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Mitigation of Flooding and Cyclone Hazard in Orissa, India

P. CHITTIBABU[2], S. K. DUBE[1], J. B. MACNABB[2], T. S. MURTY[2], A. D. RAO[1], U. C. MOHANTY[1] and P. C. SINHA[1]
[1]*Centre for Atmospheric Sciences, Indian Institute of Technology, Hauz Khas, New Delhi, 110 016, India;* [2]*W.F. Baird & Associates Coastal Engineers, Suite 500, 1145 Hunt Club Road, Ottawa, Canada, K1V 0Y3*

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Abstract. Storm surges generated by the strong tangential wind stresses and normal atmospheric pressure gradients at the sea surface due to tropical cyclones (TC'S) have been studied with the goal of detecting any significant and systematic changes due to climate change. Cyclone and storm surge data for the 19th and 20th centuries for the Bay of Bengal coast of the state of Orissa in India are available to varying degrees of quality and detail, the data being more scientific since the advent of the India Meteorological Department in 1875. Based on more precise data for the period 1971 to 2000, statistical projections have been made on the probable intensities of tropical cyclones for various return periods. The super cyclone of October 29, 1999 (SC1999) appears to have a return period of about 50 years. The cyclones of 1831, 1885 and possibly the one in 1895 could have been super cyclones. During the 19th century, there were 72 flooding events associated with cyclones, whereas in the 20th century there were only 56 events. There was no observational evidence to suggest that there was an increase either in the frequency or intensity of cyclones or storm surges on the coast of Orissa. However, the impact of cyclones and surges is on the increase due to increase of population and coastal infrastructure.

1. Introduction

Storm surges generated by tropical cyclones (TC's) are considered. As an example of surges from TC's, the Bay of Bengal coast of Orissa in India (Figure 1) is used.

The state of Orissa situated on the Bay of Bengal coast of India periodically experiences loss of life and severe damage from tropical cyclones originating in the Bay of Bengal (Murty *et al.*, 1986; Dube *et al.*, 1994, 1997, 2000a, b; Das *et al.*, 1983). The coastal districts of Orissa (Figure 2) have experienced in the past, severe flooding, not only due to storm surges originating in the Bay of Bengal, but also flooding from the rivers as well as from heavy precipitation associated with tropical cyclones and monsoon depressions. These flooding events in the deltaic area of Orissa (Figure 3) arise due to a highly complex and non linear interaction of the storm surge, the tide, coastal setup due to short period wind waves, normal river discharge and additional river discharge from the rivers swollen by heavy rain fall as well as direct flooding of the deltaic land by intense rainfall over several

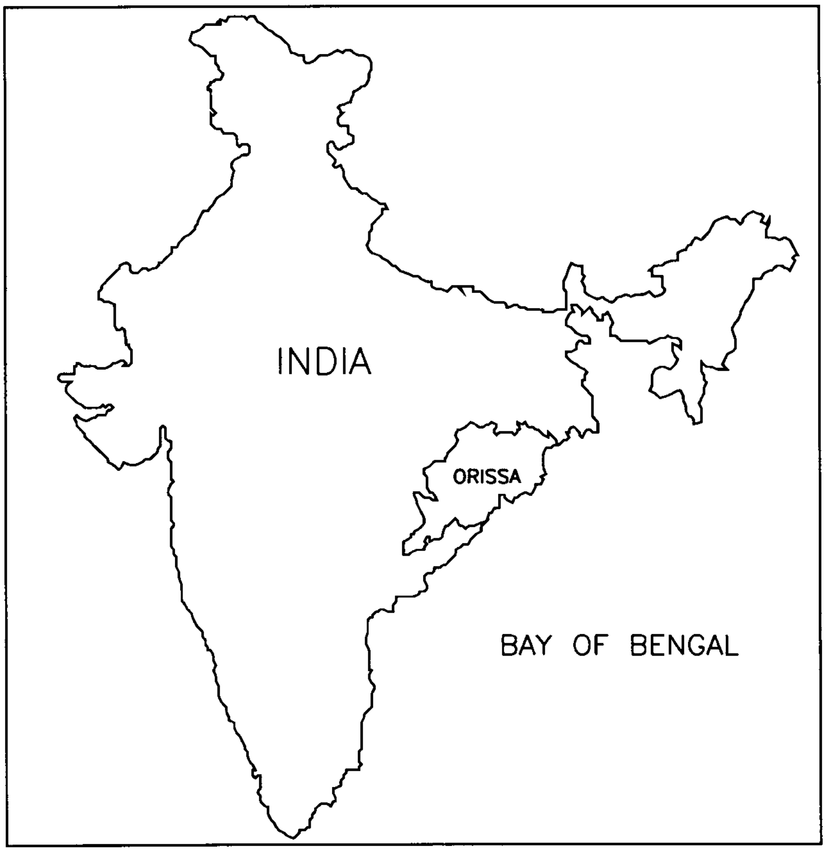

Figure 1. Bay of Bengal Coast of India showing the location of the state of Orissa.

hours to two to three days, making it very difficult for all the excess water either to seep into the ground water table or drain into the Bay of Bengal. Figure 3 shows an inundation map of the Orissa delta associated with the super cyclone of 1999 (SC1999). A comprehensive database (Table II) shows flooding events on the Orissa coast during last two centuries. The decrease in the 20th century could be due to several factors, which include: construction of river embankments starting in the later part of the 19th century (there by eliminating minor flooding events) and climate change due to natural causes.

It will be shown that the 1999 super cyclone has approximately a 50 year return period. It is interesting to note that the severe flooding experienced in the deltaic area (as well as some flooding in the upper reaches of the rivers) during the June–July 2001, also has roughly a return period of 50 years. In general, almost all the loss of life and over ninety per cent of the damage associated with a cyclone event is due to flooding, with the remaining ten per cent due to the direct action of wind (on trees, power poles, buildings, etc) (Gonnert *et al.*, 2001). Flooding associated with cyclones is due, in varying degrees, to the following three phenomena:

Figure 2. Coastal districts of Orissa.

- An increase in water level (or storm surge) in the Bay of Bengal produced by low pressure and the strong wind field of the cyclone.
- High tides in the Bay of Bengal.
- High water levels in the rivers as a result of the heavy rainfall associated with the cyclone.

For this study the magnitudes of the sea level rise associated with cyclones were estimated by undertaking computer simulations of storm surges. The resulting data were combined with typical tidal elevations to predict the total increase in sea level elevations for which the flood protection systems must be designed.

2. Cyclones Affecting Orissa

Some of the cyclone parameters that are required for storm surge computations are as follows:

- Central pressure deficit (ΔP) of the cyclone measured in hectopascals (hPa). This is the difference between the pressure at the center of the cyclone and the standard ambient atmospheric pressure at mean sea level (1,013.2 hPa).
- Maximum sustained wind speed, W_{max} measured in knots.

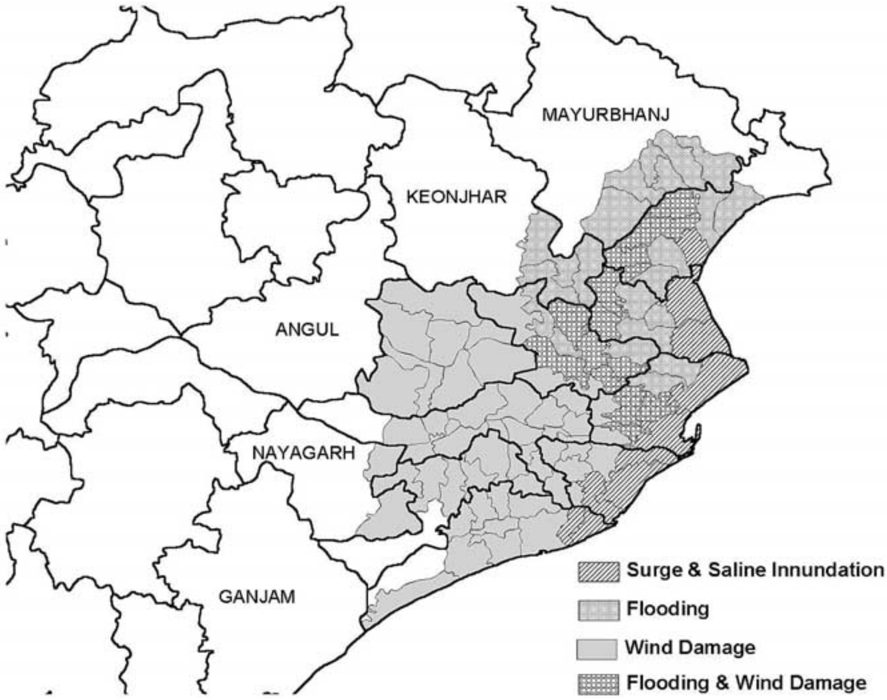

Figure 3. Flooding due to super cyclone.

Table I. India Meteorological Department (IMD) cyclone classification by sustained wind speed

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)

- Radius of maximum winds, R_{max} measured in km. This is the distance between the cyclone center and the location of the maximum wind speed.
- Location of the cyclone track.

The intensity of cyclonic disturbance is reported as the maximum sustained wind speed, W_{max} as well as the central pressure deficit (ΔP). When defining the intensity of the cyclone using sustained wind speeds, the following international classification system is used (as shown in Table I):

For the coast of Orissa, descriptive cyclone and surge data are available for the 19th and 20th centuries and instrumentally observed data began to be available since 1875 when the India Meteorological Department (IMD) was established. Starting in the 1960's, with the advent of remote sensing techniques through weather satellites, the quality of data, as well as the geographical coverage has improved substantially.

This discussion includes tropical cyclones (TC's) originating in the Bay of Bengal and impacting the coastal region of Orissa. TC's during the pre (April–May) and post (October–December) monsoon periods are considered. In addition intense depressions during the monsoonal periods, and especially during the south-west monsoon are also considered. However, attention is paid only to those situations where either flooding from the Bay of Bengal (storm surge) or flooding in the rivers of Orissa (Figure 2) occurred due to heavy rainfall associated with either the TC's or the MD's (monsoonal depressions). A few severe cyclones that caused wind damage, but no flooding were also included.

In this study, two different databases were used, which have some overlap: the first one is the cyclone database of the India Meteorological Department (IMD) and this database covers the period 1877–2000. The IMD came into existence in 1875, however prior to this, descriptive information on cyclones in Orissa was provided by the British East India Company for the period 1804 to 1875.

A second database on cyclones in Orissa covering the period 1804 to 2000 was prepared based on the East India Company records, described in Bhatta (1997), various reports prepared by the government of Orissa, various publications by the IMD and also SAARC Meteorological Research Centre (SMRC, 1998), Das (2000) and Dube *et al.* (2000a, b). To our knowledge, this is the most comprehensive cyclone database available for Orissa at present covering the 19th and 20th centuries.

Table II lists this database. Figure 4 shows in histogram format, the number of tropical cyclones that made a landfall on the coastline of each of these six districts. This diagram is prepared based on the first database referred to above and covers the period 1877 to 2000 based on data of the India Meteorological Department (IMD).

An examination of Table II reveals that there were a total of 128 flooding events associated with TC's and monsoon depressions (MD) in Orissa during the 19th and 20th centuries.

According to Figure 4, the maximum impact was in the Balasore District (the northern most coastal district of Orissa), followed by Puri and Ganjam districts, as far as the frequency of cyclone landfall is concerned.

Table II. Flooding due to cyclones in Orissa (based on Bhatta, 1997; SMRC, 1998; Anon., 1972, 1999a, b; Chandra, 1986; Choudhury *et al.*, 2001; Das, 2000; Ghosh, 1997; Law, 1968; Pandey *et al.*, 1986)

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(1) 1804	After the British East India company conquered Orissa in October 1803, the serious problems, which the administration faced, were not political, but how to deal with natural disasters (cyclones), which seem to happen almost every year.		
(2) 1806	Cyclone mentioned.		Flooding mentioned.
(3) 1807	Cyclone mentioned.		Flooding mentioned.
(4) 1809	Cyclone mentioned.		Flooding mentioned.
(5) 1812	Cyclone mentioned.		Flooding mentioned.
(6) 1814	Cyclone mentioned.		Flooding mentioned.
(7) 1817	Cyclone mentioned.		Flooding mentioned.
(8) 1820	Cyclone mentioned.		Flooding mentioned.
(9) 1823 27 May	"Balasore, unbelievably violent winds and rain".	Inundation up to 10 km inland. Terrible storm surge.	Several ships and whole villages disappeared.
(10) 1826	Cyclone mentioned.		Flooding mentioned.
(11) 1831	Balasore	2 to 5 m surge.	22,000 humans.
31 October	Following this cyclone the Superintendent of Embankments, suggested building a bund along the sea coast.	Extensive inundation.	83,566 cattle.
(12) 1832 October	Balasore. Storm was more violent than 1823 and 1831 events.	The surge was very destructive.	
(13) 1833 May	Balasore district was affected. Second recorded cyclone in northern Bay of Bengal in May. First one in 1823.		Second recorded cyclone in the Bay of Bengal in May. First one in 1823.
(14) 1834 May	Severe cyclone.	No flooding.	Wind damage.
(15) 1835	Cyclone mentioned.		Flooding mentioned.
(16) 1837	Cyclone mentioned.		Flooding mentioned.
(17) 1838	Cyclone mentioned.		Flooding mentioned.
(18) 1840 April 27–May 1	Puri, Cuttack and Balasore districts. Cyclone crossed south of Puri.		Most severe in Puri district.
(19) 1841	Cyclone mentioned.		Flooding mentioned.
(20) 1842	Severe storm over Cuttack and Puri districts.		Most violent over Puri.
(21) 1844	Cyclone mentioned.		Flooding mentioned.
(22) 1845	Cyclone mentioned.		Flooding mentioned.
(23) 1846	Cyclone mentioned.		Flooding mentioned.
(24) 1847	Severe cyclone.	No flooding	Wind damage.

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(25) 1848 October 13–14	Balasore, Cuttack and Puri districts were affected.	Surge.	Surge destroyed crops in Cuttack district. A part of the tower of Konark Temple was blown off.
(26) 1850 April	Worst cyclone since 1832. False Point to Midnapore.	Surge	Great damage by surge at the mouth of Subarnarekha River.
(27) 1851 October 20–23	Severe cyclone in Cuttack, Balasore districts.		Crops damaged. Five vessels driven ashore. Six ran into Baitarani River.
(28) 1852	Cyclone mentioned.		Flooding mentioned.
(29) 1854	Cyclone mentioned.		Flooding mentioned.
(30) 1855	Cyclone mentioned.		Flooding mentioned.
(31) 1856	Cyclone mentioned.		Flooding mentioned.
(32) 1857	Cyclone mentioned.		Flooding mentioned.
(33) 1858	Cyclone mentioned.		Flooding mentioned.
(34) 1859	Cyclone mentioned.		Flooding mentioned.
(35) 1862	Cyclone mentioned.		Flooding mentioned.
(36) 1863	Cyclone mentioned.		Flooding mentioned.
(37) 1864 October	Severe cyclone over False Point. This cyclone and another one in A.P. in November convinced the British Government to have a Met. Dept. which was formed in 1875 (I.M.D.)	Surge	Great damage in Balasore and Cuttack districts.
(38) 1866	Cyclone mentioned.		Flooding mentioned.
(39) 1867 October 31– November 1	Severe cyclone hurricane force winds at False Point.	Small surge. No river flooding.	No great loss of life or property damage.
(40) 1868	Cyclone mentioned.		Flooding mentioned.
(41) 1870	Cyclone mentioned.		Flooding mentioned.
(42) 1871	Cyclone mentioned.		Flooding mentioned.
(43) 1872 1st week of July	Cyclone affected 10 miles north to 10 miles south of Balasore.	High floods in Mahanadi. Surges in Puri, Cuttack districts.	42,211 animals killed. 21 people killed.
(44) 1874 October 15	Southern part of Balasore district.	Surge at Chandbali.	Several ships destroyed. Humans – 105, Cattle – 10,000.
(45) 1875	Cyclone mentioned.		Flooding mentioned.
(46) 1877	Cyclone mentioned.		Flooding mentioned.
(47) 1879	Cyclone mentioned.		Flooding mentioned.
(48) 1881	Cyclone mentioned.		Flooding mentioned.
(49) 1882	September 6–15	Crossed south Orissa coast.	Flooding mentioned.
(50) 1883	Cyclone mentioned.		Flooding mentioned.
(51) 1884	Cyclone mentioned.		Flooding mentioned.

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(52) 1885 September 19–23	Cuttack (False Point) 243 kph winds. Pc = 919 hPa. Cyclone traveled with a speed of 21 kph. The relief operations continued until 1888. This severe cyclone is still referred to as "Sunia Batasa".	7 m surge at False Point. 6.36 m at Jumbo	5,000 deaths by drowning. 300 deaths by falling trees. 50,000 houses destroyed. 10,000 cattle dead. Mishra gave the following data: Humans killed – 22,440, cattle killed – 26,973, number of houses destroyed – 100,000, number of fallen trees – 152,000, money spent by government for relief and restoration 139,126 Rs.
(53) 1886	Cyclone mentioned.		Flooding mentioned.
(54) 1887 26 May	False Point to Sagar Island.	Major Surges (at least 2 ft (0.61 m) over spring tide) at False Point, Jumbo	Ship capsized, 776 drowned. Worst marine disaster in modern India
(55) 1888 September 13–20	Unique – a Pacific typhoon re-energized. Did not originate in the Andaman Sea like all others. Crossed at False Point.		Minor damage.
(56) 1889 September 16–22	Cyclonic storm crossed coast of Ganjam District near Gopalpur.		
(57) 1889 November 19–20	A rather remarkable example of the very rapid disintegration of a very powerful storm due to low range hills in Orissa. Crossed Ganjam coast near Gopalpur.	At Puri about 20 foot (6.1 m) surges. Also smaller surges in Chilka Lake.	Great damage to crops in Cuttack, Puri districts
(58) 1890 18 June	North of Gopalpur to Cuttack.	Surge	Extensive damage by the surge
(59) 1890	Near Puri.		Limited damage
1st July	Heavy rain.		
(60) 1890 September 22–28	Cyclonic storm crossed the coast between Visakhapatnam and Gopalpur.		
(61) 1891 September 19– 3 October	Crossed the coast south of False Point.		
(62) 1891 November 1–7	Between Puri and False Point and up to 50 miles inland its worst effects were felt.		Several sloops and large steamers were either destroyed or damaged 548 humans, 3,592 cattle killed.
(63) 1892 10 June	Lowest pressure 28.67 inches of mercury. 1 mb = 0.3 inches Pc = 955.7 mb. Fierce cyclone between Puri and False Point.		Very heavy rain. The cyclone affected a very large area.
(64) 1892 September 7–12	Cyclonic storm crossed the coast near Puri		

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(65) 1893 May 23–26	One of the most severe cyclones in May in the Bay of Bengal in 25 years.		Excessive rain over Balasore, Puri, Cuttacks, Keonjhar districts. 5,000 houses and river embankments destroyed.
(66) 1893 September 9–19	Crossed the coast between Balasore and Sagar Island.		
(67) 1893 September 21–26	Cyclonic storm crossed the coast between False Point and Puri.		
(68) 1894 July 11–17	Cyclone mentioned.		Flooding mentioned.
(69) 1895 September	False Point.	Up to 7 m water levels (Tide plus surge) on northern coast of Orissa.	More than 5,000 deaths of humans.
(70) 1898 September 11–16	Cyclonic storm crossed Orissa coast.		
(71) 1900 September 14–28	Crossed the coast near Chandbali.		
(72) 1900 October 6	Heavy rain fall.	Floods in Puri for the second time in the year.	
(73) 1901 November	2 cyclones. Heavy rain fall		Lot of damage north of Balasore.
(74) 1905 September 22–26		Cyclonic storm crossed the coast between Visakhapatnam and Gopalpur.	
(75) 1909 October 26–27	Ganjam district severely affected, Puri and Balasore less affected, violent winds. Less Rain.		22 humans and many cattle killed. Damage in several lakhs of rupees. 15 lakhs damage in Gopalpur alone. The Madras government gave RS 5,000 for relief effort in Ganjam district.
(76) 1910 May 13–17	Crossed the coast near Gopalpur		
(77) 1911 September 20–24	Severe cyclone crossed the coast between Visakhampatnam and Gopalpur		
(78) 1912 October 28– November 2	Severe cyclone crossed the Orissa-West Bengal coast.		
(79) 1923 November 13–18	Ganjam district including Srikakulam area of A.P. severe cyclone.	High floods in the rivers in Ganjam district. Puri district was also affected.	Immense destruction of communication services including railways. Considerable damage to crops. 20 humans and a few hundred cattle killed. A large number of public and private properties including irrigation works were damaged.

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(80) 1924 November 19	Cyclone crossed Ganjam district near Gopalpur.		Much damage in Mandasa and Uddanam in Tekkali Taluk (now in A.P.). Roads within a radius of 40 miles from Berhampur were damaged. Many cattle killed. Damage to crops in part of Puri district. Irrigation tanks, plantations and some houses were damaged in South Ganjam district.
(81) 1926 September 14–24	Crossed North Orissa coast.	The Storm caused floods in M.P.	Heavy loss of human lives and cattle.
(82) 1928 October 1–6	Cyclonic storm crossed the coast north of Puri.		Considerable damage to trees, roads, houses, even PUCCA buildings in Puri.
(83) 1933 August 2–4	Crossed the coast between Chandbali and Balasore.	Floods in Cuttack	Loss of life in Cuttack. Homes destroyed.
(84) 1936 October	Cuttack, Puri, Balasore and Dhenkal districts were hit by a cyclone.	Floods in Mahanadl, Kathjori and Brahmani Rivers.	Considerable damage to crops houses and trees. Several country boats and steamers were capsized.
(85) 1938 October 9–10	Severe cyclone hits Ganjam and Puri districts.		Maximum damage in Chatrapur Taluk of Ganjam district. 2,000 acres of paddy land destroyed in that district. In Puri district, paddy fields were flooded by salt water. Houses damaged in Gopalpur.
(86) 1942 October 16	Very severe cyclone hits Balasore district. Mayurbhanj, Puri, Cuttack and Ganjam districts were also affected.		Exhaustive effects of damage are contained in 12 files of the Revenue Commissioner.
(87) 1942 November 15–16	Less severe than one on 16 October 1942. The cyclone was close to Orissa coast and weakened.		Coastal strip along Ganjam and Puri districts severely damaged. Great loss of life.
(88) 1943 September 22–28	Crossed the coast near Balasore.		
(89) 1943 October 30–31	A moderate cyclone hits Puri and Ganjam districts.		
(90) 1948 August 12–14	Severe cyclonic storm crossed the coast near Balasore.		
(91) 1950 September 12–14	Cyclonic storm crossed Orissa coast south of Balasore.		Widespread rain, locally heavy in some areas.
(92) 1951 July 22–28	Crossed the coast near Puri.		

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(93) 1953 September 21–29	Cyclonic storm crossed the coast between Chandbali and Balasore.		
(94) 1955 September 29–5 October	Crossed the coast between Puri and Chandbali.		
(95) 1957 August 19–24	Cyclonic storm crossed between Gopalpur and Puri.		Wide spread rain.
(96) 1959 June 27–2 July	Cyclonic storm crossed the coast at Chandbali.		It caused very heavy rain in the Southern sector of the storm.
(97) 1959 September 29–1 October	Cyclone hits Balasore, Cuttack and Mayurbhanj districts. It crossed the coast near Balasore.	At Chandbali, Basudebpur, Bhograi, Balasore, Baliapal and Basta.	151,083 acres of paddy land destroyed in Balasore district. 32,287 acres in Cuttack district. One interesting observation, 54 acres of paddy land was covered by sand in Cuttack district. In Mayurbhanj district 2,000 acres of rabi crops were damaged. In Balasore District – people killed – 75, cattle killed – more than 1,000, paddy crops destroyed – 800,000 acres.
(98) 1967 October 9–11	Crossed the coast between Puri and Paradeep.	Water levels up to 9 m (this could be an over-estimate) at Paradeep. Surge penetrated 25 km inland.	1,000 people killed, 50,000 cattle killed. Damage in crores of rupees.
(99) 1968 September 10–12	Crossed the coast near Gopalpur		
(100) 1968 September 26–28	Crossed the coast near Gopalpur.	Flooding.	78 people died. 22,285 animals died. Damage in Ganjam and Puri districts is about 9 M USD (at 1968 price levels). 11,589 cattle, 9,982 goats and sheep, 127 pigs and 587 fowl died.
(101) 1968 September 29–2 October	Severe cyclonic storm crossed the coast near Gopalpur.		
(102) 1968 October 21–28	Severe cyclonic storm crossed the coast near Puri. Floods in Chilika Lake. Number of people, thousands of cattle killed. Vast areas of paddy fields destroyed. A coastal strip 15 miles wide severely affected. 17 Rail bridges and culverts damaged.		
(103) 1968 November 10–13	Cyclone.	Surge in Chilika Lake and flooding.	

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(104) 1969 August 13–18	A monsoon cyclone crossed the north Orissa coast.		
(105) 1970 June 7–9	Cyclonic storm crossed the north Orissa Coast.		
(106) 1971 September 7–14	Severe cyclonic storm crossed south Orissa coast.		90 people killed. 8,000 cattle killed. Considerable damage to crops, houses, telecommunications and other properties in Ganjam, Puri and Cuttack districts.
(107) 1971 30 October	Paradip, 175 kph winds. Pc = 966 hPa Water levels up to 6 m. The surge penetrated 5 km inland and 25 km through the rivers. 4 to 5 m surges north of Chandbali.	7,623 deaths. People homeless: greater than one million. 8,214 square miles were totally destroyed. 107,665 cattle killed. 3.3 million acres of crops valued at about 100 M USD (at 1971 price levels, in 1971, roughly 1 USD – 8 Indian Rupees) was destroyed. Over 0.8 million homes were damaged to varying degrees. Over 10,000 educational institutions were destroyed. Several thousand government buildings were damaged. Hundreds of miles of embankments and roads were destroyed. Several irrigation works and public and private institutions were damaged.	
(108) 1972 July 13–15	Cyclonic storm crossed the coast near Balasore. $\Delta P \sim 30$ hPa		Damage to railway tracks, irrigation works, houses, crops.
(109) 1972 10 September	Barua. Severe cyclone.	3.4 m surge and 0.8 m tide. Barua to Chandbali.	100 people killed. 8,000 cattle killed. House damaged – 200,000. Crops damaged – 1,400,000 acres. Number of people affected – 4.5 million. Heavy damage in Ganjam, Puri and Cuttack districts.

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(110) 1972 September 22	Gopalur. Severe cyclone. $W_{\max} \sim 136$ kph.		Inundation in Puri district. Damage to houses and crops in Ganjam and Puri districts. Mishra gave the following data. No of people affected – 2.4 M. Humans died – 130. Cattle died – 10,047. Houses destroyed – 401,352 (damage is estimated as 503.2 C.R. at 2001 price levels). Crop damage – 9.1 C.R. (1972 price levels).
(111) 1973 11 October	Chandbali	Mild surge in rivers and estuaries caused saline water intrusion in the coastal areas of Northern Orissa and W.B.	100 people killed. People affected – 1.5 m. Houses damaged – 60,000. Damage to crops – 1 M RS. Road rail telecommunications damaged. Bridges damaged.
(112) 1973 November 3–9	Severe cyclone crossed north of Paradeep. $\Delta P \sim 23$ hPa.	3 to 4.5 surges near Paradeep.	Damages to crops between Paradeep and Chandbali about 2,100 acres.
(113) 1974 September 26–30	Cyclonic storm crossed the coast near Paradeep. $P_e \sim 986$ hPa, $W_{\max} \sim 93$ kph.		
(114) 1978 August 26– 2 September	Cyclonic storm crossed the coast between Chandbali and Balasore. $P_e \sim 986$ hPa, $W_{\max} \sim 83$ kph.		Trees uprooted in Balasore district. Fishing boat capsized near Digha. One person killed. Many huts collapsed.
(115) 1979 August 6–10	Severe cyclone crossed the coast near Balasore. $P_e \sim 970$ hPa.		Extensive damage to crops, houses, communications.
(116) 1981 August 7–10	Cyclonic storm crossed the coast north of Puri. $P_e \sim 980.7$ hPa, $W_{\max} \sim 83$ kph.		Due to flood in Vamsadhara, Rushikulya and Indravati Rivers, extensive areas in Puri, Ganjam, Koraput and Kalahandi districts covering an area of 36,536 hectares was affected. 47 blocks in the State affected covering 1,017 villages. Crops affected 3,690 hectares. People killed – 15. Houses collapsed fully – greater than 500. Houses collapsed partly – 1,200. Cultivated land sandcast – 2,173 hectares.

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(117) 1981 September 24–28	Severe cyclone crossed the coast near Puri. $P_e \sim 983$ hPa, $W_{\max} \sim 102$ kph.		5 launches were lost. Many houses destroyed in Cuttack district. A number of villages in low-lying areas of Balasore and Cuttack districts submerged. 7,000 acres of paddy land submerged.
(118) 1981 December 4–11	Severe cyclone southeast of Paradeep.		The districts, which suffered some damage, were Balasore, Cuttack and Puri, the worst affected being Cuttack. About 2,800 villages and a population of about 13 lakhs were affected. Cropped area of 57,571 hectares was affected due to cyclone and saline inundation leading to loss of about Rs. 90 lakhs. Loss to betel vines was about Rs. 162 lakhs. About 200 houses and 296,575 thatched houses were damaged. The estimated loss on this account was about Rs 55 lakhs. Damage to 1,364 public institutions, roads, river embankments, etc. was estimated at about Rs . 317 lakhs. Some fishing vessels berthed in Paradeep port were sunk. About 400 livestock were lost.
(119) 1982 June 1–4	Between Paradip and Chandbali. Severe cyclone.	2 m surges along Orissa and W.B. coasts. Peak surge of 4.8 m, 35 km north of Dhamra Harbor.	245 deaths. Large number of cattle killed. Heavy damage to crops and property in Puri, Cuttack and Balasore districts.
(120) 1984 10 October	Severe cyclone made landfall north of Chandbali. $\Delta P = 22$ HPA. $W \sim 50$ knots.	In Cuttack and Balasore districts, telephone and power lines were snapped.	
(121) 1985 20 September	Close to Puri. $\Delta P = 20$ HPA	2.8 m surges. Inundation lasted for 3 days.	Substantial damage.

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(122) 1985 16 October	Near Balasore. $\Delta P = 26$ HPA	2 m along the coast of Balasore District.	Damage due to salt water inundation. 8,000 houses collapsed. 84 deaths. Mishra gave the following data: Human deaths – 45. Missing – 32, Livestock – 1,073, Population affected – 4.0 M. Number of villages affected – 7,506. Crops damaged – 745,628 acres. Number of houses damaged – 31,013.
(123) 1989 May 23–27	Severe cyclone crossed the coast about 40 km northeast of Balasore. $W_{\max} = 139$ kph.	3 to 6 m surges in the coastal areas of Balasore district. 5 to 6 feet (1.5 to 1.8 m) surges penetrated the Subarnarekha River in Baliapal block and affected a few villages.	People killed – 24. People affected – 3.7 million. Houses damaged – 92,000. Cattle killed - 1,625. Considerable damage to crops.
(124) 1989 July 21–25	Cyclonic storm crossed the North Andhra – south Orissa coast near Kalingapatnam. $W_{\max} = 102$ kph.		
(125) 1992 November 3–7	Cyclonic storm crossed the South Orissa and North Andhra coast near Visakhapatnam.		
(126) 1995 7–10 November	Gopalpur. Severe cyclone. $W_{\max} = 111$ kph.	1.5 m 96 killed. 284,253 hectares of crops damaged.	
(127) 1999 17–21 October	Gopalpur. 180 kph winds. During 1949–1999, the most severe cyclone, which crossed the coast of Gopalpur and Balasore, is the one in October 1971. This one is the second most severe cyclone up to this time (till October 21st, 1999 during 1949 to 1999).	2 m surge in Rushikulya River and inundation in Berhampur due to heavy rain. Flooding occurred in Mahanadi, Brahmani, Salandi, Baitarani and Subarnarekha River basins.	147 deaths. Extensive damage. Orissa government requested central government for 158 M USD. 2.16 million people had been affected. Partial information received by 27 October 1999 shows that in Ganjam district alone the following are casualties of animals: Buffaloes – 454. Bullocks – 299. Cows – 867. Calves – 616. Sheep – 2,600. Goats – 3,386. Pigs – 141. Poultry birds – 640,812. 359,000 houses in Ganjam district and 18,277 in other districts have either collapsed fully or partly. 5,994 fishing boats and 96,202 fish nets were damaged in Ganjam district.

Table II. Continued

Serial No. & Date	Cyclone information	Surge information	Loss of life, damage
(128) 1999 29–30 October	Paradip. 300 kph winds. Pressure deficit ~98 hPa (in the top 3 cyclones in the Bay of Bengal affecting India), since weather records are kept.	7.5 m surge	9,885 deaths. Damage in excess of 2.8 B USD. Orissa government requested central government for 1.3 B USD (based on information received by 27 November 1999). Animal casualties are also heavy. Buffaloes – 13,464. Bullocks – 52,973. Cows – 156,424. Calves – 90,232. Sheep – 103,127. Goats – 196,212. Pigs – 8,945. Poultry Birds – 1,151,245. Number of houses damaged – 1,579,582. Paddy crop damage – 440 M USD. Internet gives the following information. Total number of people affected – 15 million. Number of cattle killed – 297,205. Number of houses damaged – 924,993.

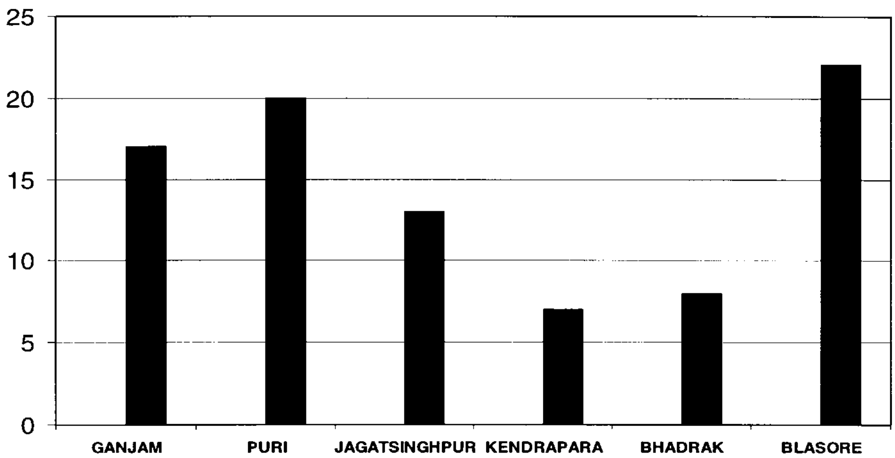

Figure 4. District-wise frequency of cyclones along the coast of Orissa (1877–2000).

Table III. Return periods for flooding in the 19th century (Bhatta, 1997)

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

Table IV. Return periods for flooding in the 20th century

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

3. Analysis of Cyclone and Flooding Data

Return periods for various cyclone events could be determined by sorting the data based on flood depths. Table III presents the return periods for the flooding events in the 19th century (Bhatta, 1997).

In the 20th century, due to the existence of river embankments, minor events were effectively eliminated. Based on the information contained in Table II, return periods for moderate and severe cyclone induced flooding events in the 20th century were determined and are shown in Table IV. It should be noted that severe flooding events occurred ppredominantly in the northern parts of Orissa.

From the 200 years of historic cyclonic flood information, it was determined that cyclones that cause moderate flooding in Orissa have a 4 year return period, while cyclones that cause severe flooding have a return period of approximately 10 years. Table V lists the cyclones that occurred in Orissa in the 20th century as reported by the IMD. The maximum sustained wind speed of each cyclone is noted as well as the classification based on the wind speeds (as noted above).

Based on Table V, the number of cyclones in the 20th century listed by category is as follows:

For the storm surge simulations made in this study, the following assumptions were made with respect to radius of maximum winds ($R_{\max}$) and maximum sustained winds ($W_{\max}$):

- $R_{\max}$ = 45 km.
- $W_{\max}$ (when direct measurements are not available) is determined from ΔP using standard methods (Murty, 1984; Dube *et al.*, 2000; Gonnert *et al.*, 2001). Although cyclone track information is available since 1875, systematic listing of accurate ΔP values for individual cyclone events did not commence un-

Table V. Cyclones of the 20th century (IMD)

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 VI. Number of cyclones by category – 20th century

Storm category	Number of storms
SC	1
VSCS	8
SCS	30
CS	11
CDP	0
Total	50

Table VII. Moderate to severe cyclone events on the coast of Orissa during 1971–2000

Number	Date	ΔP (hPa)
1	29 October 1999	98
2	21 November 1988	71
3	30 May 1982	61
4	1–14 September 1972	56
5	26–31 October 1971	47
6	7 November 1995	47
7	17 October 1999	47
8	23 May 1989	43
9	20 September 1972	38
10	11 October 1973	33
11	5 December 1981	30
12	4 November 1986	24
13	1 October 1983	22
14	12–15 October 1984	22
15	13–17 October 1985	22
16	19–21 September 1985	20

til approximately 1971 with the advent of remote sensing techniques using weather satellites. Therefore, using the cyclone database of the India Meteorological Department (IMD) for the period 1971 to 2000, 16 moderate to severe storm surge events in Orissa were identified with defined ΔP values. The tracks of these 16 events and the coastal districts of Orissa are shown in Figure 5. The ΔP values of the 16 tracks shown in Figure 5 are listed in Table VII.

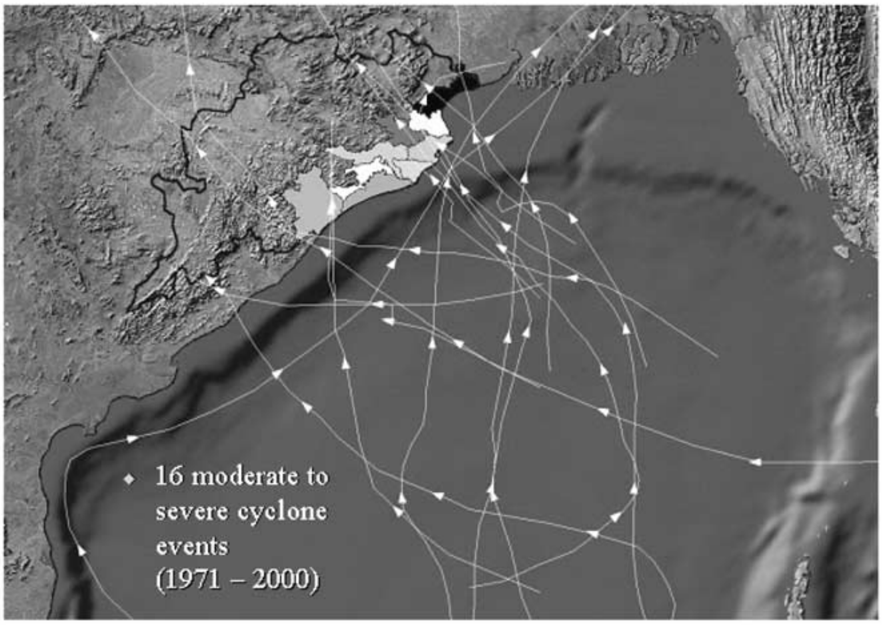

Figure 5. Cyclone tracks impacting the coast of Orissa during the period (1971–2000).

Statistical projections based on extreme value analysis (Gumbel, 1958) of the ΔP values listed in Table VII suggest the following values of ΔP for various return periods as shown in Table VIII. The first entry in Table VII (with the highest ΔP value) is the Super Cyclone that occurred in October of 1999. This cyclone caused approximately Rs. 6,170 Crores and almost 9,885 lives were lost during the 3-day storm. Figure 3 shows the flooded area due to the SC1999 in the northeastern part of Orissa, which illustrates the areas that were inundated by storm surge and saline water from the Bay of Bengal, river flooding as well as flooding due to excessive rainfall. The figure also indicates areas where the majority of the damage was due to winds from the Super Cyclone.

Table VIII suggests that the Super Cyclone has a return period of approximately 50 years. For this preliminary study of feasibility, the 50-year return period event was used for computation of the storm surge amplitudes which, when combined with tidal data, was used to design the flood protection system along the coast of Orissa.

4. Storm Surges on the Orissa Coast

Computer simulation of storm surges described below is used to determine the design water level to be used for the flood protection systems. The following sections describe the factors considered in determining the design water level for storm surge and river embankments. The 16 cyclone tracks noted above were represen-

Table VIII. Values of ΔP by return period for the coast of Orissa return period

Return period years	ΔP (hPa)
2	20.9
5	43.2
10	60.2
20	77.1
25	82.5
30	87.0
40	94.0
50*	99.4
100	116.3

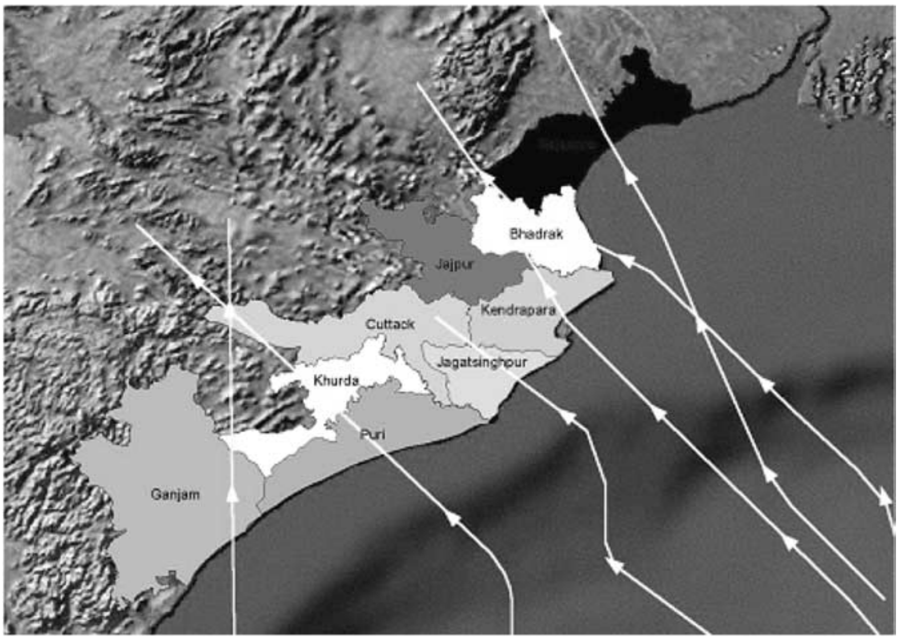

Figure 6. Synthesized cyclone tracks for computer simulations.

ted by six tracks in order to provide more complete geographical coverage of the coastal area of Orissa. Each of the six tracks intersects each of the coastal districts as shown in Figure 6.

The parameters of the Super Cyclone (ΔP, R_{max}, etc.) were then applied to the six "synthesized" tracks and used as input to the numerical storm surge model. The Indian Institute of Technology (IIT-D) numerical storm surge model was used

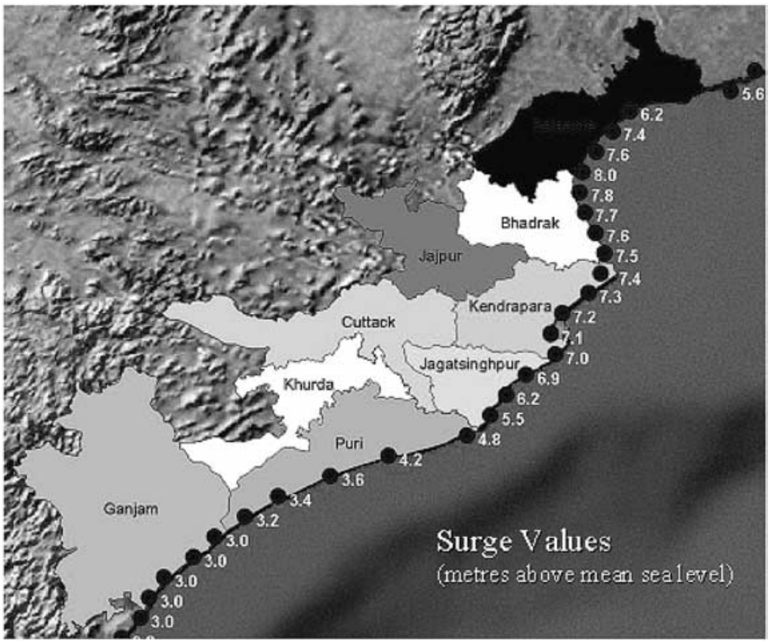

Figure 7. Maximum values of storm surge amplitudes on the Orissa coast on a 50 year return period.

to compute storm surges along the Orissa coast. The IIT-D model has been documented in Chittibabu (1999), Dube *et al.* (2000) and Gonnert *et al.* (2001). The model was run with a grid resolution of 10.5 km along the coastline, and with a variable grid size (minimum grid size of 500 m) in the direction perpendicular to the coast. The model is a semi-explicit finite difference model with the following characteristics:

- vertically integrated shallow water coastal zone numerical model
- curvilinear representation of coastal boundaries
- variable grid representation (varies from 500 m near the coast to 14 km in the offshore)
- radiation-type boundary conditions are used at the open boundaries
- uses a dynamic storm model (Jelesnianski, 1973) to simulate storm winds. The maximum probable surge amplitudes calculated for the coast of Orissa are shown in Figure 7.

In the southern part of Orissa, the surge values are smaller than those in the northern part (almost 50% smaller). The lowest value of the surge is 3.0 m and the highest value is 8.0 m. This difference is due to the nearshore topography and orientation of the coastline with reference to the storm tracks. Shallow water and flat slopes close to the shoreline result in larger surges than deeper water and steeper nearshore slopes. These results are quite consistent with the historical events listed in Table II.

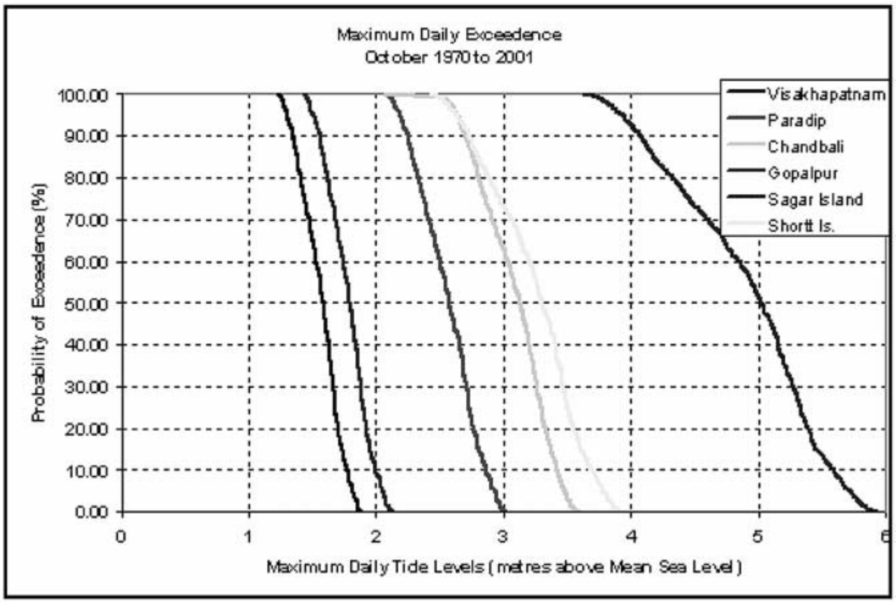

Figure 8. Maximum daily exceedence of tide levels at various locations.

5. Tidal Amplitudes, Wave Setup and Total Water Level

Thirty years (1970 to 2000) of hourly tidal predictions were produced for six locations along the coast of Orissa using a tidal prediction model (WXTide). The stations were chosen to ensure the entire coast of Orissa was included in the analysis. These locations were:

- Visakhapatnam (Andhra Pradesh)
- Gopalpur
- Paradip
- Chandbali
- Shortt Island
- Sagar Island (West Bengal)

Storm surge generating cyclones are most prevalent in October with the next highest storm surges occurring in May. For the purpose of this study, water level (tidal) data were obtained for the month of October and the maximum daily water level was determined for the 30-year period. The exceedence plot shown in Figure 8 was used to determine the 50% exceedence value for each station.

The 50% exceedence water levels were then interpolated for all of the grid points used in the storm surge model along the coast of Orissa. Wave set-up is the increase in water level caused by wave action at the shoreline. This is dependent on the magnitude of the wave heights and the local bathymetry near the shoreline. For this study, a value of 0.5 m was assumed for the entire coastline of Orissa. Figure 9 shows a computer simulation of the wave field for the super cyclone.

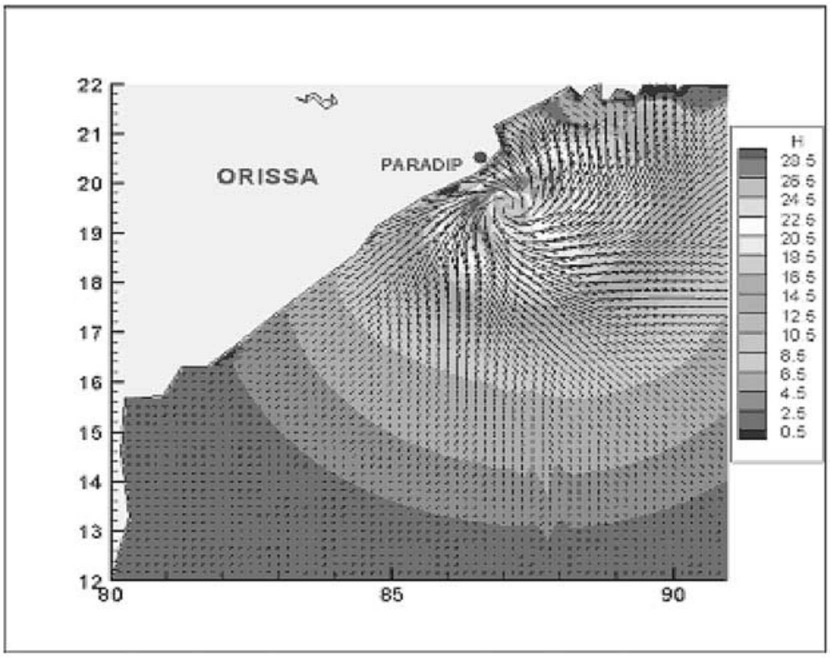

Figure 9. Simulation of wave field for the SC1999.

The design water level was defined to be the sum of the following:

- storm surge amplitude with 50 year return period (Figure 7), median value (50% exceedence) of daily maximum water level occurring in October,
- tidal amplitudes (Figure 8), and
- wave setup.

The total design water level is computed by addition of these three components and is then used in the engineering design of the crest elevation of the flood protection structures. Figure 10 shows the distribution of the total design water level for the coast of Orissa.

6. Rainfall during Cyclone Events

Due to the geographical variation in precipitation, estimation of the total volume of rainfall over a given area during a cyclone event is imprecise. A literature search of cyclone meteorology did not provide any quantitative estimates of precipitation during a cyclone event. However, it was noted that the greatest intensity of precipitation during a cyclone generally does not last more than 3 days (±1 day). In order to determine the amount of rain that could occur over the coastal area of Orissa, specifically for the 21 protection areas shown in Figure 11, isohyetal maps supplied by the Department of Water Resources were obtained for both of the October 1999 cyclones. The isohyetal information was applied to the 21 protection

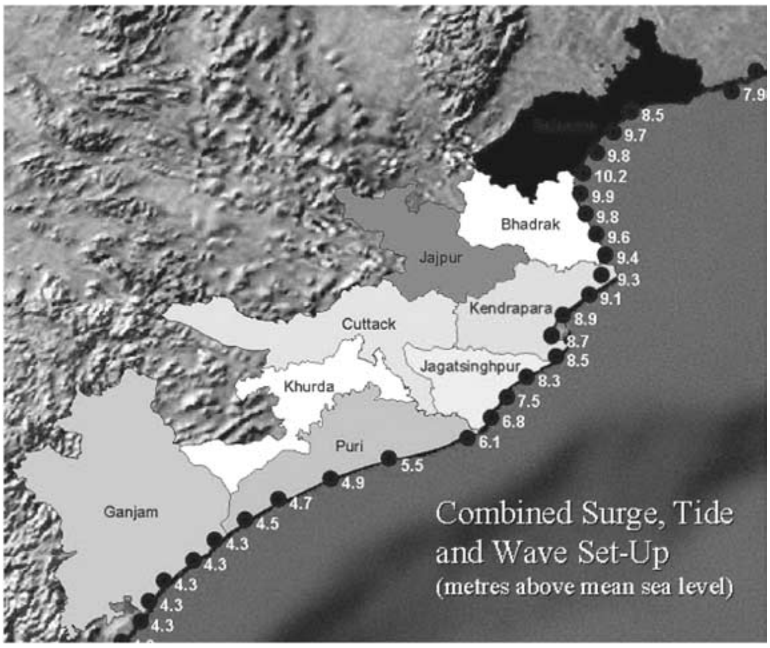

Figure 10. Total water level on a 50 year return basis.

areas to determine the rainfall within each area. Figure 12 shows the isohyetal maps for Orissa for SC1999, superimposed over the 21 protection areas. Table IX lists the total amount of rainwater over each region (in millions of m^3) for the three-day period as well as an average hourly rate.

This cyclone predominantly impacted middle and northern Orissa and had less of an impact in southern Orissa. It can be seen from Table IX that the total amount of rain that fell over the northern part of the coastal region of Orissa during the three-day event was approximately 5.4 km^4.

Figure 13 shows the isohyetal maps for Orissa for the period October 17–19, 1999. Table IX lists the amount of rain that fell over the 21 proposed protection areas during this four-day event. In contrast to the SC1999, this cyclone had maximum impact in the southern part of Orissa. It is assumed that the two cyclones occurring within an interval of ten days (and which are probably the most intense events that can occur for those areas) provided the most probable upper limits for the amount of rainfall over the coastal region of north and south Orissa. In Table IX, column 5 lists the maximum amount of rainfall in the 21 protection areas, irrespective of which cyclone contributed to the precipitation. Using this information, the maximum rainfall assumed for the 21 protection areas is 5.7 km^3. The hourly rainfall rate, as shown in Table VIII, varied from 2,000 to 7,000 m^3/km^2. To fully protect the coastal area of Orissa from flooding, both storm surge flooding due to cyclones and river flooding due to cyclone and monsoon rains must be considered. Protection from these flooding sources has been proposed through the construction

Figure 11. 21 protection areas for the Orissa delta from flooding.

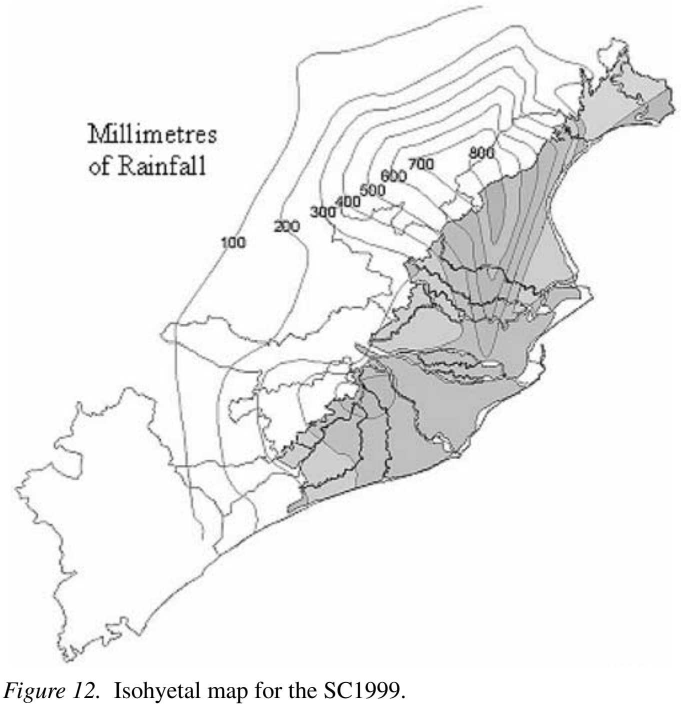

Figure 12. Isohyetal map for the SC1999.

Figure 13. Isohyetal map for the severe cyclone October 17–19, 1999.

of a continuous series of dykes or embankments to fully contain the areas of land that exist between the major tributaries in the study area. This requires embankments to be constructed along both sides of the major rivers to contain the river flow as well as parallel to the coastline along the Bay of Bengal to prevent inundation from the sea. It is anticipated that these embankments will be constructed from materials excavated locally and, possibly, material dredged from rivers or offshore locations. In general, due to the number of major rivers, the construction of these embankments will transform the deltaic plain of Orissa into a series of protected "islands" as shown in Figure 11. The creation of these protected areas will have an impact on the existing drainage and irrigation systems in the coastal area of Orissa. In addition, the removal of monsoon and/or cyclone rainwater from within the protected areas during severe rainfall must also be considered.

7. Global Warming and Storm Surges in Orissa

Climate change due to natural causes could have a profound effect on cyclone tracks. For Orissa, no significant shift in the tracks of tropical cyclones was detected. It has been speculated by IPCC (1995, 1996) that human-induced global

Table IX. Rainfall in 21 protected areas during SC1999

Protection Area (#)	Protection area (km^2)	October 17–20 total rainfall (m^3)	October 29–31 total rainfall (m^3)	Maximum total rainfall (m^3)	Maximum rainfall rate (m^3/h)	Maximum rainfall rate ((m^3/h)/km^2)
1	502.6	179,756,500	–	179,756,500	1,872,464	3,726
2	215.6	79,269,500	–	79,269,500	825,724	3,830
3	132.7	33,277,000	39,825,000	39,825,000	553,125	4,167
4	325.9	80,058,000	128,826,000	128,826,000	1,789,250	5,490
5	794.0	201,826,500	280,029,000	280,029,000	3,889,292	4,898
6	929.2	240,054,500	348,799,000	348,799,000	4,844,431	5,214
7	1,072.2	262,459,000	447,823,000	447,823,000	6,219,764	5,801
8	29.1	5,816,000	11,283,000	11,283,000	156,708	5,389
9	1,589.5	328,149,000	631,601,000	631,601,000	8,772,236	5,519
10	58.6	11,714,000	23,428,000	23,428,000	325,389	5,556
11	248.1	49,620,000	99,075,000	99,075,000	1,376,042	5,546
12	171.0	34,190,000	68,380,000	68,380,000	949,722	5,556
13	1,640.3	301,129,500	608,624,000	608,624,000	8,453,111	5,153
14	253.4	39,889,500	75,369,000	75,369,000	1,046,792	4,131
15	123.9	20,522,500	38,050,000	38,050,000	528,472	4,265
16	500.9	77,986,500	194,299,000	194,299,000	2,698,597	5,387
17	851.1	127,663,500	381,092,000	381,092,000	5,292,944	6,219
18	138.7	20,803,500	54,956,000	54,956,000	763,278	5,503
19	3,149.9	331,621,500	1,624,971,000	1,624,971,000	22,569,042	7,165
20	865.9	–	279,690,000	279,690,000	3,884,583	4,486
21	461.7	–	62,841,000	62,841,000	872,792	1,891
Total	13,965.2	2,425,806,500	5,398,961,000	5,657,987,000		

warming will increase the frequency and intensity of tropical cyclones and hence frequency and amplitude of storm surges.

The 200-year cyclone and surge data record for Orissa was examined which shows the reduction in the flooding events during the last century. There could have been two different reasons for the significant reduction (by about 30%) of flooding causing tropical cyclones and monsoon depressions.

First, construction of saline and river embankments starting in the later part of the 19th century might have partly eliminated minor flood events. Second, climate change due to natural causes might also have played a role. In any case it is quite obvious that there is no observational support to the contention that human-induced global warming increased the storm surge activity. If at all, there is evidence that the activity has actually decreased.

Next, an examination of the intensity of tropical cyclones and amplitude of surges generated by them did not show any increase either, in the 20th century. Unfortunately, accurate central pressure deficit (ΔP) values are systematically available earlier only since about 1970. However, descriptive information available earlier appears to suggest that the surge amplitudes were about the same. The super-cyclone of October 1999 appears to have a return period of about 50 years and at least three events similar to that in intensity could have occurred prior to that since the beginning of the 19th century (1831, 1885 and probably in 1895. Had the 1971 cyclone been slightly more intense, it would have been classified as a super cyclone). Hence there is no evidence to the suggestion that global warming caused increased amplitudes of storm surges.

However, there is one unmistakable fact: the impact of tropical cyclones and storm surges has increased dramatically in recent years. This is due to increase in the coastal population and in the infrastructure. For example, only less than 8% of the present coastal infrastructure existed in the 19th century in Orissa. Most of the increase in infrastructure occurred only in the later part of the 20th century.

8. Summary and Conclusions

To protect the coastal districts of Orissa from strom surge flooding due to tropical cyclones as well as rain induced river flooding, a detailed analysis of storm surges and rain fall is carried out. Based on the past 30 year historical cyclone data, total water level on the Orissa coast on a 50 year return period is calculated. The total water level comprises of storm surge, astronomical tide and wave setup. Construction of a continuous series of dykes or embankments to fully contain the areas of land that exist between the major tributaries in the coastal area is proposed to protect from these flooding sources. Change of tropical cyclones tracks and their intensity due to climate change and global warming also investigated. It is concluded that there is no evidence of increase of storm surge amplitudes due to global warming.

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