MAUSAM, 48, 2 (April 1997), 283-304

551.515.2 : 551.509.326 (267.64 : 267.37)

Storm surge in the Bay of Bengal and Arabian Sea : The problem and its prediction

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सार — जब कभी उष्णकटिबंधीय चक्रवात आते हैं, तो समुद्र में चक्रवातीय तूफान के कारण उठने वाली ऊँची लहरों से भारत और उसके समीपवर्ती देशों में आने वाली संभावित बाढ़ की आशंका बनी रहती है। समुद्र की उत्ताल तूफानी लहरों से उत्पन्न आपदाओं के कारण जान-माल की भारी हानि होती है। तटीय संरचनाओं और कृषि की क्षति होती है। जिसके कारण ये देश प्रत्येक वर्ष आर्थिक हानि के शिकार होते हैं। अतः इन क्षेत्रों में आने वाली तूफानी समुद्री लहरों के सही समय का मानीटरन करना और तत्संबंधी चेतावनी देना एक गम्भीर समस्या है। इस शोध पत्र का उद्देश्य बंगाल की खाड़ी और अरब सागर में बनने वाली तूफानी समुद्री लहरों की समस्या, तूफानी समुद्री लहरों की उत्पति को प्रभावित करने वाले कारकों और तूफानी समुद्री लहरों के गणितीय पूर्वानुमान कार्य की वर्तमान स्थिति से जुड़े मुख्य पहलुओं का सिंहावलोकन करना है।

ABSTRACT. India and its neighbourhood is threatened by the possibility of storm surge floods whenever a tropical cyclone approaches. Storm surge disasters cause heavy loss of life and property, damage to the coastal structures and agriculture which lead to annual economic losses in these countries. Thus, the real time monitoring and warning of storm surge is of great concern for this region. The goal of this paper is to provide an overview of major aspects of the storm surge problem in the Bay of Bengal and the Arabian Sea, the factors affecting the generation of storm surges and the present state-of-the-art in the numerical storm surge prediction.

Key words — Storm surge, Tropical cyclone, Prediction models, Simulation, Sea level.

1. Introduction

Storm surges which are associated with severe tropical cyclones constitute the world's foremost natural disaster. Amongst other natural disasters, storm surge stands out as by far the most damaging and, indeed, as an agent of death and destruction on a scale at least as massive as that of earthquakes. Death and destruction arise directly from the intense winds characteristic of tropical cyclones blowing over a large surface of water, which is bounded by a shallow basin. As a result of these winds the massive piling up of the sea water occurs at the coast leading to the sudden inundation and flooding of coastal regions.

About 3,00,000 lives were lost in one of the most severe cyclones that hit Bangladesh (then East Pakistan) in November 1970. The Andhra cyclone devastated the eastern coast of India, killing about 10,000 persons in November 1977. These two, and most of the world's greatest human disasters associated with the tropical cyclones, have been directly attributed to storm surges.

1.1. *Frequency of tropical cyclones*

Though the tropical cyclones occur in many parts of the world, the Bay of Bengal is one of the ideal tropical cyclogenesis areas. Statistics shows that only about 7% of the global tropical cyclones form over the Bay of Bengal and the Arabian Sea (Table 1).

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TABLE 1

Yearly average and percentage of global total tropical cyclones over ocean basins

S. No.	Basin	Average	Percentage
1.	NW Atlantic	8.9	11
2.	NE Pacific	14.2	18
3.	NW Pacific	26.1	33
4.	N. Indian Ocean	5.5	7
5.	S. Indian Ocean	9.0	11
6.	AUS-SW Pacific	16.4	20
	Total	80.1	100

The formation of cyclones in these regions is strongly related to the seasonal migration of Inter Tropical Convergence Zone (ITCZ). On an average, about 5-6 tropical cyclones form in the Bay of Bengal and the Arabian Sea every year, of which 2 to 3 may be severe. More cyclones occur in the Bay of Bengal than in the Arabian Sea; the ratio of their frequencies is about 4:1.

The frequency of cyclones and severe cyclones in the Bay of Bengal and the Arabian Sea during the last 105 years from 1891 to 1995, is shown in Table 2. It may be seen from the table that the May, June, October and November are the stormiest months of the year compared to pre-monsoon season, particularly the months of October and November, are known for severe storms.

An important feature is that along a vast stretch of the Indian coasts, there are a few preferred strips which are more vulnerable to tropical cyclones. These are shown in Fig. 1 which provide the landfall of cyclonic storms on a districtwise basis.

1.2. *Storm surges in the Bay of Bengal*

Storm surges are extremely serious hazards along the east coast of India, Bangladesh, Myanmar and Sri Lanka. Although Sri Lanka is affected only occasionally by the strom surge, but the tropical cyclones of November 1964, November 1978 and the recent cyclone

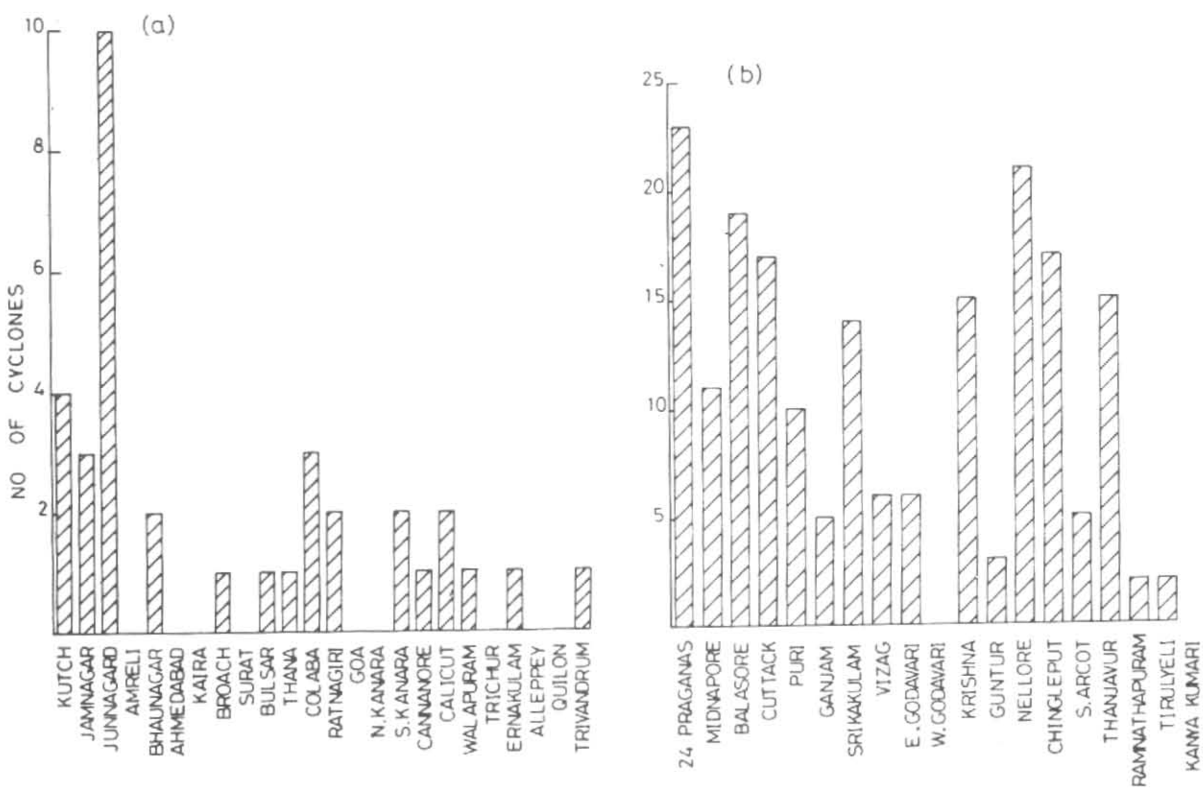


Fig. 1. Preferred strips along the Indian coasts which are more vulnerable to tropical cyclones

TABLE 2

Frequency of tropical cyclones

	Months												
	J	F	M	A	M	J	J	A	S	O	N	D	Total
Bay of Bengal													
Cyclonic storms	6	1	4	21	51	38	41	30	39	79	98	41	449
Severe cyclonic storms	2	1	2	12	36	4	8	3	16	35	51	19	189
Arabian Sea													
Cyclonic storms	2	-	-	6	19	19	3	3	7	26	29	6	120
Severe cyclonic storms	-	-	-	-	4	15	12	-	-	12	24	2	69

TABLE 3

Partial list of storm surges in Bangladesh during the period 1876-1996 (values listed are total water levels)

Date of cyclone (1)	Maximum wind speed ($km\ h^{-1}$) (2)	Observed maximum water level (m) (3)	Deaths (4)
27 Oct - 1 Nov 1876	-	13.7	-
31 Oct 1897	-	-	-
1 Nov 1912	-	-	-
20-25 Sept 1919	-	-	-
May 1926	-	-	-
May 1941	-	-	-
May 1942	-	-	-
21-24 Oct 1958	88.5	1.8	
7-10 Oct 1960	128.8	6.1	3,000
30-31 Oct 1960	209.2	9.1	5,149
6-9 May 1961	148.1	8.8	11,466
27-30 May 1961	144.8	8.8	-
25-29 May 1963	201.2	9.1	11,520
11 Apr 1964		-	196
10-12 May 1965	160	5.8	-
31 May-1 Jun 1965	-	7.6	-
11-15 Dec. 1965	209.2	3.9	873
27 Sept-1 Oct 1966	144.8	9.6	850
10-11 Oct 1967	144.8	8.8	-

TABLE 3 *Contd.*

(1)	(2)	(3)	(4)
22-24 Oct 1967	-	7.6	-
8-10 May 1968	-	4.6	-
17 Apr 1969	-		75
10 Oct 1969	-	7.3	-
5-7 May 1970	-	4.9	-
23 Oct 1970	-	-	300
13 Nov 1970	22.1	9.1	300,000
8 May 1971		5.0	-
30 Sept 1971		5.0	-
6 Nov 1971		6.1	-
18 Nov 1973		4.3	-
9 Dec 1973	122	5.1	183
15 Aug 1974	97	7.1	-
28 Nov 1974	162	5.3	-
21 Oct 1976	105	5.3	-
13 May 1977	122	-	-
10 Dec 1981	97	2.2	02
15 Oct 1983	97	-	-
9 Nov 1983	122	-	-
30 June 1984	89	-	-
25 May 1985	154	5.0	11,069
29 Nov 1989	162	3.3	2,000
19 Apr 1991	225	8.2	1,40,000
2 May 1994	200	-	170

of November 1992 have caused extensive loss of life and property in the region. Storm surges also affect Myanmar although to much less extent in comparison with Bangladesh and India. Notable storm surges which have affected Myanmar have been during May of 1967, 1968, 1970 and 1975, of which May 1975 was the worst cyclone. The storm surge due to the May 1975 event penetrated at least 100 km into the Irrawaddy river system and caused serious inland flooding (Lwin 1980).

A detailed review of the problem of storm surges in the Bay of Bengal is given by Murty (1984), Murty *et al.* (1986) and Das (1994 a, b). In this section, a brief account of the problem of storm surges in Bangladesh and the east coast of India will be given. Of all the countries surrounding the Bay of Bengal, Bangladesh suffers most from storm surges. The main factors contributing to disastrous surges in Bangladesh may be summarized as follows (Ali 1979):

(a) shallow coastal water,

(b) convergence of the Bay,

(c) high astronomical tides,

(d) thickly populated low-lying islands,

(e) favourable cyclone track, and

(f) innumerable number of inlets including world's largest river system (Ganga-Brahmaputra-Meghna)

There are about 40 events of severe storm surges in Bangladesh during the period 1800-1996. A partial list is given in Table 3.

TABLE 4

Storm surges on the Bay of Bengal coast of India

Year	Month	Location where storm crossed the coast	Area affected by storm surges	Peak surge (m)	Loss of life
1737	Oct	Mouth of Hooghly	Sunderbans	12	300,000
1789	Dec	Kakinada			20,000
1833					50,000
1839					20,000
1864	Oct	Mouth of Hooghly	Calcutta and surroundings	12	50,000
1864	Nov	Masulipatnam	Masulipatnam and surroundings		40,000
1885	Sept	False Point	North Orissa	7	Several thousand
1927		Nellore	Andhra		300
1942	Oct	West Sunderbans	West Bengal 5 m at Midnapore (64 km inland on a river)		40,000
1952	Nov	Nagapattinam	South Coromandal coast and northern shores of Palk Bay	3	Few thousand
1964	Dec	Adirampatnam	Coromandal coast and west shores of Palk Bay	6	1,000
1969	Nov	Andhra	Andhra		200
1971	Oct	Orissa	Orissa		10,000
1977	Nov	Chirala	Divi and surroundings	5	20,000
1982	Jun	Orissa	Paradip	3	250
1990	May	Divi	Divi and surroundings	4.5	250

TABLE 5

Partial list of major storm surges on the Arabian coast of the Indian subcontinent during (1782-1996) [Only those cases in which major destruction and loss of life occurred are included (Rao 1968)]

Year	Month	Area of landfall	Area of major storm surges	No. of people killed
1782	April	South Saurashtra coast	Gulf of Cambay	Several thousand
1851	May	32 km west of Karachi	Karachi and environs	
1920	June	Veeraval	Gulf of Cambay	
1964	June	Naliya	North and south shores of the Gulf of Kutch	
1975	October	Porbandar	Saurashtra	
1977	November	Karwar	Karwar and environs	
1982	November	Veeraval	Gulf of Cambay	
1996	June	South of Saurashtra coast	Gulf of Cambay	

Like Bangladesh, the east coast of India is also prone to storm surges. Some of the significant storm surge events along the east coast of India are listed in Table 4.

1.3. *Storm surges in the Arabian Sea*

Although the frequency of storms and storm surges is less over the Arabian Sea than the Bay of Bengal, major destructive surges can occur occasionally. A partial list of major storm surges on the Arabian coast of India during 1782-1996 is given in Table 5.

1.4. *Destruction potential*

Although the frequency of tropical cyclones in the Bay of Bengal and the Arabian Sea is not quite high, even though the coastal regions of India,

TABLE 6

Deaths in tropical cyclones

Year	Countries	Deaths
1970	Bangladesh	300,000
1737	India	300,000
1886	China	300,000
1923	Japan	250,000
1876	Bangladesh	200,000
1897	Bangladesh	175,000
1991	Bangladesh	140,000
1833	India	50,000
1864	India	50,000
1822	Bangladesh	40,000
1780	Antiles (W. Indies)	22,000
1965	Bangladesh	19,279
1963	Bangladesh	11,520
1961	Bangladesh	11,466
1971	India	10,000
1977	India	10,000
1963	Cuba	7,196
1900	USA	6,000
1960	Bangladesh	5,149
1960	Japan	5,000
1973	India	5,000
1985	Bangladesh	11,069

Bangladesh and Myanmar suffer most in terms of loss of life and property caused by the surges. The reason besides the inadequate accurate prediction, are the low lands all along the coasts and considerably low-lying huge deltas, such as, Gangetic delta and Irrawaddy delta. Table 6 lists the number of deaths associated with several deadly cyclone disasters where death tolls were in excess of 5000 lives.' These major surges usually occurred unexpectedly.

There can be little doubt that the number of casualties would have been considerably lower if the surge could have been predicted, say, 24 hours in advance allowing for effective warnings in the threatened area. The prediction, must, of course, be accurate enough so that one can distinguish between the dangerous surges and the surges that cause little harm, as people can not be evacuated from exposed areas for every approaching storm. Some success has been achieved in predicting storm surges by computer oriented numerical models. The purpose of the present paper is to give a review of recent developments in predicting the storm surges in the Bay of Bengal and Arabian Sea. A real time storm surge prediction system is also proposed here for disaster management (Dube *et al.* 1994).

2. Data input for surge prediction models

In order to achieve greater confidence in surge prediction over the Indian seas one should have the good knowledge of the input parameters for the model. These parameters include the oceanographic parameters, meteorological parameters (including storm characteristics), hydrological input, basin characteristics and coastal geometry, wind stress and sea bed friction and information about the astronomical tides. It has been seen that in many cases these input parameters strongly influence the surge development. A brief account of these data input is given below :

2.1. *Meteorological input*

This is mainly concerned with the characteristics of the tropical storm. The main characteristics required are :

(a) The pressure drop (difference between ambient pressure surrounding the storm and the central pressure),

(b) vector motion of the storm,

(c) point of landfall,

(d) duration of the storm,

(e) maximum sustained winds and

(f) the radius of maximum wind.

Parameters (a), (e) and (f) are estimated from satellite imageries. The parameters (b), (c) and (d) are obtained from the forecast of India Meteorological Department/Weather Bureau.

Parameters (a), (e) and (f) of tropical cyclone are needed for the computation of wind field in a cyclone which is the foremost requirement for the computation of surges. Differing assumptions have been made by various workers (Murty *et al.* 1986) about the dependence of surface atmospheric pressure and wind speed on distance from the centre of the cyclone using different cyclone models. One of the most important questions raised in this regard is whether or not any of these cyclone models give an accurate estimate of the associated wind field. Since the computation of storm surges is carried out by forcing the ocean model by wind stress which is proportional to square of the speed of the wind, any error in estimation of the wind may lead to substantial error in wind stress and thus in storm surges. Since no real time wind observations exist at the moment, especially in Indian Seas, one has to live with these compromises.

2.2. *Oceanographic data*

Data on oceanography are concerned with the following :

(a) bathymetry,

(b) astronomical tides and

(c) inshore currents in closed regions.

Modelling experiments show that the surge is very sensitive to the basin depth. Most of the northern Bay of Bengal is very shallow and is characterized by sharp changes in sea bed contours. The shallowness of water may considerably modify the surge heights in this region. Therefore, accurate bathymetry maps are needed for improved surge prediction.

Astronomical tides and the inshore currents also influence the surges through non-linear interaction in shallow water. Experiments have been made to study the tide-surge interaction with the help of numerical models (Johns *et al.* 1985, Sinha *et al.* 1996).

2.3. *Basic characteristics and coastal geometry*

The location of the highest surge depends predominantly on the coastal geometry of the basin. Experiments suggest that the curving coasts not only shift the peak surge position but also affect its height (Dube *et al.* 1982). Some recent modelling experiments show that the surge is sensitive to the way of coastline representation. It is seen that conventional method of coastline representation by orthogonal straight line segments tend to over-reflect the wind driven water (Johns *et al.* 1981).

2.4. *Surface and bottom stress*

The surface stress and sea-bed friction is usually parameterized by conventional quadratic law. Wind is the main generating mechanism of the surge, the height of the wave depends on the strength of the wind. Special care should be taken while computing the surface winds associated with a tropical cyclone.

2.5. *Hydrological input*

The main hydrological information needed is

(a) river discharge in the sea and

(b) rainfall distribution.

The results of river-ocean coupled mathematical models show that the discharge of fresh water carried by the rivers may modify the surge situation, especially in the northern Bay of Bengal, where one of the world's largest river systems, Ganga-Brahmaputra-Meghna, join the sea (Dube *et al.* 1986). Another dynamic effect of these inlets and estuaries is the potentially deep inland penetration of surge originating in the sea.

The impact of heavy precipitation, associated with tropical cyclone, on surge height has not been considered in the models for the Indian seas. However, it is expected to influence the surge amplitude.

For the development of any forecasting storm surge model for the Indian seas one must take the above factors into consideration as far as possible.

3. Methods of storm surge prediction

3.1. *Empirical methods*

Empirical formulae have been devised for many coastal regions of the world by correlating the sea surface elevation with sea-level pressure, the strength and direction of the prevailing wind, etc. The development of these relations requires a large series of observations to establish meaningful correlations, for the purpose of prediction. There have been some attempts to develop empirical methods for forecasting the storm surges in the Bay of Bengal (*e.g.*, Chaudhury and Ali 1974, Rao and Majumdar 1966, Qayyum 1983, Das *et al.* 1978). But in the absence of sufficiently large series of accurate observations, these methods have not been found to be much useful.

Rao and Mazumdar (1966) used empirical relations to prepare a nomogram similar to that designed by Sverdrup and Munk (1947) to estimate the amplitude of surge from wind data. Rao (1968) later used this nomogram to classify the coast of India (and the coasts of Bangladesh and Myanmar for comparison) into three types of vulnerability to storm surges. This classification of Rao (1968) is shown in Fig. 2.

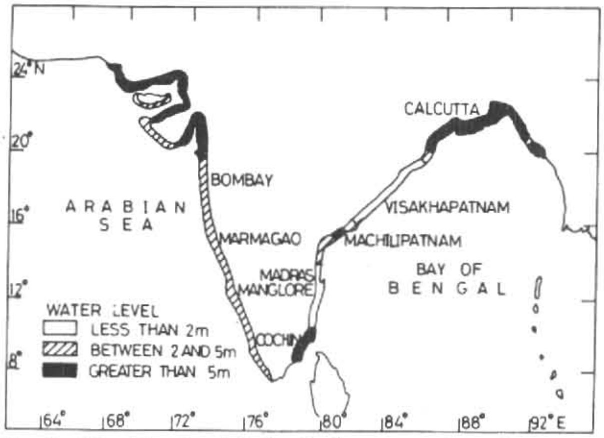


Fig. 2. Classification of the Indian coast into three types of vulnerability to storm surges (After Rao 1968)

3.2. *Numerical storm surge prediction*

One of the possibilities of surge prediction is to solve the hydrodynamic equations governing the motion in the sea. Unfortunately, the analytical solutions of these equations are not possible without making major simplifying assumptions, in which many important parameters may have to be dropped.

The best alternative is the numerical solution of the hydrodynamic equations. The numerical technique consists of solving the governing equations at a discrete set of points in space and at discrete instants of time. The general system of equations, that represent storm surges, has been treated numerically with success during the last 3 to 4 decades. Most of the initial work on numerical modelling of storm surges associated with tropical cyclones has been done for the Atlantic and Pacific regions.

In India, the study of the numerical storm surge prediction was pioneered by Das (1972). He conducted a numerical experiment and computed the surge generated by an idealized cyclone striking the coast of Bangladesh. Das *et al.* (1974) extended the above study for application to the coast of West Bengal and north Orissa. They used a two-dimensional linear model and telescoping grids. The grid scheme used for three different types of tracks is illustrated in Fig. 3. Nomograms for the strom surge as a function of the storm intensity and speed of movement of cyclone are given in Fig. 4. Ghosh (1977) has evolved an objective method to predict the storm surges on the entire east coast of India north of 10° N. He developed the

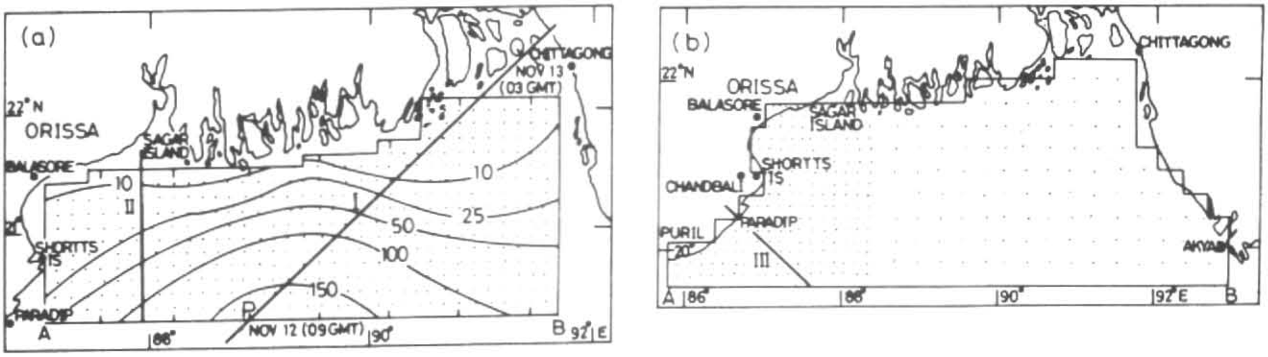


Fig. 3. Grid scheme for three different types of tracks

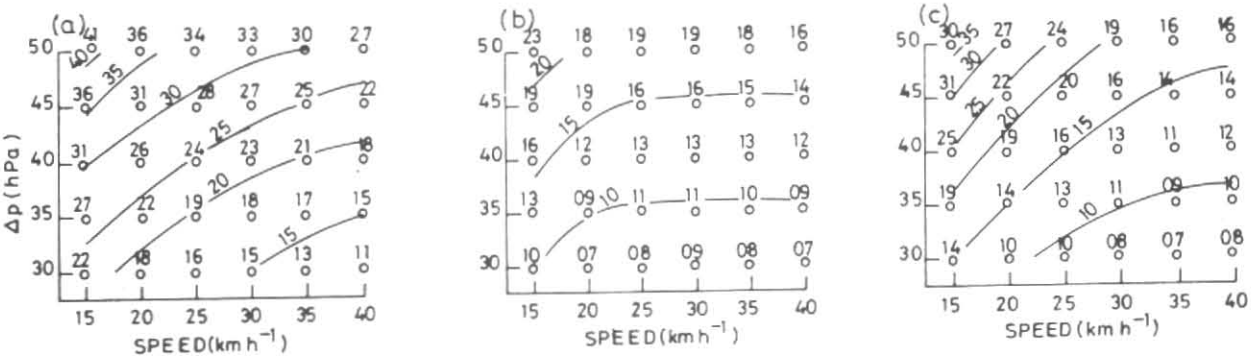


Fig. 4. Nomograms for the storm surges as a function of the storm intensity and speed of movement of cyclone

nomograms based on the model outputs of Jelesnianski (1972). The nomograms were prepared separately for the northern part and for the remaining part of the coast. Two typical nomograms prepared in this manner are shown in Fig. 5. Johns (1981) and Johns & Ali (1980) have developed a non-linear model for the simulation of surges along the Bangladesh coast in which the dynamic effects of the Ganga-Brahmaputra-Meghna river system as well as those of islands near the Meghna estuary have been incorporated.

Modelling of storm surges in the Indian seas has attracted more attention to the Bay of Bengal. Very few modelling studies have been carried out for the west coast of India (Dube *et al.* 1985, Sinha *et al.* 1984, Ghosh *et al.* 1983).

In all these storm surge prediction models for the Bay of Bengal the coastal boundary is approximated by conventional orthogonal straight line segments. Modelling experiments have shown that the surge is sensitive to the way of construction of the coastal boundary. An effective means of achieving greater accuracy is a precise representation of the shorelines which are curved and/or broken by bays or estuaries. Murty & Henry (1983) and Henry & Murty (1982) developed a series of numerical models for tides and surges in the Bay of Bengal. Besides using regular grids (Fig. 6) they also used irregular triangular grid (Fig. 7) which has advantage of representing coastal geometry with greater accuracy. In storm surge models, curvilinear boundary representation depending on the application of conformal mapping have previously been considered by various workers for other regions of the world (*e.g.*, Jelesnianski 1965). The Centre for Atmospheric Sciences (CAS) at the Indian Institute of Technology (IIT), New Delhi have developed a numerical storm surge prediction model for the Bay of Bengal which, is capable of dealing with curved coasts. The treatment of the coastal boundaries involve a procedure leading to a realistic curvilinear representation of both the western and eastern sides of the Bay of Bengal (Johns *et al.* 1981). This coastal representation has another added advantage of taking

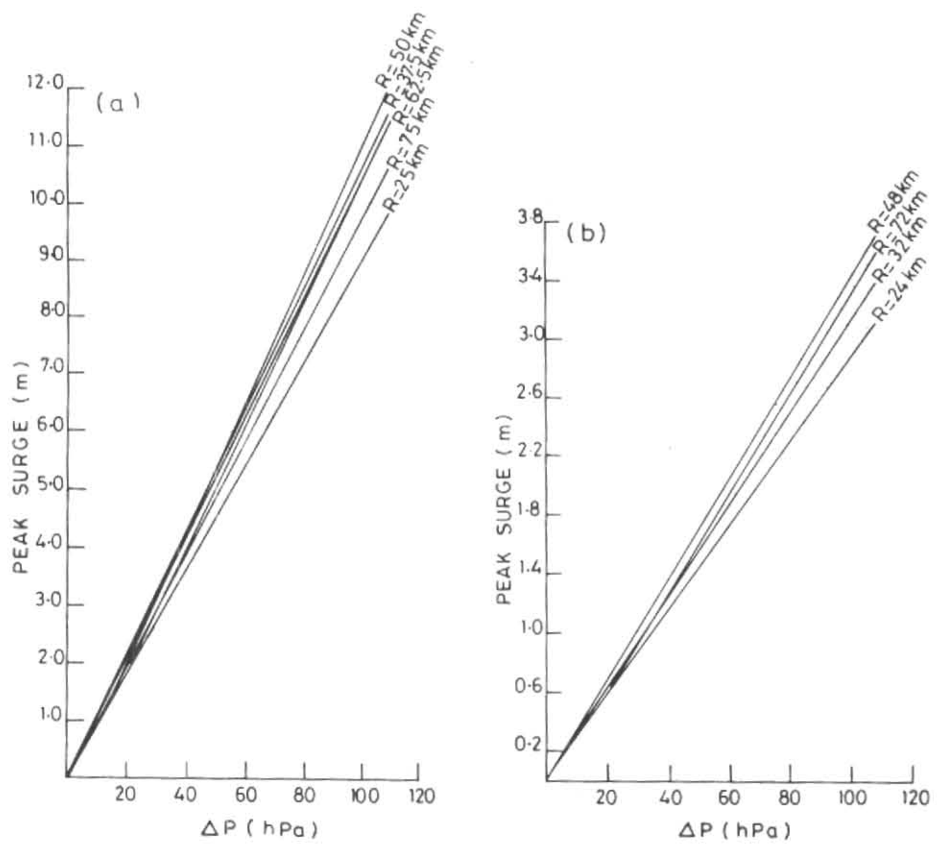


Fig. 5. Same as Fig. 4 but for the northern part and remaining part of the coast

Fig. 6. Regular grids

automatically into account the finer resolutions in the shallow regions of the northern Bay. The model is fully non-linear and has successfully been used to simulate the surges generated by several severe cyclonic storms (Das *et al.* 1983, Dube *et al.* 1985).

3.3. *Operational models*

Operational numerical storm surge prediction models have been developed and are being routinely used for several coastal regions of the world, such as, North Sea (Flather 1976, Flather and Proctor 1983), the Gulf of Mexico and Atlantic coast (Jelesnianski and Chen 1979), Hong Kong, China etc. A review of these models is given in Jiping *et al.* (1990), Jelesnianski (1989), Murthy (1984) and Sundermann and Lenz (1983).

Most of these models require large computing power. Therefore, for routine forecasting of storm surges, especially providing multiple forecast scenarios, the models can not be used in the absence of access to sufficient computing facility. To overcome this difficulty, most of the forecasting offices use the nomogram methods of Jelesnianski (1972) for prediction of storm surges associated with tropical cyclones. The nomograms have been developed from modelling studies of a large number of bathymetries and approach angles.

The second WMO International Workshop on Tropical Cyclones (WMO 1990) recommended the use of personal computers by the developing countries in

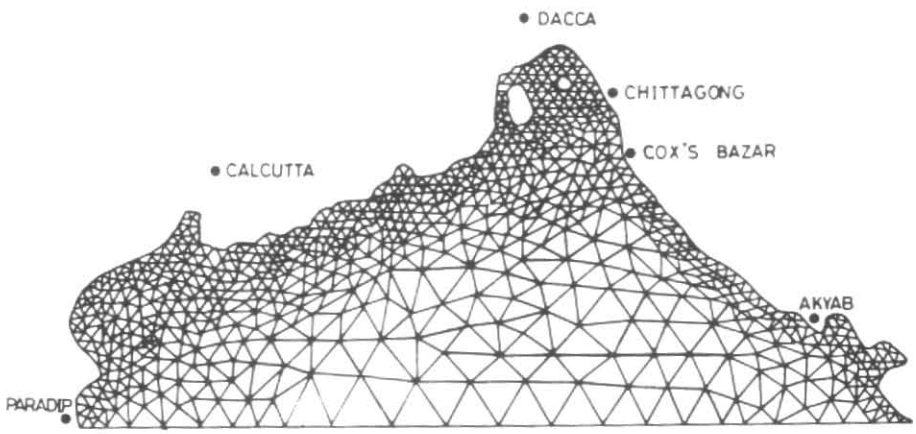


Fig. 7. Irregular triangular grids

order to adopt the stand-alone storm-surge forecasting system. Recent advent of powerful personal computers (PC) has opened up the possibility of running dynamical models in real time on PC-based work stations in a operational office. In fact, a PC-based work station (the Automated Tropical Cyclone Forecasting System, ATCF) is already in operation at the Joint Typhoon Warning Centre, Guam for the past many years. The Australian Bureau of Meteorology Research Centre, together with their Bureau Severe Weather Programme Office has also developed an Australian work station for storm surge forecasting. In India efforts have been made towards adaptation of the IIT, New Delhi Surge Model (Dube *et al.* 1994) on the Personal Computers for its use as an operational system. The first version of this storm surge prediction system has been implemented at IIT, Madras. The operational feasibility test of the system is undergoing at present.

4. Basic features of the model

In this section, we will briefly describe some of the basic features of the model proposed to be used as a real time storm surge prediction system (Dube *et al.* 1994). An overall flow chart of this system is shown in Fig. 8.

4.1. *Dynamic storm model*

In the above predictive system the surge is generated by a cyclone, tracking across the analysis area. In view of the strong associated winds and consequently high values of wind stress, the forcing due to barometric changes have been neglected. Thus, the surface wind field associated with tropical cyclone is the primary requirement for modelling storm surges. The wind field at the sea surface is derived by using a dynamic storm model developed by Jelesnianski and Taylor (1973). This storm model uses as input the radius of maximum wind and the pressure drop. The main portion of the storm model is a trajectory model and a wind speed profile approximation scheme. The trajectory model represents a balance between pressure gradient, centrifugal, Coriolis and surface frictional forces for a stationary storm.

4.2. *Storm surge model*

Vertically-integrated numerical storm surge prediction model of IIT, New Delhi has been adopted for the surge prediction which may be used as a menu-driven stand-alone system. The details of the model and the numerical solution procedure are described in Das *et al.* (1983) and Dube *et al.* (1985). Only a brief description of specific features will be presented here.

The model is fully non-linear and is forced by wind stress and quadratic bottom friction. It is found that the non-linear advection terms have significant effect on the final results, especially in the shallow coastal waters of the head Bay of Bengal. Therefore, for operational applications, the non-linear terms can not be left out. The treatment of the coastal boundaries in the model involve a procedure leading to a realistic curvilinear representation of both the western and the eastern sides of the Bay of Bengal. This coastal representation has another added advantage of taking automatically into account the finer resolutions in the shallow regions of the northern Bay. A desirable feature of storm surge simulation scheme is the ability to incorporate increased resolution adjacent to the coastline. This has been achieved by using a variable grid which leads to a substantial refinement of resolution

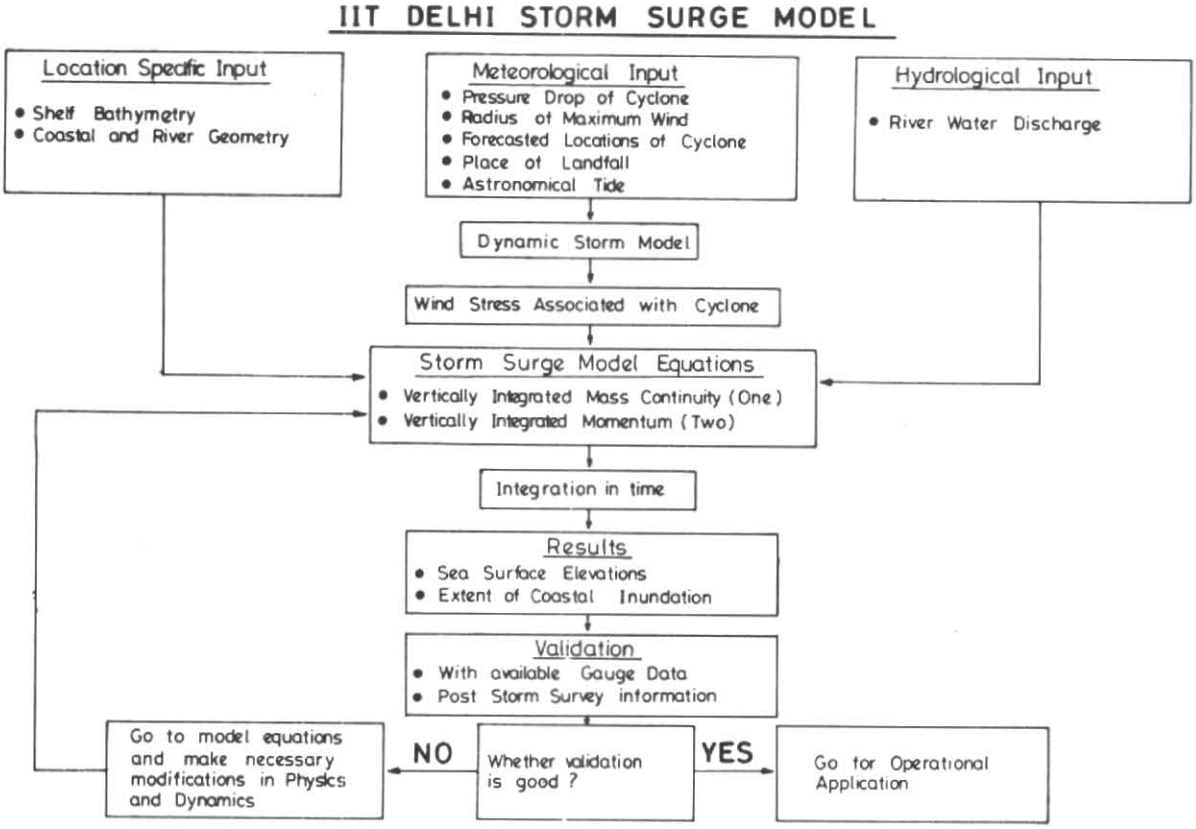


Fig. 8. A model for real time storm surge prediction system

near the coastline and a coarser resolution in the deeper waters. This type of grid assists in the incorporation of a more detailed bathymetric specification in the important coastal region.

With the specification of east-west grid points, the first off-shore grid point at which the elevation is computed is, on average about 5 km from the coastline.

4.3. *Integration procedure*

A conditionally stable semi-explicit finite difference scheme with staggered grid is used for the numerical solution of the model equations. The staggered grid consists of three distinct types of computational points on which the sea surface elevations and the zonal and meridional components of depth-averaged currents are computed. Following Sielecki (1968), the computational stability is achieved by satisfying the CFL (Courant-Friedrich-Lewy) criterion. In the present model this condition is satisfied by limiting the time step of integration to 3 minutes.

4.4. *Bottom stress*

The bottom stress is computed from the depth-integrated current using conventional quadratic law with a constant coefficient of 0.0026. This value has been decided by performing several numerical experiments (Johns *et al.* 1983).

4.5. *Boundary and initial conditions*

The coastal boundaries are taken as vertical side-walls across which the normal transport vanishes. The model has also option to take continuously deforming shoreline, however, it is not included in the present operationalization system due to unavailability of detailed onshore topography data. The normal currents across the open sea boundaries are prescribed by a radiation type of condition given by Heaps (1973). As usual it is assumed that the motion in the sea is generated from an initial state of rest.

4.6. *Bathymetry*

The bathymetry for the model is derived from the Naval Hydrographic charts and is interpolated at the model grid points by using cubic spline interpolation scheme. With this procedure sufficiently accurate and realistic bathymetry is generated over the continental shelf.

5. Operating procedure

Storm surge prediction model is run from a terminal menu. The steps are as follows (Dube *et al.* 1994) :

(a) Forecast domain is first set up by executing appropriate window. An arbitrary number of stations around the forecast place of landfall of the cyclone are provided for peak surge display. The duration of the forecast or the number of iterations are also provided.

(b) Next step is to provide the required characteristics of tropical cyclones for computing the wind stress forcings. These include (*i*) Cyclone positions (Lat.-Long.), (*ii*) pressure Drop (hpa) and (*iii*) radii of maximum winds (meters) at any time interval (preferably six hourly observations). This input data is determined from INSAT imageries and cyclone detecting radars at surface synoptic analysis by the India Meteorological Department.

(c) The final step is to run the storm model and the surge model. Storm model produces required surface wind stress associated with tropical cyclone at the model time steps. The output of the surge model is sea-levels, current fields and peak surge envelope for three forecast scenarios, (*i*) cyclone landfalling at the forecasted location on the coast, (*ii*) landfall at some distance (preferably 50 or 100 km) to the left of the forecast location and (*iii*) landfall to the right of the forecasted location.

(d) One has a choice to display these fields in any order or combination from the menu. The user may zoom into any part of the coastal regions to get clear picture, if indeed.

(e) The whole process of running the model for a 48-hour forecast takes 15-16 minutes of time.

This storm surge forecast system has the ability to investigate multiple forecast scenarios to be made in real time. For example, three 48-hour forecasts can be carried out on a 20 MHz PC-AT 386 in around 15 minutes. As the cyclonic storm approaches the coast and India Meteorological Department's forecasts become more accurate, the tracks of the cyclone are updated.

6. Validation experiments

In order to validate the model, several simulation experiments have been performed by using the data of severe cyclonic storms hitting the coastal regions in the Bay of Bengal and Arabian Sea. In the present paper an attempt has been made to compare the simulated sea surface elevations with observations from local tide gauges wherever possible or with post-storm survey estimates of the Meteorological Departments of India, Bangladesh, Myanmar and Sri Lanka.

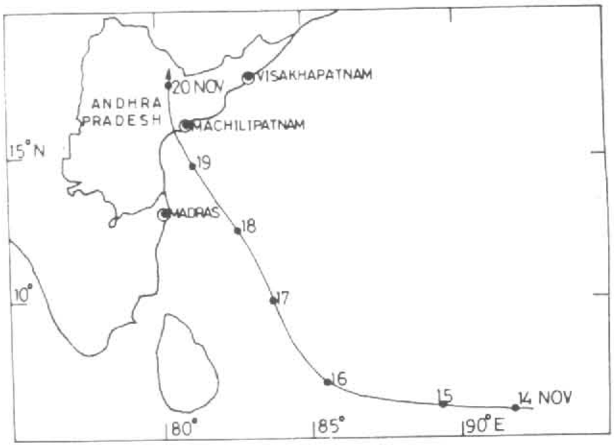


Fig. 9. Andhra cyclone (November 1977)

6.1. *East coast of India*

6.1.1. *November 1977 Andhra cyclone*

A severe cyclonic storm with a core of hurricane winds hit the Andhra coast of India on 19 November 1977. The genesis area of the cyclone was in Malayasia region from where it moved westward as a low pressure area becoming concentrated into a deep depression with its centre near 6°N, 92°E on the morning of 14 November. Whilst continuing to move generally westwards, the system rapidly intensified and on the morning of 16th, lay near 7°N, 85.5.°E with a well-developed core of winds exceeding 30 m/s. On the evening of 16 November, the storm changed its course towards a more northerly track and continued to follow this until landfall at the Andhra coast. The history of the strom just before the landfall is shown in Fig. 9. Satellite reports indicated that the storm attained its peak intensity on 18th and maintained this on 19th. The maximum wind speed associated with the storm during this period was estimated to be about 70 m/s at a distance from the centre of about 40 km. A pressure drop of 80 hPa was estimated at the centre of the cyclone.

A major part of the destructive effect of the cyclone was felt along the main coast south of Machilipatnam in Andhra Pradesh. This resulted from the surge-induced sea surface elevations which caused widespread flooding

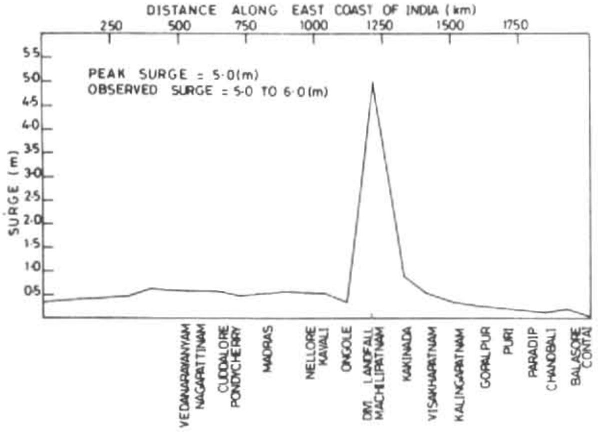


Fig. 10. Model computed peak surge values associated with Andhra cyclone closest to Divi Island

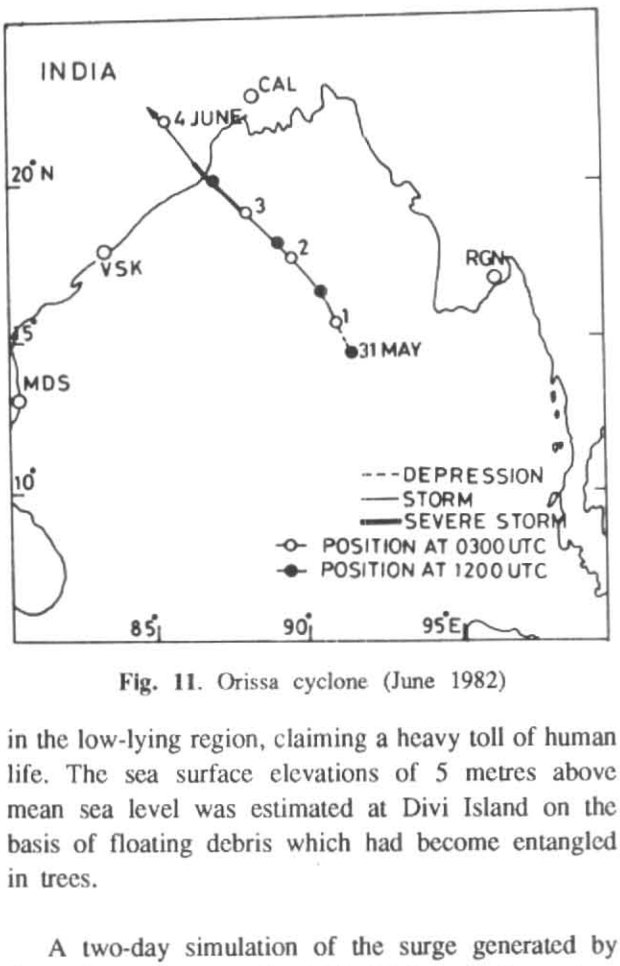


Fig. 11. Orissa cyclone (June 1982)

in the low-lying region, claiming a heavy toll of human life. The sea surface elevations of 5 metres above mean sea level was estimated at Divi Island on the basis of floating debris which had become entangled in trees.

A two-day simulation of the surge generated by the cyclone commenced at 1200 UTC on 17 November. Model-computed peak surge values associated with the storm are shown in Fig. 10. It may be seen that the maximum model-simulated surge of 5 meters occurs at a grid point closest to Divi Island. This is in very good agreement with the post-storm survey estimated sea level of about 5 meters in that region.

6.1.2. *Orissa cyclone (June 1982)*

A cyclonic storm, which formed over the east central Bay of Bengal on 1 June 1982 and was expected to cause a gale wind speed of 75 to 85 kmph, suddenly intensified into a hurricane with a wind speed of 150 to 200 kmph in the afternoon of 3 June. The storm crossed the north Orissa coast in between Paradeep and Chandbali at 1800 UTC on the same day with a wind speed of 200 kmph (Fig. 11). India Meteorological Department estimated a pressure drop of 50 hPa and a radius of maximum winds of 40 km at landfall (from satellite, radar and surface observation analysis). Observations of peak sea surface elevations were estimated to be more than 3 meters at Dharma port which is about 55 km to the right of the landfall point. This is in close agreement with the model-computed peak surge (Fig. 12).

6.1.3. *Andhra cyclone (May 1990)*

A severe cyclonic storm with a core of hurricane winds crossed Andhra coast at the mouth of river Krishna on the evening of 9 May 1990 at about 1330 UTC (Fig. 13). The cyclone started as a well-marked low pressure area over southeast Bay of Bengal and rapidly concentrated into a deep depression at 0300 UTC of 5 May, 1990 with its centre near 10.0° N and 85.5° E. On that evening it intensified further into a severe cyclonic storm by 6th morning when it was centered near 10.5°N, 83.5° E. The cyclone attained hurricane intensity around 0600 UTC of 6 May. It moved in west- northwesterly direction till 7th morning and changed its course to a north-northwesterly direction till its landfall on 9 May.

Based on the observation of INSAT-1B, India Meteorological Department estimated the lowest central pressure of the cyclone to be 920 hPa and the maximum sustained winds of 127 knots at about 25 km from the centre.

The cyclone caused heavy damage to the life and property in the coastal region. A surge of 4-5 meters is reported from the region. At Edirumondi the level of Krishna river rose by about 4 meters and at Nagayalanka about 25 km north of Edirumondi the rise in level was reported as 3-4 meters. Although the May 1990 cyclone was very similar to that of 1977 Andhra cyclone, the number of casualties in the former was only few hundred as compared to the other in which about 10000 persons died. This can be attributed to better cyclone monitoring and warning system of

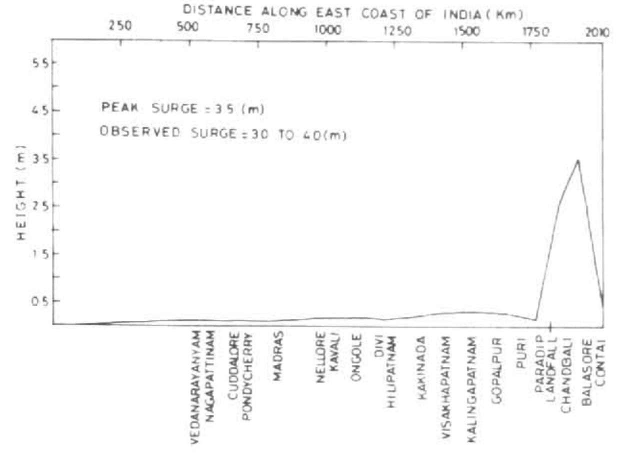


Fig. 12. Observed peak surge elevations in close agreement witht the model-computed peak surge for Orissa cyclone (June 1982)

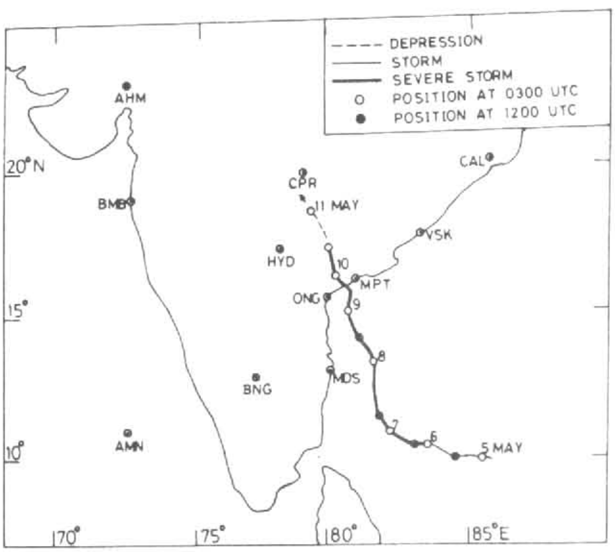
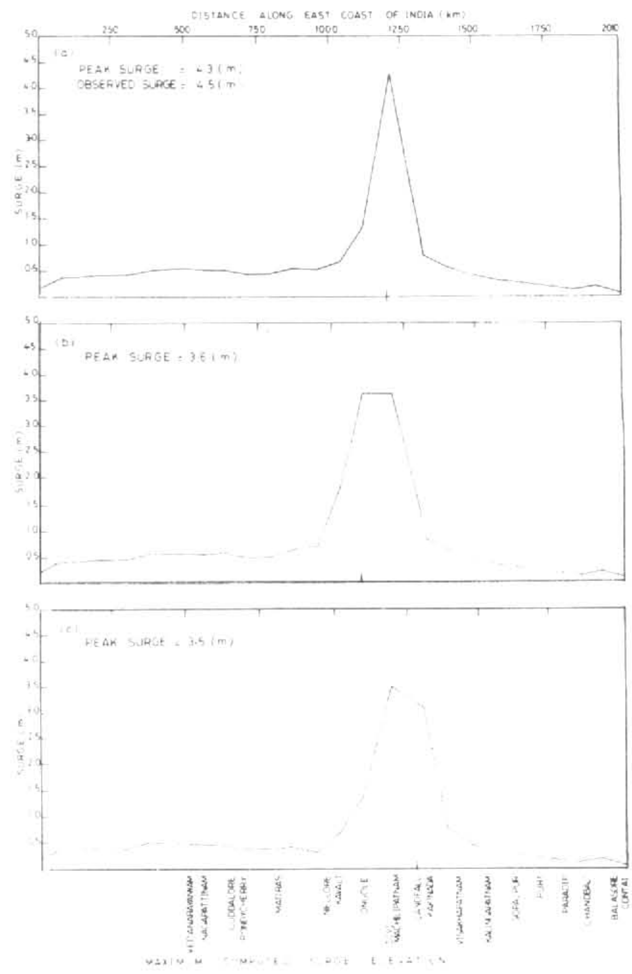


Fig. 13. Andhra cyclone (May 1990)

IMD at present Fig. 14 (a) depicts the model-computed peak surge envelop along the east coast of India. It may be noted that the model-computed result of maximum surge height compares favourably with observed estimates. Figs. 14(b) and (c) provide two other forecast scenarios when the landfall of the cyclone is 100 km to the south and north respectively of actual landfall point.

6.1.4. *Tuticorin cyclone (November 1992)*

A deep depression formed over south Bay of Bengal in the morning of 11 November 1992 near 7.5°N and



Figs. 14(a-c). Model-computed peak surge envelop (a) along the east coast of India, (b) when the landflal of cyclone is 100 km to the north and (c) when the landfall of the cyclone is 100 km to the south

86.5°E about 800 km east-southeast of Nagapattinam. It followed a steady westerly track and intensified into a cyclonic storm by the same evening and lay about 500 km south-southeast of Nagapattinam. After crossing Sri Lanka, it emerged into the Gulf of Mannar and was about 180 km south-southeast of Tuticorin on the 13th morning. Later it changed its course suddenly and moved north-westwards, intensified into a severe cyclonic storm on the 13th afternoon and crossed south Tamilnadu coast near Tuticorin on the same evening (Fig. 15).

Based on the observation of INSAT-2A, India Meteorological Department estimated the lowest central pressure of the cyclone to be 988 hPa and the maximum sustained winds of 55 knots.

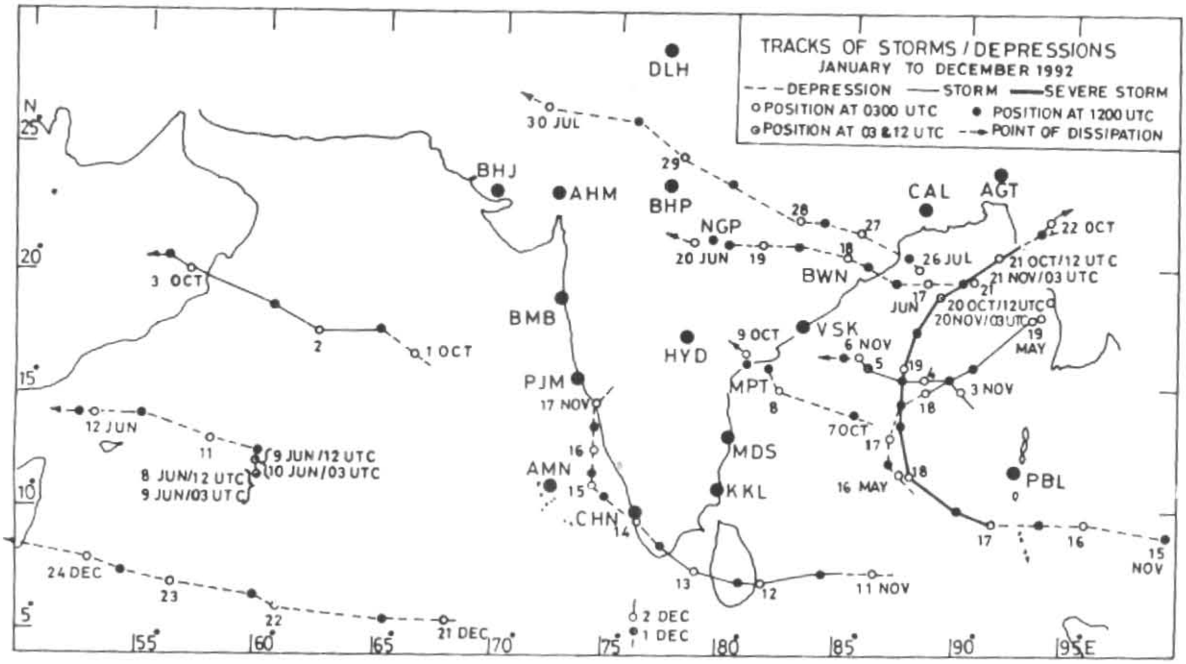


Fig. 15. Tuticorin cyclone (November 1992)

The cyclone caused considerable amount of damage in the coastal districts of Tamilnadu and Kerala after it crossed the coast near Tuticorin. Storm surges of 1 to 1.5 meter height inundated coastal length of about 70 km upto 200 to 300 m inland in Tamilnadu at the time of cyclone crossing the coast. Fig. 16 shows the model-computed peak surge envelop along the Tamilnadu coast of India. Computed results of maximum surge height of more than 1 meter compares well with observations.

6.1.5. *Karaikal cyclone (December 1993)*

A depression formed over southeast Bay of Bengal at 0830 hr IST of 2 December 1993 near 8.0°N and 87.0°E about 900 km east-south-east of Nagapattinam. Moving in a west-northwesterly direction it concen- trated into a cyclonic storm by mid-day of the same day centered near 8.5°N and 86.0°E. Moving in the same direction it became severe on 3rd morning and was located about 400 km east-southeast of Nagapattinam. The system intensified further into a severe cyclonic storm with a core of hurricane winds at 0530 hr of IST of 4 December 1993 when it was centered near 10.8°N and 80.8°E about 100 km east-southeast of Nagapattinam. Continuing to move in the same direction the severe cyclonic storm, with a core of hurricane wind, crossed north Tamilnadu coast near

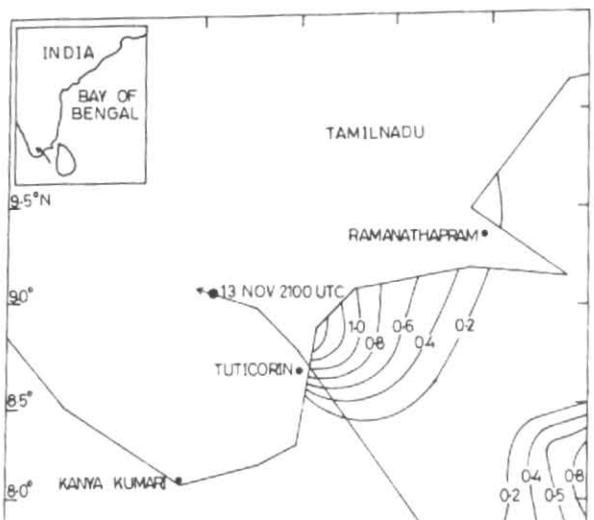


Fig. 16. Model-computed peak surge envelop along the Tamilnadu coast of India for Tuticorin cyclone (November 1992)

Karaikal around 1100 hr IST of 4 December (Fig. 17). India Meteorological Department estimated a pressure drop of 50 hPa and maximum sustained wind speed of 167 kmph at about 30 km from the centre. Storm surge of about 1 meter was estimated close to the landfall point. This is in good agreement with the model-computed peak surge (Fig. 18).

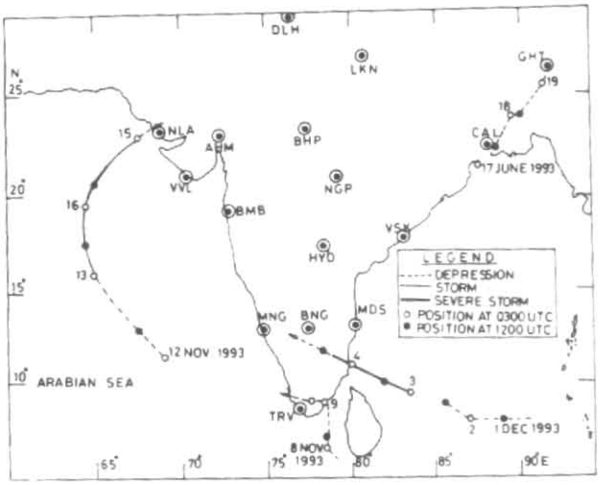


Fig. 17. Karaikal cyclone (December 1993)

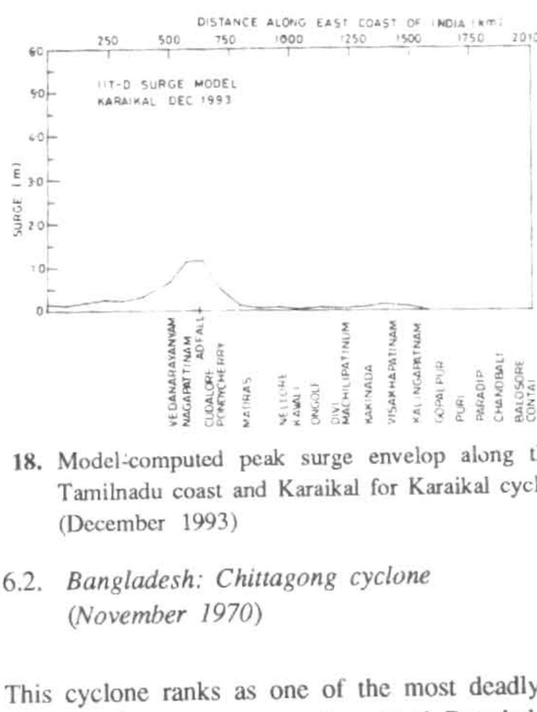


Fig. 18. Model-computed peak surge envelop along the Tamilnadu coast and Karaikal for Karaikal cyclone (December 1993)

6.2. *Bangladesh: Chittagong cyclone (November 1970)*

This cyclone ranks as one of the most deadly, if not the deadliest, storm ever devastated Bangladesh. The origin of this cyclone can be traced back to the remnant of a tropical storm that moved westward across Malaya on 5 November. The system appeared as a depression over the south central Bay of Bengal on November 8. While attaining storm intensity on November 9, it moved very slowly northward. Sustained winds reached hurricane intensity as it moved inland on 11 November. The cyclone made a landfall about 80 km to the north of Chittagong on the morning of 13 November (0520 hr Bangladesh standard time). The track of the cyclone is shown in Fig. 19. The observed range of maximum surge at Chittagong and neighbourhood was reported to be between 4.2- 7.2m. This is

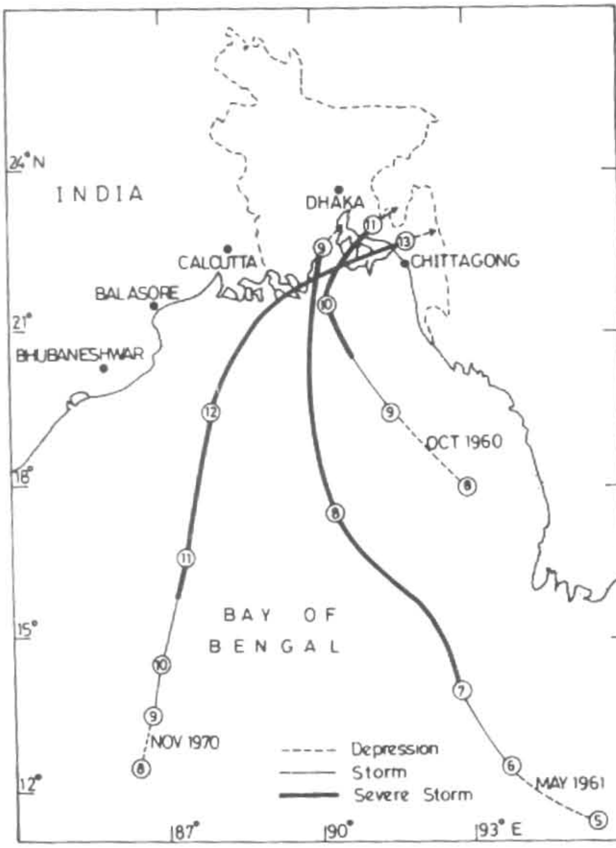


Fig. 19. Bangladesh : Chittagong cyclone (November 1970)

in good agreement with model computed peak surge (Fig. 20).

6.3. *Myanmar: Bassein cyclone (May 1975)*

A severe cyclonic storm crossed the Myanmar coast between Bassein and Gawlion on the night of 7 May 1975. This caused large scale damage in the deltaic region of Myanmar. The genesis area of the cyclone was in the Andaman sea, where a low was formed from 1 to 3 May which intensified into a depression on the evening of 4th with its centre near 12.5°N, 97°E. Moving northwestwards, it intensified into a cyclonic storm on the evening of 5th. Continuing to move northwest it became severe on the morning of 6th with its centre at 0300 UTC near 15°N, 94°E. Then moving slowly northwestward and later northwards, the storm was centered near 16°N, 93.5°E on 7th morning. Later it recurved northeastwards and crossed Myanmar coast. The history of this storm is shown in Fig. 21. The time variation of the sea surface elevations at selected stations is depicted in Fig. 22 (Dube *et al.* 1984). During this cyclone no observed surge records were available. However, according to

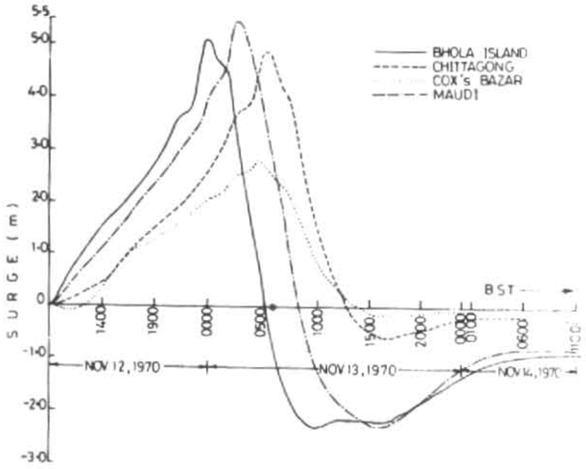


Fig. 20. Model computed peak-surge at Chittagong

Fig. 21. Myanmar : Bassein cyclone (May 1975)

the post-storm survey, tidal waves in the range of 3 to 5 meters above the normal astronomical tide were reported to have affected the deltaic regions of Myanmar right from the mouth of Irrawaddy to the extreme northern regions of the Gulf of Martaban. This is in good agreement with our predicted sea level elevations.

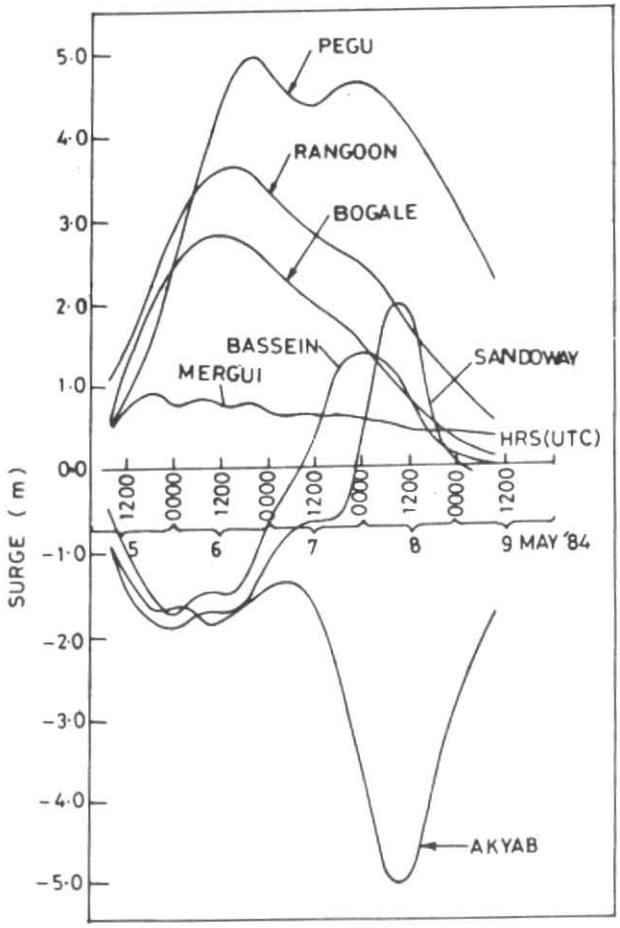


Fig. 22. Time variation of the sea surface elevation at selected stations

6.4. *Sri Lanka : Rameswaram cyclone (December 1964)*

A severe cyclonic storm crossed the Sri Lanka coast about 50km to the north of Trincomalee on 22 December at about 0600 UTC. Moving northwestward it crossed Sri Lanka and struck the Indian coast about 30km to the south of Tondi on 23 December at 0600 UTC. This was one of the severest storm that have occurred in Indian seas and probably the most severe storm which affected Sri Lanka and extreme south of the Indian peninsula. The track of the cyclone is shown in Fig. 23. Computed maximum sea surface elevations for the landfall of the cyclone in Sri Lanka and later in India are shown in Fig. 24.

A peak surge of 3.7 m is predicted at about 50km north of Trincomalee while near Tondi (India) a peak surge of 5.6 m is predicted (Rao *et al.* 1994). This is in agreement with the reported flooding and surge in the region (Rao and Mazumdar 1966).

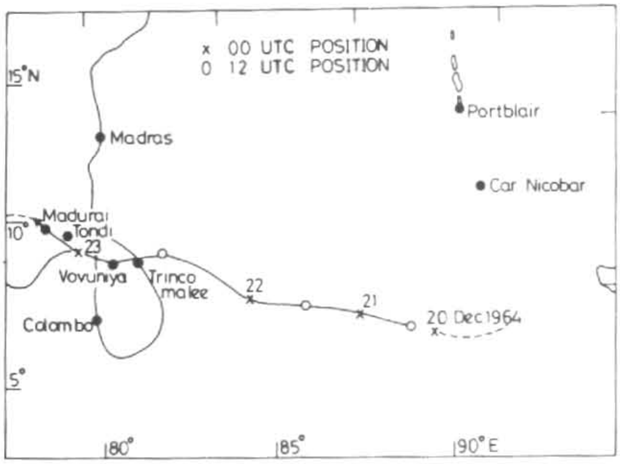


Fig. 23. Sri Lanka : Rameswaram cyclone (December 1964)

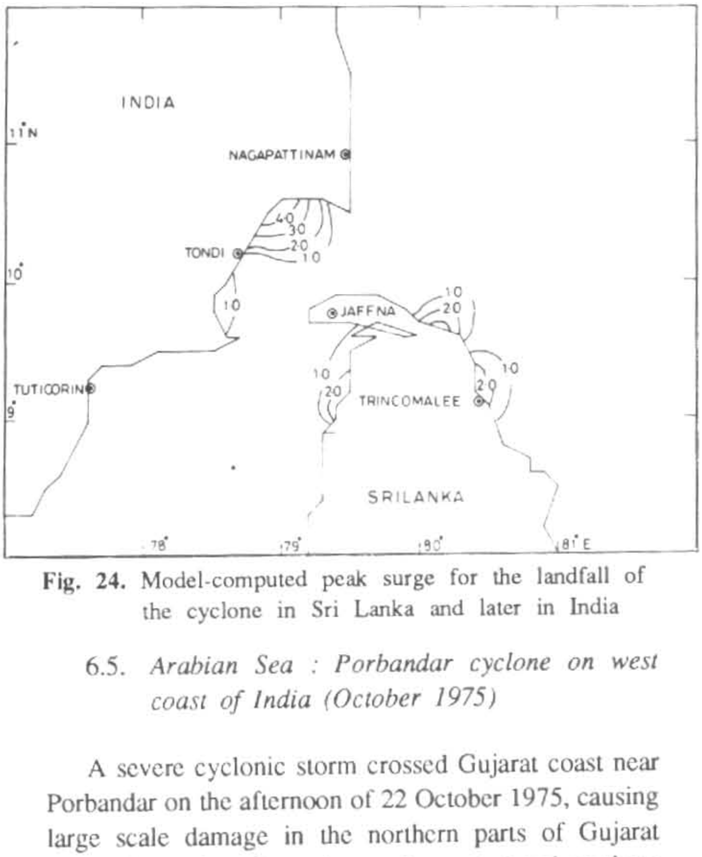


Fig. 24. Model-computed peak surge for the landfall of the cyclone in Sri Lanka and later in India

6.5. *Arabian Sea : Porbandar cyclone on west coast of India (October 1975)*

A severe cyclonic storm crossed Gujarat coast near Porbandar on the afternoon of 22 October 1975, causing large scale damage in the northern parts of Gujarat state. The cyclone formed over the central and southern Bay of Bengal on the morning of 15 October and intensified into a depression, moved west-northwest and lay centered 50km east-southeast of Ongole at 0300 UTC on 18 October. At this time a low pressure area formed over east central Arabian Sea with its centre near 14°N, 73°E.

The depression in the Bay of Bengal crossed the Andhra coast near Ongole on the afternoon of 18 October, weakened into a low pressure area and moved into the Arabian Sea between Harnai and Ratnagiri.

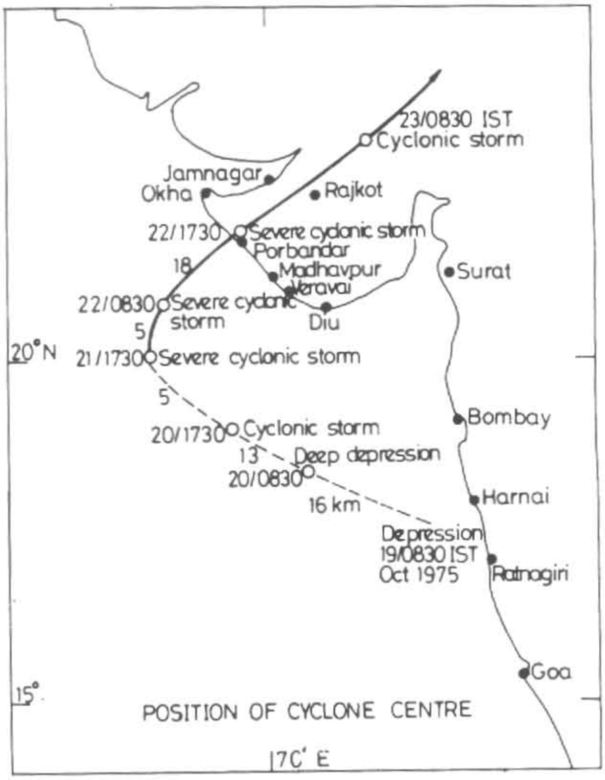


Fig. 25. Arabian Sea: Porbandar cyclone on west coast of India (October 1975)

The system over the Arabian Sea also moved north westward. Finally, the two systems merged and concentrated into a deep depression by the evening of 19 October, centered near 17°N, 73.5°E. The subsequent history of storm is shown in Fig. 25. While continuing to move northwestward, the system intensified into a deep depression and then into a cyclonic storm with its centre near 19°N, 69.5°E on the evening of 20 October. On the morning of 21 October, the storm started to deviate towards the north and then moved north-northeast and by that evening it had concentrated into a severe cyclonic storm. The system further intensified and, on the morning of the 22nd, Lay near 20.8°N, 69°E with a core of hurricane winds. The reported maximum wind speed associated with the storm during this period was 115 knot. The distribution of the predicted maximum sea-surface elevations, observed surge and the time of occurrence along the Gujarat coast are given in Fig. 26 (Dube *et al.* 1985).

7. Prediction of inland inundation

While the accurate prediction of surge is very important, it is also necessary to have an idea of the

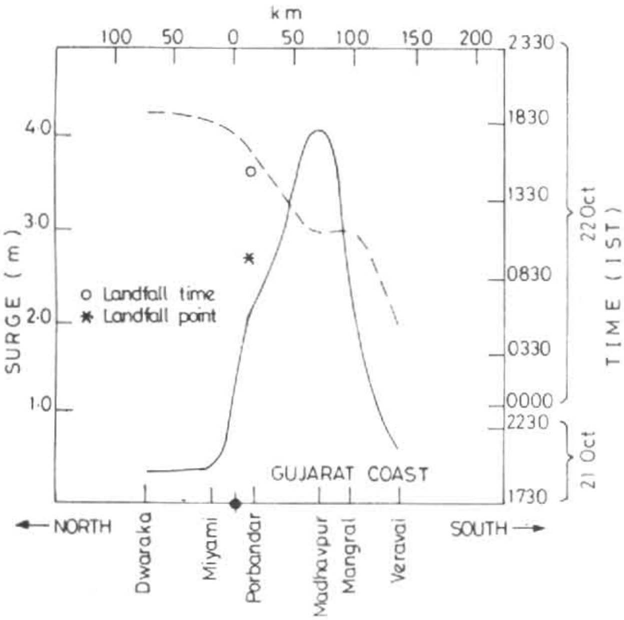


Fig. 26. Distribution of the predicted maximum sea surface elevations, observed surge and the time of occurrence along the Gujarat coast

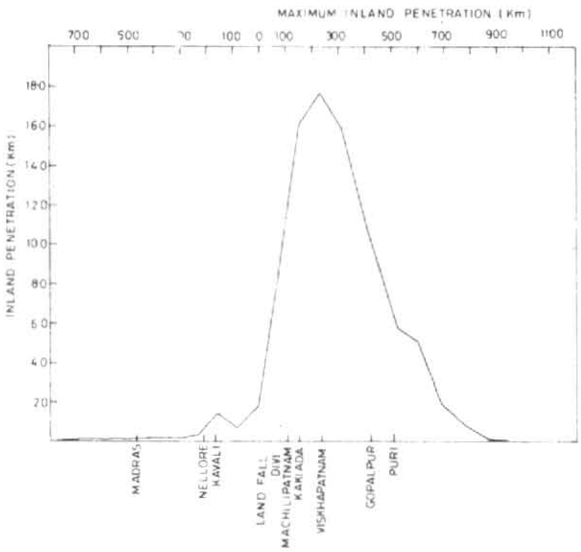


Fig. 27. Predicted maximum inland inundation associated with Andhra Cyclone 1990

extent of inland inundation of surge from the sea, so that the coastal stretch upto which significant flooding is expected can be estimated for the purpose of evacuation. Keeping this in view a model has been developed for the prediction of inland inundation along the east coast of India and Bangladesh (Johns *et al.* 1982, Dube *et al.* 1986).

Frequently, the lateral boundaries in numerical storm surge prediction models are taken to be vertical side-walls through which there is no flux of water. In actuality, however, the water will usually move continuously inland and the use of idealized vertical side-walls may lead to misrepresentation of the surge development. Thus, instead of using the conventional solid wall boundary at the coast, the model uses a continuously deforming lateral fluid boundary and includes the onshore topography in order to route the storm surges over the land. The model has been tested with idealized coastal topography along the east coast of India and Bangladesh coast. Fig. 27 gives an estimate of inland inundation along the east coast of India in association with the surge generated by 1990 Andhra cyclone.

8. Sea level rise and storm surge

The issue of the sea level rise as a consequence of climatic warming and the greenhouse effect is of extremely grave concern for Bangladesh. The projected worldwide rise of sea level during the next 100 years will be particularly hard-felt in the low-lying regions of West Bengal in India and Bangladesh. These regions have been created as a result of sediment washing down the major rivers Ganga, Brahmaputra and Meghna.

The rise in the sea level would inundate low lying areas, destroy coastal marshes and swamps, erode shoreline, cause coastal flooding and increase salinity of rivers, bays and aquifers. Mangroves and other vegetation will migrate landward with rising sea-level, but such migration will be inhibited by man-made developments. Thus the protective buffering effects of coral reefs and mangroves against cyclones will be reduced as a result of sea level rise and increased temperatures (Broadus 1993).

Rising air temperature resulting from the greenhouse warming will increase SST (Manabe and Stouffer 1980). An increase in the surface water area of warmer SST for cyclone generation is expected to increase frequency and intensity of tropical cyclones and also the duration of the cyclone season (Raper 1993). Storm surges caused by rising water resulting from landward movement of these huge storms would also increase in frequency, severity and duration. With increasing population densities in the future, through the combined effects of natural population increase and loss of coastal zone due to sea level rise, the exposure to severe storm surges will only increase.

Broadus *et al*. (1986) and Broadus (1993) have made a detailed study on the potential consequences of sea-level rise in the deltaic regions of the Nile River in Egypt and the complex Ganga-Brahmaputra-Meghna river system in Bangladesh. In the case of Bangladesh the authors have presented different transgression scenarios as a result of the projected rise in the sea level. They have also discussed the problem of exposure of population to storm surges as a result of sea-level rise. Economic considerations *vis-a-vis* sea level rise are also detailed in the study.

Dube and Rao (1991) used a continuously deforming shore-line model to determine the effect of sea-level rise on storm surges affecting the east coast of India. Their model uses an idealized onshore topography to compute the inland inundation associated with sea-level rise and storm surges. Flather and Khandker (1993) used numerical model to determine the effect of an increase in mean sea level on tidal storm surge and combined tide and storm surge levels for Bangladesh, while Brammer (1993) made an impact assessment of sea-level rise and geographical complexities for the Ganga-Brahmaputra-Meghna delta of Bangladesh. In a recent paper Sinha *et al*. (1996) studied the impact of sea level rise on the tidal circulation in the Hooghly estuary.

8.1. *Data monitoring*

Real time observations on meteorological and oceanographic parameters over Indian seas are needed to improve operational capability of surge prediction. As yet there is no systematic monitoring for the Indian Ocean as a whole, however, India is putting in three high precision tide gauges at Port Blair, Chennai and Goa.

Following suggestions are made in this regard :

(a) Installation of data buoys in the coastal and deep waters of the Bay of Bengal and the Arabian Sea.

(b) Installation of high precision sea-level gauges at selected locations along the east and west coasts of India, Bangladesh, Myanmar and Sri Lanka.

(c) The meteorological sea level data obtained in this manner will be helpful in the prediction of natural hazards, such as, storm surges, tsunamis and set up due to wind waves.

(d) Satellite altimeter will compliment the data obtained from tide gauges but cannot replace it satisfactorily because of the lack of needed precision for assessment of sea-level rise.

8.2. *Risk assessment*

Accurate assessment is essential step for measures to reduce risk. Following steps are suggested for making risk assessment:

(a) Mapping of cyclone hazards giving information on matters such as location, frequency, duration and severity including wind speeds, inland inundation, etc.

(b) Assessment about the vulnerability of people and property to mapped cyclone/surge hazard.

(c) Although the vulnerability analysis is a 'site-specific' problem even though, as tropical cyclones may threat a number of neighbouring countries, a regional approach to the problem may be very useful.

8.3. *Protection strategy*

(a) Wind speeds associated with tropical cyclones may significantly be reduced by planting bushes and appropriate trees around settlements.

(b) Maintaining and strengthening coastal mangrove swamps may effectively reduce the impact of surge.

(c) Development of a comprehensive warning system including monitoring and forecasting the tropical cyclone and its hazard conditions, advising the coastal authorities about its impact and issuing and disseminating warnings to local population.

8.4. *Disaster preparedness*

Risk reduction due to cyclone hazard also requires active preparedness plan which include following:

(a) Educating the community in the areas of risk about the hazard.

(b) Practical training about how to reduce damage in the event of cyclone hazard.

(c) Promoting ingenious ways for coping with the consequences.

9. Conclusions

The recent developments in the storm surge forecasting for the Bay of Bengal and Arabian Sea is described. A real time storm surge prediction system is proposed, which can be run in a few minutes on a personal computer. The forecasting system is based on the vertically integrated numerical storm surge model of Dube *et al.* (1985). A dynamic storm model developed by Jelesnianski and Taylor (1973) is used for computation of surface winds associated with cyclonic storms. Only meteorological inputs required for the model are positions of the cyclone, pressure drop and radii of maximum winds at any fixed interval of time. The system is operated *via* a terminal menu and the output consists of the 2-D and 3-D views of peak sea surface elevations with the facility of zooming the region of interest. The system can handle multiple forecast scenarios.

The model results reported for several case studies are in very good agreement with the available observations and estimates of the surge. The model has extensively been tested with severe cyclonic storms of the last three decades which have affected the coastal regions in the Bay of Bengal and Arabian Sea.

A brief review of the models developed for the prediction of inland inundation and the implications of sea-level rise on storm surges is also given. These model studies are preliminary in nature and require further sophistication before any conclusion may be drawn.

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