* (1997) also discussed storm surges in the Bay of Bengal and why the area is affected to such an extent by extreme sea levels. The reasons were summarized by Ali (1979) as follows:

- coastal waters (shallow bathymetry extending tens of kilometres offshore);
- convergence of the bay;
- high astronomical tides;
- thickly populated low-lying islands;
- favourable cyclone tracks impacting perpendicular to coastline; and
- innumerable inlets and river systems.

Hossain and Singh (2006), using a geographic information system, developed a method to assess the vulnerability of people in India. They conceptualized vulnerability as the exposure to hazard (cyclone) and the coping capacity of the people (for example, provision of an early warning system, capital) to adapt and reduce adverse impacts. This coping capacity also includes defense mechanisms and access to the resources (such as education, infrastructure). The report assigned risk levels from 1 (low) to 4 (high). Figure 2.12 shows the population density of India (darker purple indicates high density) and the populations in the high-risk states. Per capita income versus the assigned risk level is given in Figure 2.13, with the poorest people being the most vulnerable.