

## Chapter 5

# Simulation of storm surges in the Bay of Bengal

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### 5.1 Introduction

As a first step towards increasing the accuracy of storm surge simulation, a 2D model was developed to simulate the tides in the Bay of Bengal as described in Chapter 4. The validation of the tidal model results showed that the model was able to capture the observed tidal characteristics in the Bay of Bengal. Now that the accuracy of the tidal model is evaluated, we modified the model to simulate the storm surges (hereafter referred to as storm surge model) caused due to different low pressure systems that developed in the Bay during the past years.

The meteorological forcing for the storm surge model was obtained from the cyclone model of Holland using the data available for 136 low pressure systems (LPS) that occurred during 1974-2000 in the Bay of Bengal. The storm surge model was driven by the combined effect of tides and meteorological parameters to get the total water levels and with tides alone to compute the surge component as a difference between the elevations of two simulations. The annual maxima of sea levels, extracted from the simulations, were fitted with Gumbel distribution using r-largest annual maxima method to estimate the return periods and return levels of extreme events at 26 stations along the east coast of India. Though the model domain covered the entire Bay of Bengal, the return levels were evaluated only along the east coast of India. This work is documented in Sindhu and Unnikrishnan [2012].

Similar work has been carried out by Jain et al. [2010], who estimated the expected total water level for each coastal district of the maritime states along the east coast of India. However, the methodology followed by Jain et al. [2010] is slightly different from the present study as they had carried out storm surge simulations for

synthetic cyclonic events developed from statistically projected cyclone intensities based on the analysis of historical data. The major improvement of the present study over Jain et al. [2010] is the inclusion of the meteorological and tidal forcing simultaneously in the model in order to allow for tide-surge interaction. The non-linear interaction between tides and surge and its substantial impact on the resultant total sea level have been studied by Horsburgh and Wilson [2007], Butler et al. [2007], Johns et al. [1985] and emphasized in several earlier works as a step towards improvement for accurate assessment of total water level.

A description of the models used to generate cyclones and storm surges are given in Sections 5.2.1 and 5.2.2 respectively. The model validation using the observed hourly sea level is described in Section 5.3. The return levels of extreme sea levels are discussed in Section 5.4. The results of the study are summarized in Section 5.5.

## **5.2 Data and methodology**

The meteorological parameters represented by wind field and core pressure associated with a cyclone and tides are the major input to drive the storm surge model. The tidal elevations were obtained from FES2004 global tidal dataset, as defined in Chapter 4 while the wind fields and Mean Sea Level pressure (MSLP) fields were generated using Holland cyclone model. The schematization of Holland cyclone model and storm surge model and the input data required to drive these models are described in the following sections.

### **5.2.1 Holland cyclone model**

The large pressure drop at the core and the strong wind field around the core are the prominent feature of a tropical cyclone; the former produces surge in the deeper part of the bay, while the latter acting on the continental shelf produces the major and disastrous surge. Accordingly, it becomes essential to provide accurate wind and pressure field as the input to the storm surge model.

The MSLP is determined by using the model of Holland [1980] following Flather [1994] as

$$p = p_c + (p_n - p_c) \exp[-(r_m/r)^b] \quad (5.1)$$

where,  $p$  is the atmospheric pressure at radius  $r$ ,  $p_c$  is the core pressure,  $p_n$  (1010 hPa) is the ambient pressure,  $r_m$  is the radius of maximum winds and  $b$  is a scaling parameter that defines the shape of a cyclone with values ranging from 1 to 2.5. The parameter  $(p_n - p_c)$  gives the pressure drop at the core of the cyclone.

Empirically  $b$  is defined as [Hubbert et al., 1991; Tang et al., 1997]

$$b = 1.5 + (980 - p_c)/120 \quad (5.2)$$

where  $p_c$  is in hPa.

The symmetrical wind profile is estimated [Holland, 1980] from the gradient wind equation as given below, from which the components of wind stress,  $w_x$  and  $w_y$  are derived

$$V_g = \left\{ \frac{b \left(\frac{r_m}{r}\right)^b (p_n - p_c) \exp\left[\left(\frac{r_m}{r}\right)^b\right] + r^2 f^2}{\rho_a} + \frac{r^2 f^2}{4} \right\}^{1/2} - \frac{r|f|}{2} \quad (5.3)$$

where  $\rho_a$  is the density of air and  $f = 2\omega \sin\phi$  is the Coriolis parameter (as defined in Section 2.2). The maximum winds occur when  $\left(\frac{r_m}{r} \cong 1\right)$ , which implies

$$V_{max} = \left\{ \frac{b(p_n - p_c)}{e\rho_a} \right\}^{1/2} \quad (5.4)$$

### 5.2.2 Storm surge model

The storm surge model was developed from the tidal model by incorporating the stress terms and the MSLP fields in the vertically integrated equations of momentum (Equations (2.2) and (2.3)) described in Section 2.2. Therefore, the equations of continuity and the momentum equations in the  $x$  and  $y$  directions are as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (5.5)$$

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}(uU) + \frac{\partial}{\partial y}(vU) - fV = -g(h + \eta) \frac{\partial \eta}{\partial x} - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\tau_{sx}}{\rho} - \frac{C_d U \sqrt{U^2 + V^2}}{(h + \eta)^2} + A_H \nabla^2 U \quad (5.6)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}(uV) + \frac{\partial}{\partial y}(vV) + fU = -g(h + \eta) \frac{\partial \eta}{\partial y} - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\tau_{sy}}{\rho} - \frac{C_d V \sqrt{U^2 + V^2}}{(h + \eta)^2} + A_H \nabla^2 V \quad (5.7)$$

The symbols in Equations (5.5), (5.6), and (5.7) have been defined in detail in Section 2.2, except  $\bar{\tau}_s$ , the surface stress which is parameterized as a quadratic of the surface wind velocity ( $\bar{W}$ ) as

$$\bar{\tau}_s = k\rho_a \bar{W} |\bar{W}|; \quad \bar{W} = \sqrt{w_x^2 + w_y^2} \quad (5.8)$$

where,  $k$  is the surface drag coefficient and  $\rho_a$  is the air density. The drag coefficient  $k$  in Equation (5.8) is given as  $k \times 10^3 = 0.8 + 0.0065\bar{W}$  suggested by Wu [1982], taking into account the increase in sea surface roughness with increase in wind speed.

The Equations (5.5), (5.6), and (5.7) are transformed into finite difference form as described in Section 2.4.

In addition to the governing equations, the open boundary is modified by applying a radiation type condition [Heaps, 1973], shown by Equations (5.9) and (5.10).

Along southern boundary:

$$v + \left(\frac{g}{h}\right)^{\frac{1}{2}} \eta = 0 \quad (5.9)$$

Along western boundary:

$$u + \left(\frac{g}{h}\right)^{\frac{1}{2}} \eta = 0 \quad (5.10)$$

Unnikrishnan et al. [2006, 2011] used a similar code for the simulation of surges driven by the wind field and surface pressure fields obtained from regional climate models (HadRM2 and PRECIS, respectively).

### 5.2.3 Cyclone data for Holland model

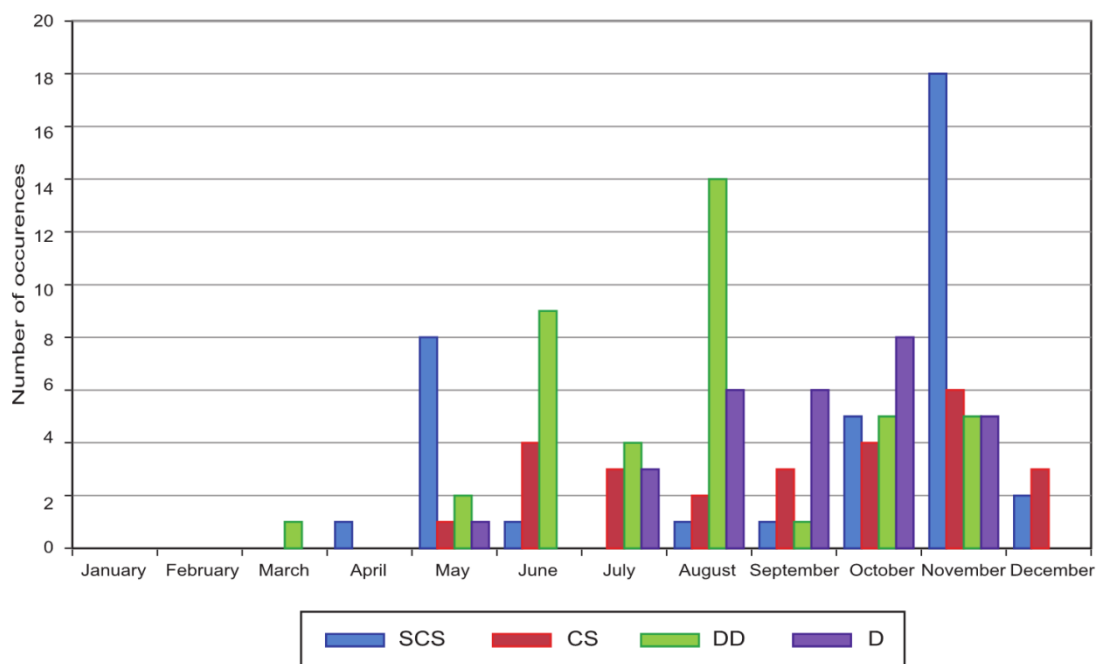
The inputs required for the generation of cyclone using Holland model are the radius of maximum winds, core pressure and the position of the core of the cyclone. Holland [1980, Table 2] showed that the mean errors and maximum errors associated with MSLP fields obtained using Equation (5.1) decreases with increase in radius of maximum winds and has minimal value at 100 km and 40-60 km. Experiments with different radii of maximum wind showed that defining 50 km as the radius of maximum winds in the cyclone model of Holland produced a more realistic surge simulation results.

For the present study, a set of 136 low pressure systems (LPS), identified during the period 1974-2000, were used. National Institute of Oceanography [2004] examined the hourly tide gauge data of 27 years (1974-2000) at Paradip, Visakhapatnam and Chennai for storm surge events and identified the associated meteorological events based on the information from the Indian Daily Weather Report and Mausam, published by the Indian Meteorological Department. The report gave a detailed account of the position and the pressure of the cyclone core for each LPS event at each day of its development till the landfall for the events identified during 1974-1988. The information about the cyclone tracks for the events that occurred during 1989-2000 were available in-house, a brief summary of which has been provided in the report.

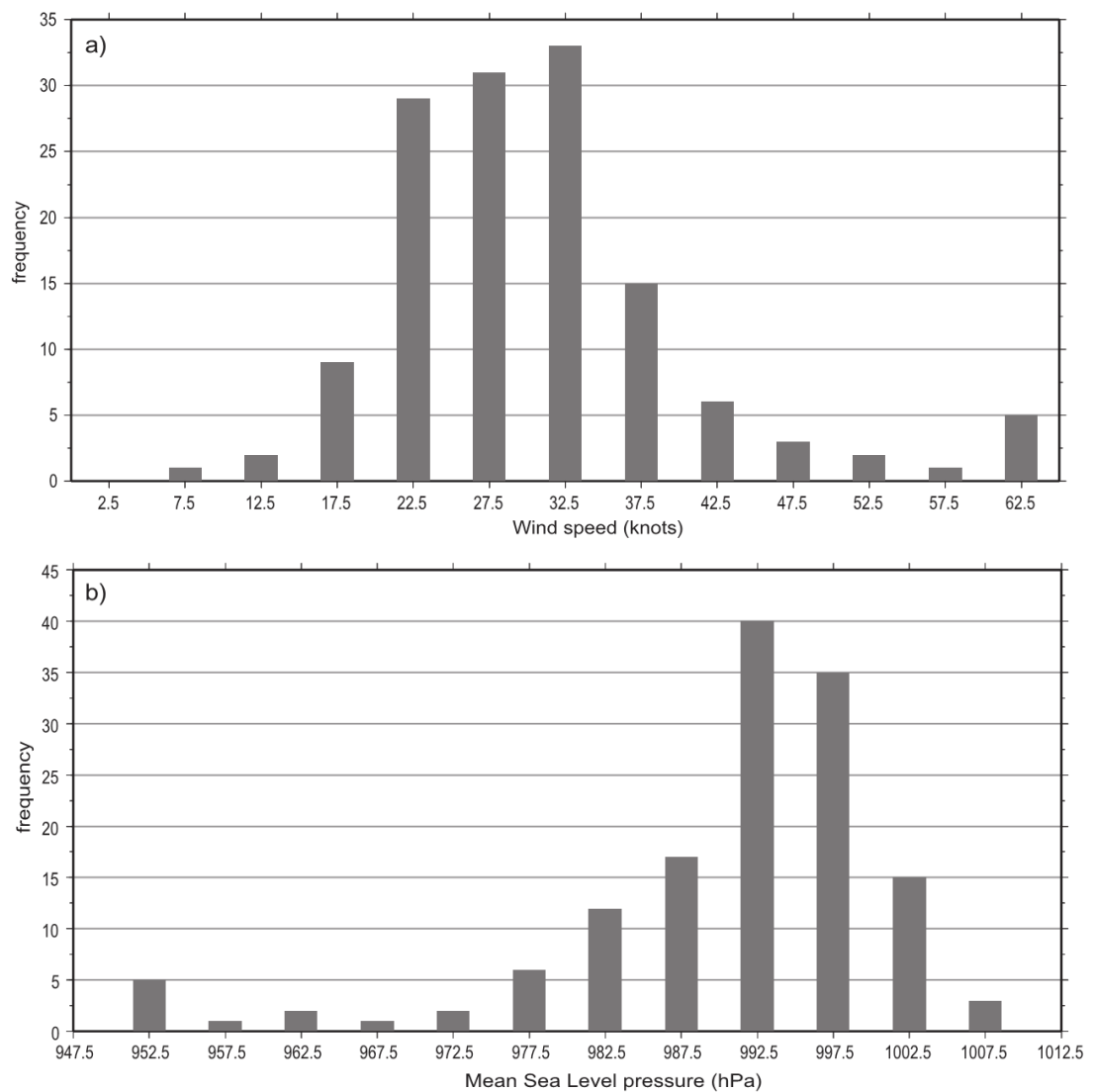
A total of 136 cyclonic events were identified during the past 27 years (1974-2000), which were analyzed for their intensities and classified, as per Table 1.3 into Super Cyclonic Storms (SCS), Cyclone Storm (CS), Deep Depression

(DD) and Depression (D). Among the 136 LPS events identified, 30 were D, 41 DD, 26 CS, and 37 SCS. It is depicted from the monthly frequency distribution of the events (Figure 5.1) that highest frequency of CS (25%) and SCS systems (49%) occur in the month of November. Cyclone formation is found to be prominent during the monsoon and post monsoon months with rare formations in the months from January to April. Figure 5.2 shows that the cyclones with core pressure 990-995 hPa, which corresponded to a wind speed of 25 – 30 knots, had the highest frequency of occurrence in the considered period.

**Figure 5.1** Monthly frequencies of cyclones classified as Depression (D), Deep Depression (DD), Cyclone Storm (CS) and Super Cyclonic Storms (SCS) for the period 1974 - 2000. Data Source: Indian Daily Weather Report and Mausam, published by the Indian Meteorological Department.



**Figure 5.2** Frequency distribution of a) wind speed (knots) (binned into 5 knots) and b) core pressure (hPa) (binned into 5 hPa classes) of cyclones identified during the period 1974 - 2000. Data Source: Indian Daily Weather Report and Mausam, published by the Indian Meteorological Department.



The tracks of cyclones that crossed different coasts of the Bay of Bengal each year and the frequency distribution of events crossing each state along the east coast of India are shown in Figures 5.3 to 5.5 and Figure 5.6, respectively. It is found that along the coast of Bay of Bengal at least three cyclonic events occur every year with maximum number of events not exceeding 7 during the period 1974 -2000. Out of the 136 LPS that formed in the Bay during the specified period, 100 (73%) systems crossed the coast of India, 13 (9%) crossed Bangladesh, 10 (7%) crossed Myanmar and 2 (1%) crossed Sri Lanka and 11 (8%) weekend or dissipated over sea. It is evident from Figure 5.6 that out of the 100 cyclones which crossed the Indian coast during the considered 27 years, Orissa had the largest fraction of 43% followed by Andhra Pradesh with 29%, West Bengal 16% and Tamil Nadu 12%. Orissa had the highest number (37 out of 57) of cyclone during the monsoon months while Andhra Pradesh had the highest frequency of cyclones in the month of October and November (9 out of 18) and some scattered events during the monsoon months.

#### **5.2.4 Schematization**

The model domain (Figure 4.7) and the bathymetry (Figure 4.8) for the storm surge model are similar to that of tidal model. The model domain, as shown in Figure 4.1, extends from 1.5°N to 23°N and 79.8°E to 103°E with open boundaries along 79.8°E and 1.5°N.

The storm surge model was driven simultaneously with tides prescribed along the open boundaries and wind forcing and Mean Sea Level Pressure (MSLP) to simulate the surges caused due to each LPS event. The tidal forcing was included in the storm surge model itself, rather than adding the individual tidal model output and the surge model output, in order to take into account the non-linear interaction between tides and surges. The composite tidal elevations at the open boundaries were extracted from FES2004 global tidal model, as described in



**Figure 5.3** Tracks of cyclone that formed in the Bay Bengal during the period 1974-1982 in different months. Data Source: Indian Daily Weather Report and Mausam, published by the Indian Meteorological Department.

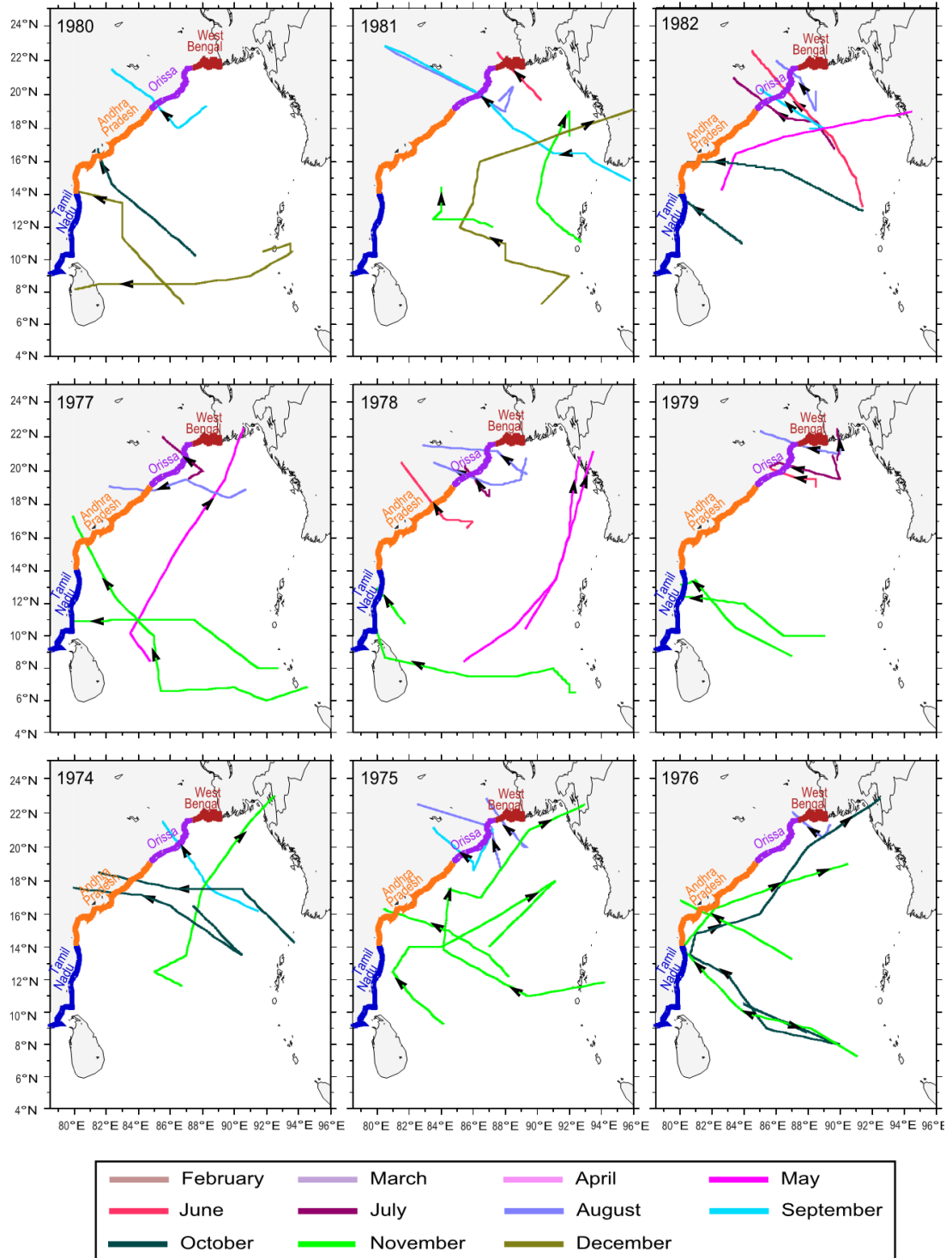


Figure 5.4 Same as Figure 5.3, but for the period 1983-1991.

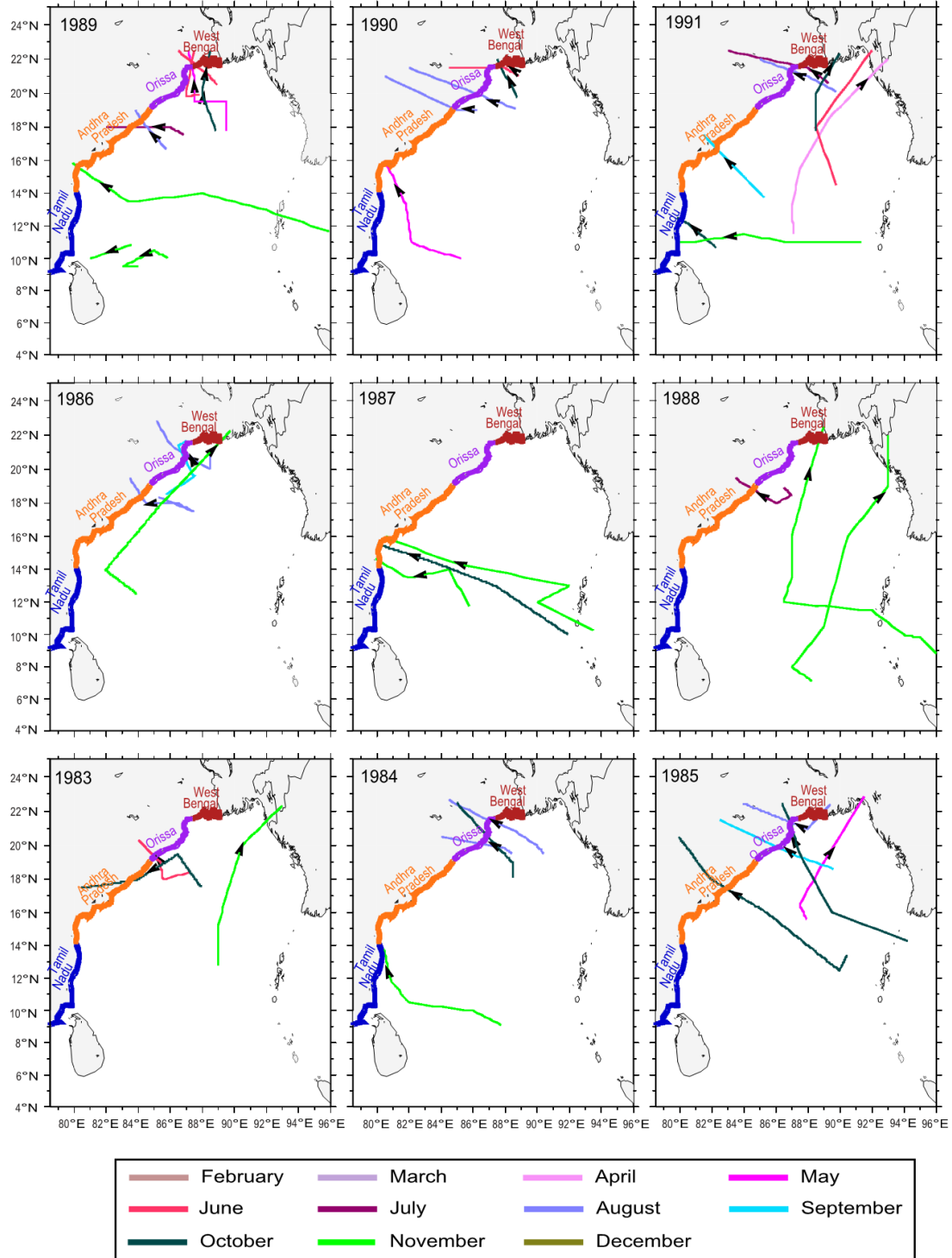
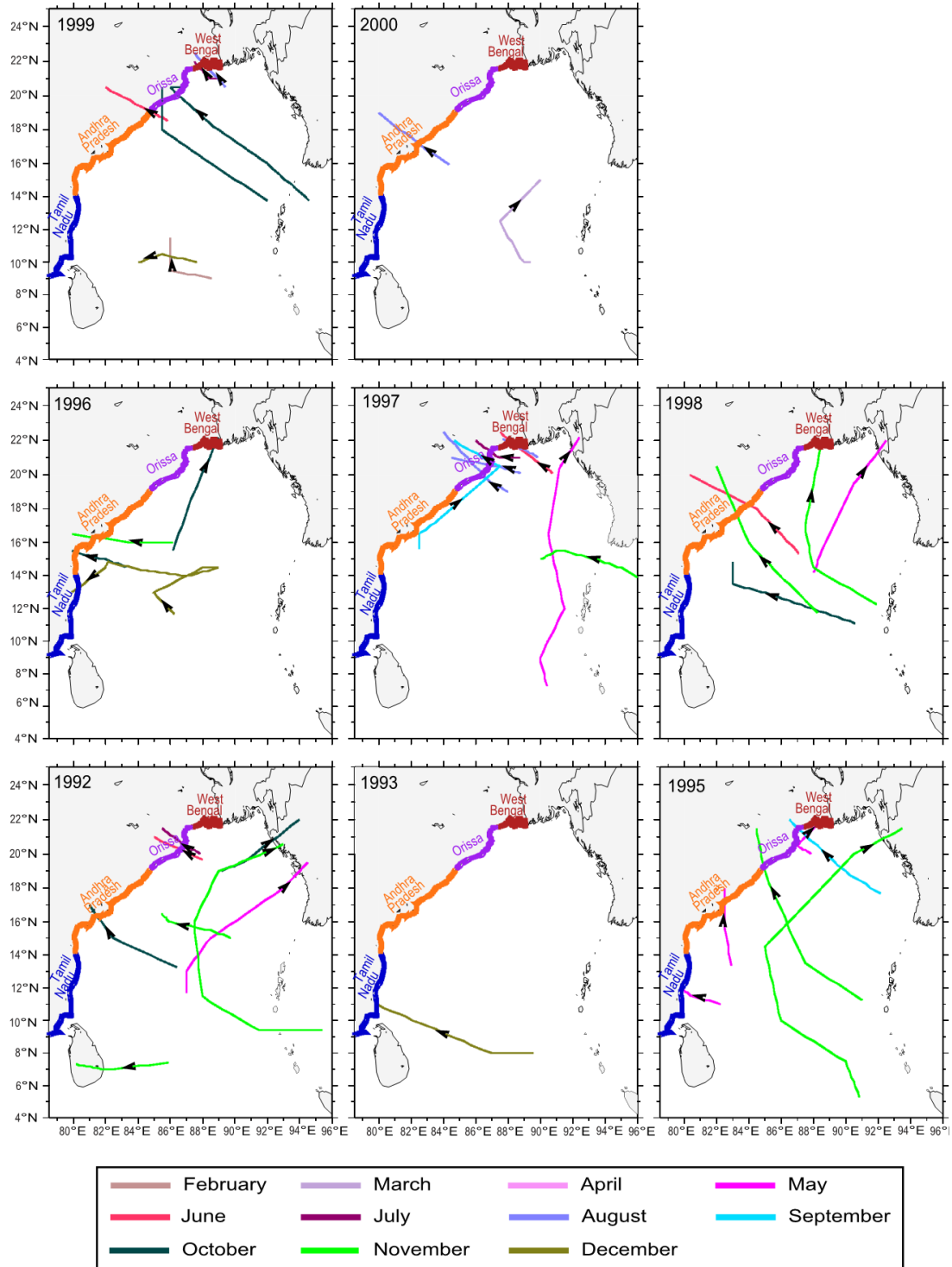
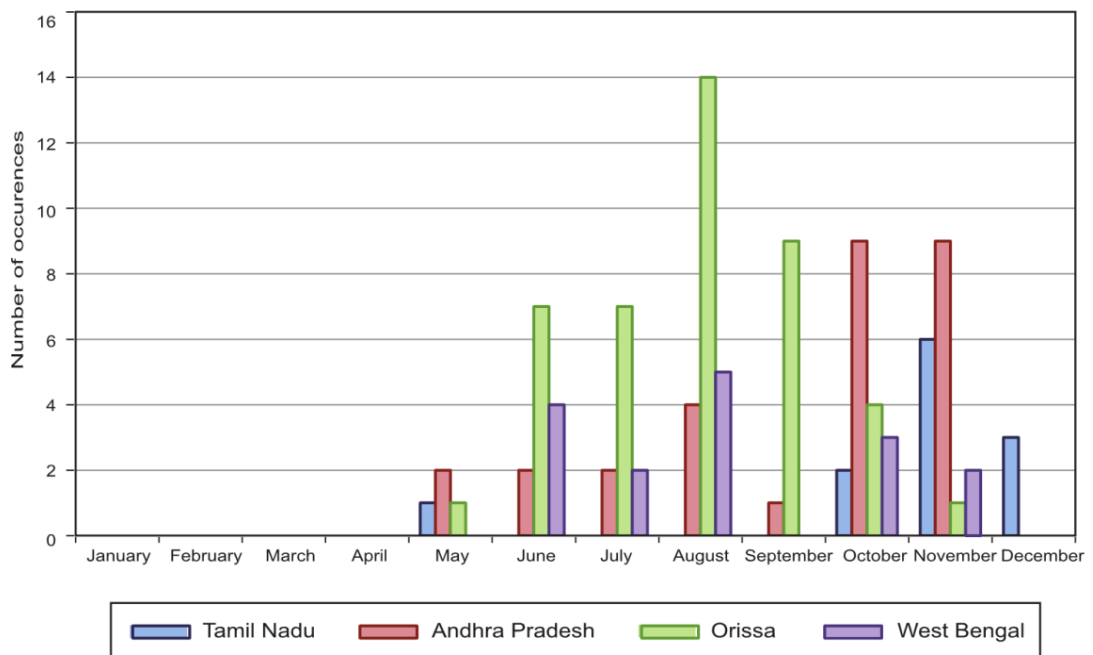


Figure 5.5 Same as Figure 5.3, but for the period 1992-2000.



**Figure 5.6** Monthly frequencies of cyclones that hit the states of Tamil Nadu, Andhra Pradesh, Orissa and West Bengal located along the east coast of India during the period 1974 – 2000. Data Source: Indian Daily Weather Report and Mausam, published by the Indian Meteorological Department.

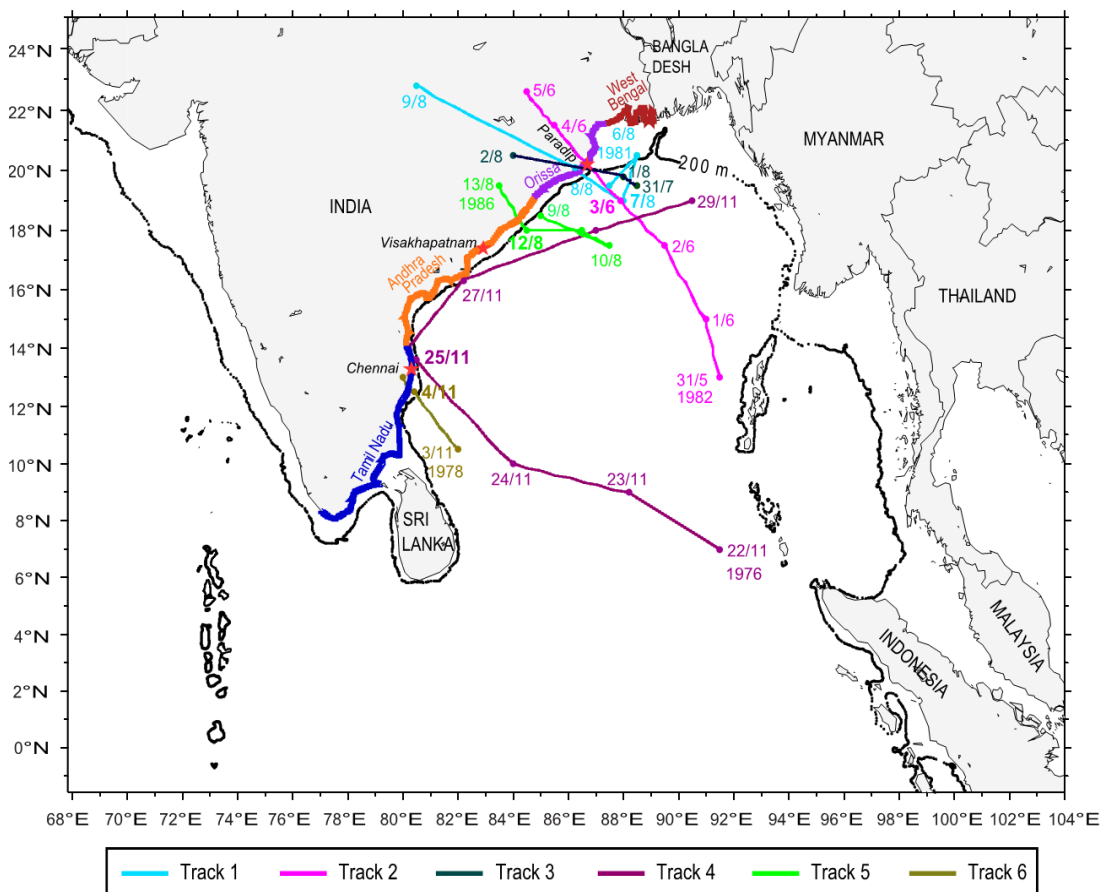


Section 4.2.2, for a period of 15 days starting from 4 days prior to the first day of cyclone formations for each event. In order to derive the meteorological forcing, the core pressure and the position of the cyclone core obtained for each of the 136 events were interpolated to every 3 hours and used in the cyclone model of Holland to derive the MSLP field and wind field (Equations (5.1) and (5.3), respectively) for each grid point and at every time step of the storm surge model. The storm surge model was run 4 days prior to the first day of cyclone formation for all the events to provide sufficient spin-up time. Therefore, the storm surge simulation provided the total sea level and the depth mean current due to combined effect of tide and meteorological forcing. In order to compute the storm surge component of total sea level, the storm surge model was run with tidal forcing alone for each event and the resulting tidal elevations were subtracted from the total sea level.

### **5.3 Validation of the storm surge model**

The model results were validated by comparing the simulated level defined at the grid closest to tide gauge location and the observed hourly tide gauge data at Paradip, Visakhapatnam and Chennai. But the spectral analysis of the time series of observed total sea level as well as the surge level showed annual peaks and some higher frequency peaks, therefore, a band pass filter was applied to them in order to carry out the validation. This filter removed the effect of annual variability as well as the high frequency winds and seiches that are not represented by the surge model. Though the simulation of storm surges were carried out for 136 LPS events that occurred in the past 27 years, the comparison is carried out for total sea level during some selected cyclonic events that crossed Paradip, Visakhapatnam, or Chennai, (tracks shown in Figure 5.7).

**Figure 5.7** The tracks of the selected cyclones that caused storm surges at Paradip, Visakhapatnam and Chennai. The storm surges produced due to these cyclonic events at the 3 coastal stations were compared against the available observed sea levels. The coastline of Indian states – Tamil Nadu, Andhra Pradesh, Orissa, and West Bengal are differentiated with different colours.



### 5.3.1 The surge at Paradip due to 7 August 1981 cyclone

A low pressure system was formed over north-western Bay of Bengal on 5 August 1981 and after meandering towards north for a day, it turned, and intensified into a cyclonic storm. Finally, the CS crossed the coast of Orissa at about 40 km north of Puri on the morning of 8 August (Track 1 in Figure 5.7), with a core pressure of approximately 982 hPa, from which the pressure drop and maximum wind speed was estimated to be 28 hPa and 40 knots using Equations (5.1) and (5.4), respectively. The storm surge simulation was carried out from 0000 UTC 1 August to 0000 UTC 9 August 1981. Initially, the model was driven only by tidal forcing until the meteorological forcing was introduced from 0000 UTC 5 August. The model simulation was carried out using tidal forcing alone for the same period so that the surge component could be derived. Figure 5.8a shows the simulated and the observed total sea level with respect to mean sea level at Paradip during the landfall. Figure 5.8a shows that the simulated peak total sea level of 2.5 m agrees well with the observed peak sea level of 2.35 m. The simulated surge at Paradip reached as high as 0.45 m, which is similar to the observed peak surge of 0.43 m.

### 5.3.2 The surge at Paradip due to 3 June 1982 cyclone

A depression that formed over the central Bay of Bengal on 1 June 1982 intensified into a CS and then into a SCS with its core pressure dropping to 980 hPa on 3 June. The storm crossed the coast of Orissa close to Paradip on 3 June (Track 2 in Figure 5.7). The pressure drop at the core of the cyclone and the maximum wind speed around the core was determined to be 30 hPa and 42 knots. The model was integrated from 0000 UTC 27 May to 0000 UTC 5 June 1982. The meteorological forcing was included in the model from 0000 UTC 31 May. The simulated and the observed total sea level are shown in Figure 5.8b. The simulated peak sea level (2.8 m) and the surge elevations (0.7 m) are in close agreement with those of observed peak levels (2.9 m and 0.8 m), respectively.

### 5.3.3 The surge at Paradip due to 1 August 1984 cyclone

A deep depression with core pressure 992 hPa developed on 1 August 1984 with its core at 19.8°N, 88°E from a low-pressure system in the northern bay and crossed the coast of Orissa between Puri and Paradip (approximately 25 km north of Paradip) on 1 August (Track 3 in Figure 5.7). The core pressure and thereby the pressure drop just before landfall was found to be 992 hPa and 18 hPa, respectively. The simulation of the surge event was carried out from 0000 UTC 27 July to 0000 UTC 2 August 1984 with meteorological forcing from 0000 UTC 31 July. Figure 5.8c shows a good agreement between the simulated and the observed sea level with peak values of 3.05m and 3.0 m respectively. Model simulation shows a peak surge of 0.33 m at Paradip, which is in close agreement with the observed surge of 0.4 m.

### 5.3.4 The surge at Visakhapatnam due to 25 November 1976 cyclone

A low pressure system which formed over the southern Bay of Bengal on 22 November 1976, moved northwest, steadily intensified into a DD that skirted the coast of Andhra Pradesh up to 27 November and then finally moved north-eastward to the coast of Arakan weakening into deep depression on 30 November morning (Track 4 in Figure 5.7). The DD had a core pressure of 996 hPa which corresponded to a pressure drop of 14 hPa. The storm surge simulation was started from rest on 0000 UTC 18 November 1976 with the tidal forcing alone and then from 0000 UTC 22 November, the model was driven by tidal forcing as well as the meteorological forcing. From Figure 5.8d, it can be seen that the simulated and the observed sea level matches well with each other with approximately same peak value of 1.6 m. The simulated maximum surge component (0.25 m) matches with the observed maximum surge component (0.22 m).



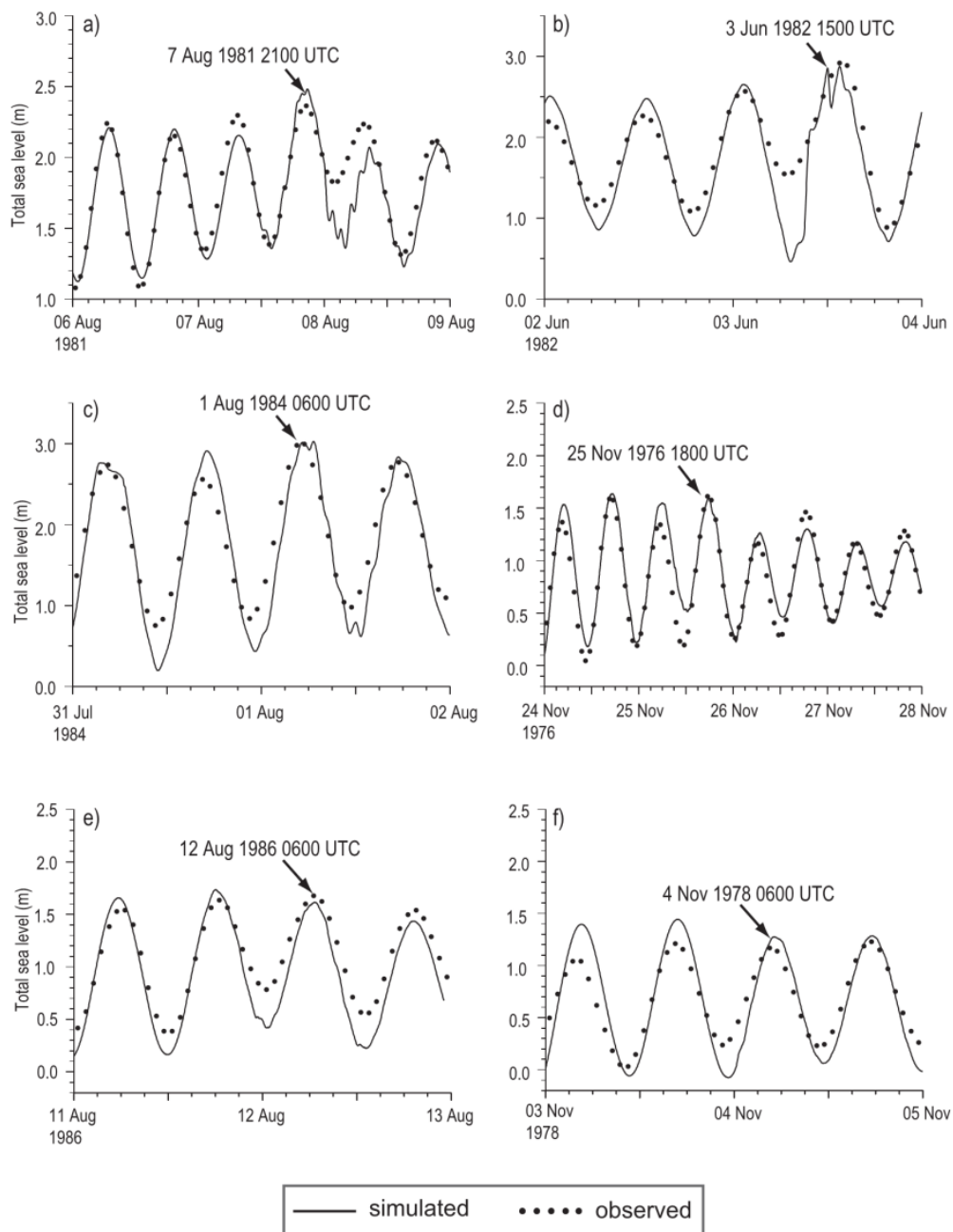
**5.3.5 The surge at Visakhapatnam due to 12 August 1986 cyclone**

A deep depression (core pressure less than 992 hPa) that developed from a low-pressure system over north-west Bay of Bengal crossed the coast of northern Andhra Pradesh near Kalingapatnam (approximately 10 km north of it) in the night of 12 August 1986 (Track 5 in Figure 5.7). The lowest pressure recorded was 985 hPa at Kalingapatnam. Initially, the tidal forcing drove the surge model from 0000 UTC 5 August to 0000 UTC 8 August and thereafter the meteorological forcing was also introduced. The simulated peak (1.65 m) and the observed peak (1.8 m) sea level match well (Figure 5.8e). The simulated maximum surge component is 0.1 m, which is less than the observed maximum surge component.

**5.3.6 The surge at Chennai due to 4 November 1978 cyclone**

A deep depression with a core pressure of 1002 hPa crossed the coast of Tamil Nadu, 50 km south of Chennai, around noon of 4 November 1978 near Cuddalore, weakened into a depression and entered into the Arabian Sea on 5 November (Track 6 in Figure 5.7). The pressure drop and the maximum winds were estimated to be 8 hPa and 20 knots, respectively. The model was allowed to spin up by forcing with tides alone for four days prior to 0000UTC November 3, after which meteorological forcing was introduced in the model. According to observations, Chennai was affected by a peak surge of 0.2 m and a maximum total sea level of 1.2 m (Figure 5.8f) whereas the model simulation shows a maximum surge component of 0.3 m and a peak total sea level of 1.3 m.

**Figure 5.8** The time series of total sea level simulated (continuous line) at Paradip due to a) 7 August 1981 cyclone, b) 3 June 1982 cyclone, and c) 1 August 1984 cyclone, at Visakhapatnam due to d) 25 November 1976 cyclone and e) 12 August 1986 cyclone and at Chennai due to f) 4 November 1978 cyclone compared with observed total sea level (dotted line). The tracks of these cyclones are shown in Figure 5.7. The arrow points to the time at which the peak surge occurred at the mentioned station.



The time series plot of observed and simulated elevations (Figure 5.8) shows the importance of the timing of the surge occurrence. Though the cyclone that hit Paradip on 3 June 1982 was more intense than that of 1 August 1984, leading to a higher surge elevation but the total sea level associated with the former event was much less as compared to that of the latter event. The reason is that the peak surge associated with landfall of 1 August cyclone occurred at the time of high tide at Paradip. Had the peak surge due to 3 June 1982 cyclone occurred 3-4 hours later, the resulting total sea level and damage would have been much higher. Thus it is very important for the forecasters to know the tidal condition of an area and the time of the occurrence of the peak surge during a cyclone event in order to issue a warning.

Figure 5.8 and the error statistics (Table 5.1) for the above events indicate that the model can reproduce the observations reasonably well. The model results could, thereby, be used for the analysis of extreme events in regions where long period observations do not exist.

**Table 5.1** Error statistics showing the comparison between the simulated and the observed surge component for stations shown in Figure 5.7.

Station name	LPS event	Standard deviation		Mean Error, ME (m)	RMSE (m)
		Observed surge (m)	Simulated surge (m)		
Paradip	08 Aug 1981	0.12	0.08	-0.001	0.08
	03 Jun 1982	0.17	0.07	0.001	0.15
	01 Aug 1984	0.15	0.06	0.001	0.12
Visakhapatnam	25 Nov 1976	0.04	0.04	0.02	0.06
	12 Aug 1986	0.15	0.05	0.02	0.12
Chennai	04 Nov 1978	0.06	0.07	0.04	0.05

## 5.4 Extreme sea level analysis

The risks associated with storm, as mentioned in Section 1.1.6 can be quantified by estimating the return periods of extreme events which are inversely related to

the exceedance probability of an event. In the present work, we have used the  $r$ -largest annual maxima method introduced by Smith [1986] and described by Tawn [1988] which is an extension of the widely used classical annual maximum method of Gumbel [1958]. This method has been chosen as it allows us to use more than one value of extreme sea level for each year, thereby allowing more reliable estimates of return periods with less number of years of data. For the  $r$ -largest annual maxima method, we used the software prepared in the Proudman Oceanographic Laboratory, UK [D. Blackman, personal communication], in which the annual maxima can be allowed to have any of the three Generalized Extreme Value (GEV) distributions. We used Gumbel distribution (GEV Type I) following Unnikrishnan et al. [2004]. They extracted the annual maxima for the period 1974-1988 from hourly tide gauge data at Paradip, Visakhapatnam and Chennai and showed that the plot of the annual maxima against a function  $(-\ln(-\ln P))$ , where  $P$  is the cumulative probability density function, produced a straight line suggesting that Gumbel distribution can be used for the analysis. The cumulative distribution function for Gumbel fit can be written as

$$G(x; \alpha, \beta) = \exp\{\exp[-(x - \alpha/\beta)]\} \quad (5.11)$$

where,  $\alpha$  and  $\beta$  are the location and the scale parameters, respectively. The ' $r$ -largest annual maxima' were selected following the criteria suggested by Tawn and Vassie [1989] that ' $r$ ' must be large enough to obtain a reasonable estimate of the parameters and that the values selected should fall in the tail of the distribution. The  $r$ -largest maxima approach has been used by Bernier and Thompson [2006]; Lowe et al. [2001]; Flather et al. [1998]; Tsimplis and Blackman [1997] for studying the changes in extreme sea levels due to regional climate change. Bernier et al. [2007] and Marcos et al. [2009] mapped the distribution of extreme sea levels in the Southern Europe and Northwest Atlantic, respectively by applying the  $r$ -largest maxima methodology on the available long tide gauge records as well as on the output of a 2D surge model at locations having poor data.

McInnes et al. [2009] estimated storm surge return levels along the south-eastern coastline of Australia by simulating individually the surge events

identified in the tide gauge records for the northern Bass Strait. They performed  $r$ -largest GEV analyses with  $r=2$ ,  $r=3$  and  $r=4$  on the simulated surge heights and selected 2-largest GEV fits to estimate the return levels as it gave smaller uncertainties.

#### **5.4.1 Return periods of extreme events along the east coast of India**

The statistical analysis was carried out on the annual maxima of pressure drop ( $\Delta P$ ), simulated total sea level and surge component. For each LPS event in the Bay of Bengal, the surge component maxima were obtained first and then the total sea level maxima were picked up by defining a window width of 48 h consisting of 24 h before and 24 h after the occurrence of peak surge in order to avoid the maxima that may be only due to spring tide. The annual maxima of total sea level and the surge component were then fitted to Gumbel distribution to obtain the scale and the location parameters and thereby the return period was estimated as the reciprocal of Gumbel cumulative distribution function.

The 5-year and 50-year return levels for the total sea level and surge levels were estimated using the annual maxima for the period 1974-2000 for different stations along the east coast of India, selected from the 114 stations shown in Figure 4.7. As seen from Figure 4.7 and Table 4.1, among the 43 stations located along the east coast of India, 5 are Standard Ports and 13 are Secondary Ports. Apart from these port stations, 8 other main stations were also found to be included in these 43 stations, which are tabulated (in italics) in Table 5.2. Therefore, the return levels were estimated for 26 major stations along the east coast of India using the  $r$ -largest maxima method. For most of the stations in the present study, it was found that considering ' $r$ ' greater than 3 led to inclusion of non-extreme values in the extreme value estimation. Therefore, statistical estimations were done for; one maximum per year ( $r=1$ ), two maxima per year ( $r=2$ ) and three maxima per year at each station. The sensitivity of the estimates to the value of ' $r$ ' used in the analysis is demonstrated in Table 5.2.

**Table 5.2** The 5-year and the 50-year simulated return levels at 26 stations along the east coast of India obtained by the analysis of the surge (difference between the total sea level and tidal elevation) maxima through the r-largest annual maxima method. The station numbers correspond to the stations shown in Figure 4.7 and tabulated in Table 4.1. The return levels at each station are given for different 'r' values, one maximum per year (r=1), two maxima per year (r=2), and 3 maxima per year (r=3). The estimated standard errors associated with the return levels are given in brackets. The shelf width (km) at each station grid point is also shown.

St no	Station Name	Shelf Width (km)	5 year return surge level			50 year return surge level		
			r=1	r=2	r=3	r=1	r=2	r=3
10	Nagapattinam	84	0.13 (0.024)	0.11 (0.01)	0.10 (0.012)	0.29 (0.05)	0.22 (0.031)	0.18 (0.023)
11	<i>Porto Nova</i>	20	0.10 (0.019)	0.09 (0.01)	0.08 (0.012)	0.22 (0.04)	0.19 (0.03)	0.17 (0.023)
12	Cuddalore	57	0.10 (0.018)	0.08 (0.01)	0.08 (0.011)	0.21 (0.038)	0.17 (0.025)	0.15 (0.02)
13	Pondicherry	71	0.13 (0.025)	0.11 (0.02)	0.10 (0.014)	0.30 (0.053)	0.24 (0.036)	0.21 (0.028)
<b>15</b>	<b>CHENNAI</b>	32	0.08 (0.013)	0.07 (0.01)	0.07 (0.01)	0.16 (0.027)	0.14 (0.02)	0.13 (0.016)
16	<i>Pulicat</i>	30	0.16 (0.028)	0.14 (0.02)	0.13 (0.016)	0.34 (0.058)	0.28 (0.04)	0.25 (0.031)
18	<i>Gudur</i>	40	0.25 (0.041)	0.21 (0.03)	0.19 (0.023)	0.52 (0.085)	0.41 (0.057)	0.36 (0.044)
19	<i>Nellore</i>	20	0.12 (0.021)	0.10 (0.01)	0.09 (0.012)	0.26 (0.046)	0.20 (0.03)	0.18 (0.023)
20	<i>Kavali</i>	40	0.27 (0.044)	0.21 (0.03)	0.19 (0.024)	0.56 (0.091)	0.42 (0.058)	0.36 (0.045)
22	Surya Lanka	37	0.55 (0.101)	0.46 (0.07)	0.43 (0.058)	1.20 (0.212)	0.96 (0.144)	0.84 (0.113)
24	<i>Machilipatnam</i>	100	0.38 (0.066)	0.32 (0.05)	0.30 (0.039)	0.81 (0.138)	0.66 (0.097)	0.57 (0.075)
26	Sacramento Shoal	30	0.13 (0.024)	0.11 (0.02)	0.11 (0.014)	0.28 (0.051)	0.23 (0.034)	0.20 (0.027)
<b>27</b>	<b>KAKINADA</b>	50	0.18 (0.026)	0.15 (0.02)	0.14 (0.015)	0.35 (0.053)	0.29 (0.037)	0.25 (0.028)
<b>29</b>	<b>VISAKHAPATNAM</b>	49	0.10 (0.014)	0.09 (0.01)	0.09 (0.010)	0.19 (0.03)	0.17 (0.023)	0.16 (0.02)
30	Bhimunipatnam	58	0.23 (0.038)	0.19 (0.03)	0.18 (0.024)	0.49 (0.08)	0.38 (0.054)	0.35 (0.045)
32	Kalingapatnam	44	0.20 (0.034)	0.17 (0.02)	0.16 (0.02)	0.42 (0.07)	0.34 (0.047)	0.30 (0.037)
33	Baruva	55	0.23 (0.037)	0.21 (0.03)	0.19 (0.023)	0.47 (0.07)	0.40 (0.055)	0.36 (0.044)

**Table 5.2** Continued

St no	Station Name	Shelf Width (km)	5 year return surge level			50 year return surge level		
			r=1	r=2	r=3	r=1	r=2	r=3
34	Gopalpur	83	0.26 (0.04)	0.22 (0.03)	0.21 (0.026)	0.53 (0.085)	0.44 (0.058)	0.39 (0.048)
35	Chilka Mouth	92	0.34 (0.05)	0.29 (0.04)	0.26 (0.032)	0.67 (0.103)	0.55 (0.071)	0.50 (0.059)
36	<i>Puri</i>	85	0.39 (0.053)	0.37 (0.04)	0.34 (0.04)	0.76 (0.114)	0.70 (0.089)	0.63 (0.075)
37	Devi River Entrance	34	0.27 (0.043)	0.24 (0.03)	0.22 (0.026)	0.56 (0.09)	0.46 (0.059)	0.42 (0.05)
<b>38</b>	<b>PARADIP</b>	41	0.47 (0.075)	0.41 (0.05)	0.40 (0.046)	0.97 (0.15)	0.78 (0.09)	0.73 (0.086)
39	False Point	65	0.95 (0.014)	0.88 (0.01)	0.83 (0.009)	1.87 (0.28)	1.64 (0.202)	1.52 (0.017)
<b>40</b>	<b>SHORTT ISLAND</b>	104	0.73 (0.010)	0.73 (0.08)	0.68 (0.073)	1.40 (0.20)	1.36 (0.162)	1.24 (0.134)
41	<i>Chandipur</i>	160	1.57 (0.023)	1.49 (0.19)	1.39 (0.016)	3.10 (0.415)	2.83 (0.36)	2.58 (0.298)
<b>43</b>	<b>SAGAR ROADS</b>	195	1.39 (0.187)	1.35 (0.16)	1.35 (0.146)	2.60 (0.368)	2.59 (0.31)	2.46 (0.268)

Though the estimated 5-year and 50-year return simulated surge level showed a decrease of 18% and 25%, respectively with the increase of the number of maxima taken per year, the standard errors associated with them reduced considerably (37% and 43%), respectively, a result of increasing sample size of extreme values and thereby, justifying the use of  $r=3$ . Therefore, it was decided to include at least 3 maxima ( $r=3$ ) per year to estimate the return levels.

The statistical analysis was done on the pressure drop of annual extreme events, to get the return periods of the  $\Delta p$  for the Bay of Bengal (Table 5.3). The 5-year return estimate for pressure drop is found to be 43 hPa, suggesting the occurrence of cyclonic storms, but the 50-year and 100-year return estimate for pressure drop is 61 hPa and 72 hPa which can cause severe cyclonic storms.

The spatial variation of return levels of total sea level along the east coast of India (Figures 5.10a and 5.11a) generally increases towards the head bay, the

lowest being at Nagapattinam and the highest being at Sagar Island, which is similar to the increasing tidal range.

**Table 5.3** The return periods of pressure drop ( $\Delta p$ ) for the cyclones in the Bay of Bengal region. The  $\Delta p$ , used in the estimate of return period, is given as the difference between the core pressure of each cyclone at the time of crossing the coast and the ambient pressure (1010 hPa).

Return Period (years)	$\Delta P$ (hPa)
2	30.5
5	42.7
10	50.8
20	58.6
25	61.1
50	68.7
100	76.2

However, the return levels of surge component (Figures 5.10b and 5.11b) show a different pattern. Along the coast of Orissa, the 50-year return levels are smaller in the southern part than those in the northern part with the highest value of 2.6 m at Chandipur. Chittibabu et al. [2004] obtained a similar trend for the 50-year return levels of storm surge maxima along the coast of Orissa and attributed it to the near-shore topography and orientation of coastline of the region. The variations of the return levels of total water levels at different stations along the east coast of India (Figure 5.11b) are found to be consistent with the nomogram developed by Jain et al. [2010]. However the relatively higher estimates obtained by Jain et al. [2010] as compared to the present study could be probably due to the inclusion of wave setup and the linear addition of tidal amplitudes to the maximum surge levels.

The analysis of Figures 5.10b and 5.11b with respect to Figure 5.9 highlights that shallow and wide continental shelves result in larger surges than

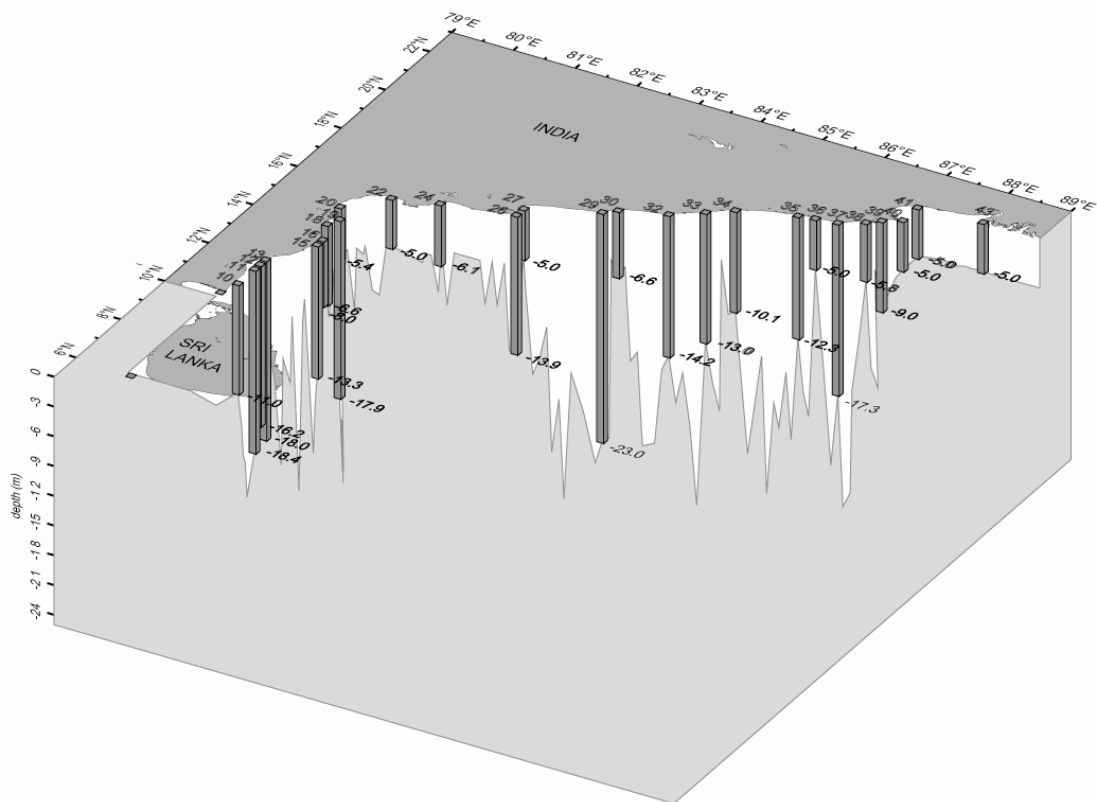


deep and narrow shelves. The stations along the coast of Tamil Nadu show lower 5-year and 50-year return levels of surge component than other stations due to its narrow shelf and deeper bathymetry. Along the coast of Andhra Pradesh, Machilipatnam, Surya Lanka, Kavali and Gudur are found to be sensitive regions as they show considerably high return levels of surge component due to their shallow bathymetry. The 50-year surge level (0.8 m) at Surya Lanka is found to be highest along the coast of Andhra Pradesh, which can be attributed to the geometrical configuration of the coastline forming a cove shaped bay at this area. Though Machilipatnam is deeper (6.1 m) than Surya Lanka (5.0 m) (Figure 5.9), the 5-year and 50-year return levels (0.6 m and 0.3 m, respectively) at this station are comparable to those at Surya Lanka and found to be higher than those at Kakinada (with similar depth of 6.0m) by 40 cm. The reason for this characteristic feature is assessed to be the wide shelf (approximately 100 km) as compared to that of Surya Lanka and Kakinada, where its approx 50 km (Table 5.2), which shows the effect of wide shelf on the height of surge component.

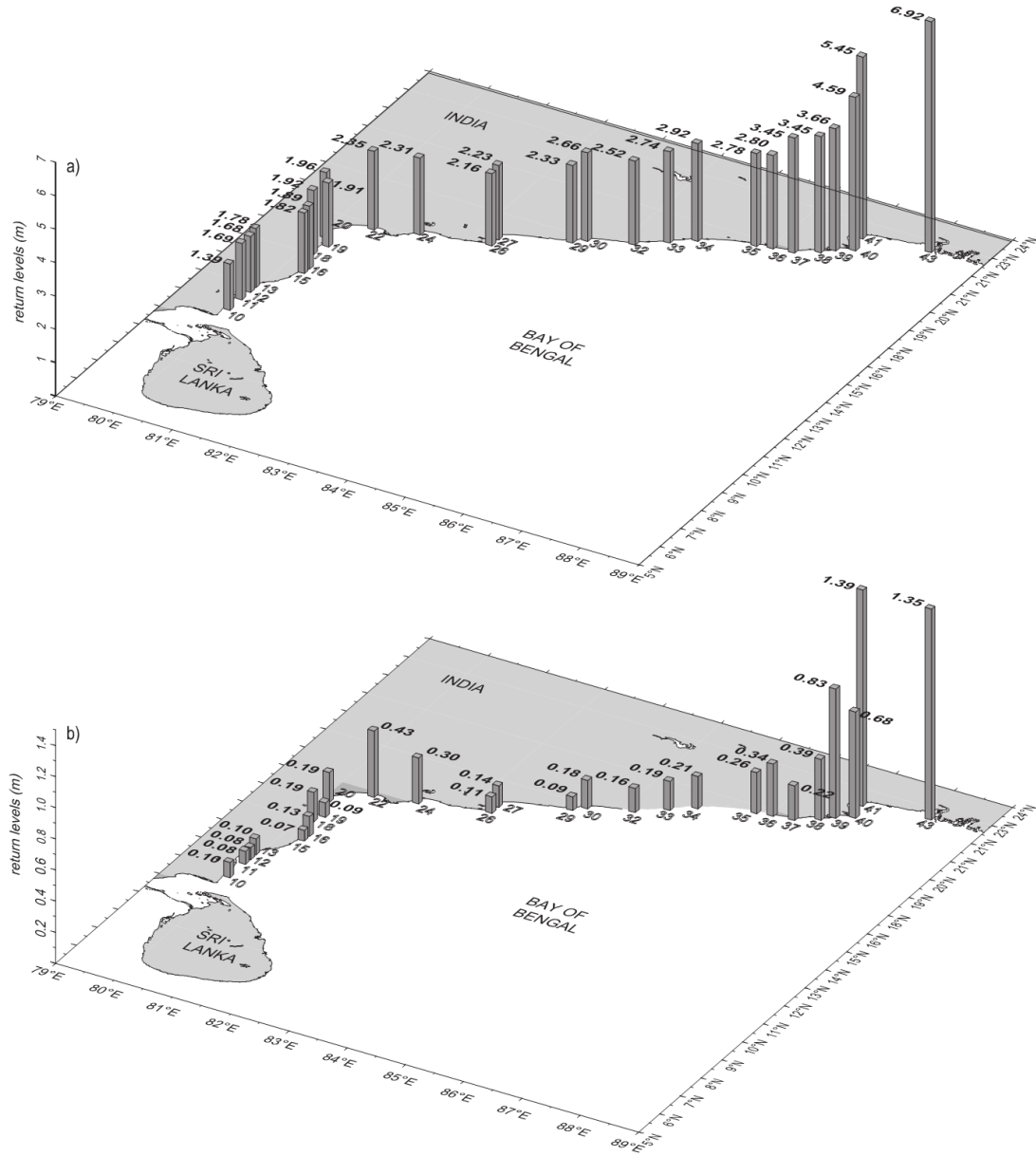
The effect of orientation of coastline on the height of surge component can be discerned at Surya Lanka where the return levels are substantially higher by almost 60 cm than that at Kakinada (shelf width = 50 km) in spite of its narrow shelf (about 37 km) and similar bathymetry. This effect was confirmed by analyzing the surge elevation produced at the two stations due to cyclones of similar intensities. For instance, a deep depression with core pressure of 1000 hPa crossed the coast of Surya Lanka on 16 October 1987 to produce a surge of 20 cm while similar system when crossed the coast of Kakinada on September 1991, produced a surge of 5 cm. The highest return levels for surges are obtained along the coast of Orissa, especially the northern coast because of its very wide shelf and shallow bathymetry. Chandipur is found to be highly prone to extreme events with highest 5-year and 50-year return levels of surges (1.4 m and 2.6 m, respectively) followed by Sagar Roads (1.3 m and 2.5 m, respectively) and False Point (0.8 m and 1.5 m, respectively). The total sea level at Chandipur is lower than that Sagar Roads but the return levels of surge component is the highest which could be due to the geometrical configuration coastline in the region. The

50-year return levels at Paradip and Puri (0.7 m and 0.6 m, respectively) are relatively high compared to the stations in the southern coast of Orissa as they are characterized by relatively shallower depths (Figure 5.9). Though the continental shelf at Chilka and Gopalpur (85 km) are as wide as the shelf at Puri, the return levels at these stations are lower by approximately 10 and 20 cm, respectively due to the deeper depths at these stations.

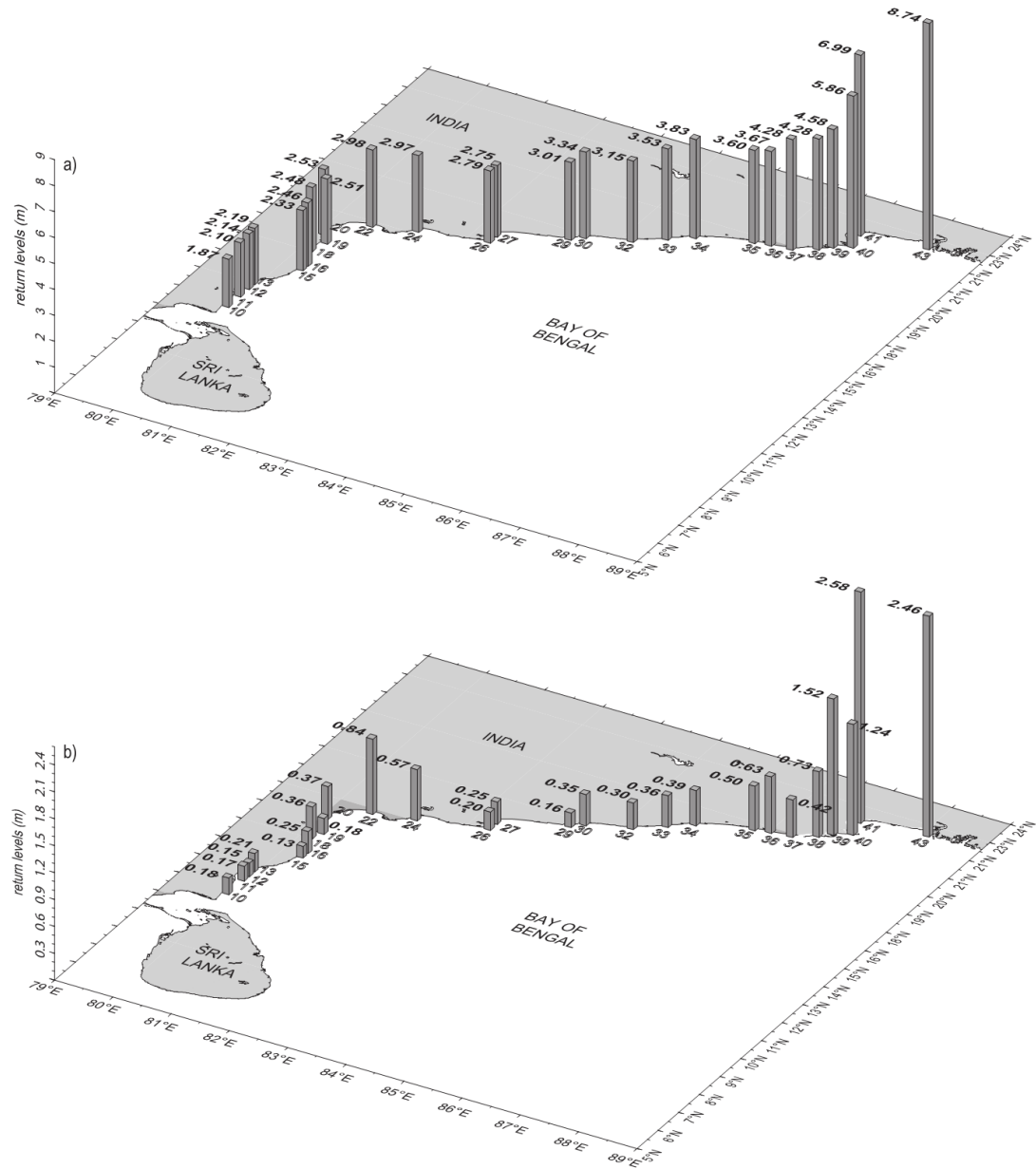
**Figure 5.9** A 3D view of the bathymetry along the east coast of India. The shaded portion represents the depth value at each grid nearest to a land point along the east coast of India. The column and the corresponding value show the depth values at 26 stations along the coast. The stations are marked as numbers that correspond to the numbers in Table 5.2.



**Figure 5.10** The 5-year return a) total sea level and, b) surge level for 26 stations along the east coast of India. The stations are marked as numbers that correspond to the numbers in Table 5.2.



**Figure 5.11** The 50-year return a) total sea level and, b) surge level for 26 stations along the east coast of India. The stations are marked as numbers that correspond to the numbers in Table 5.2.

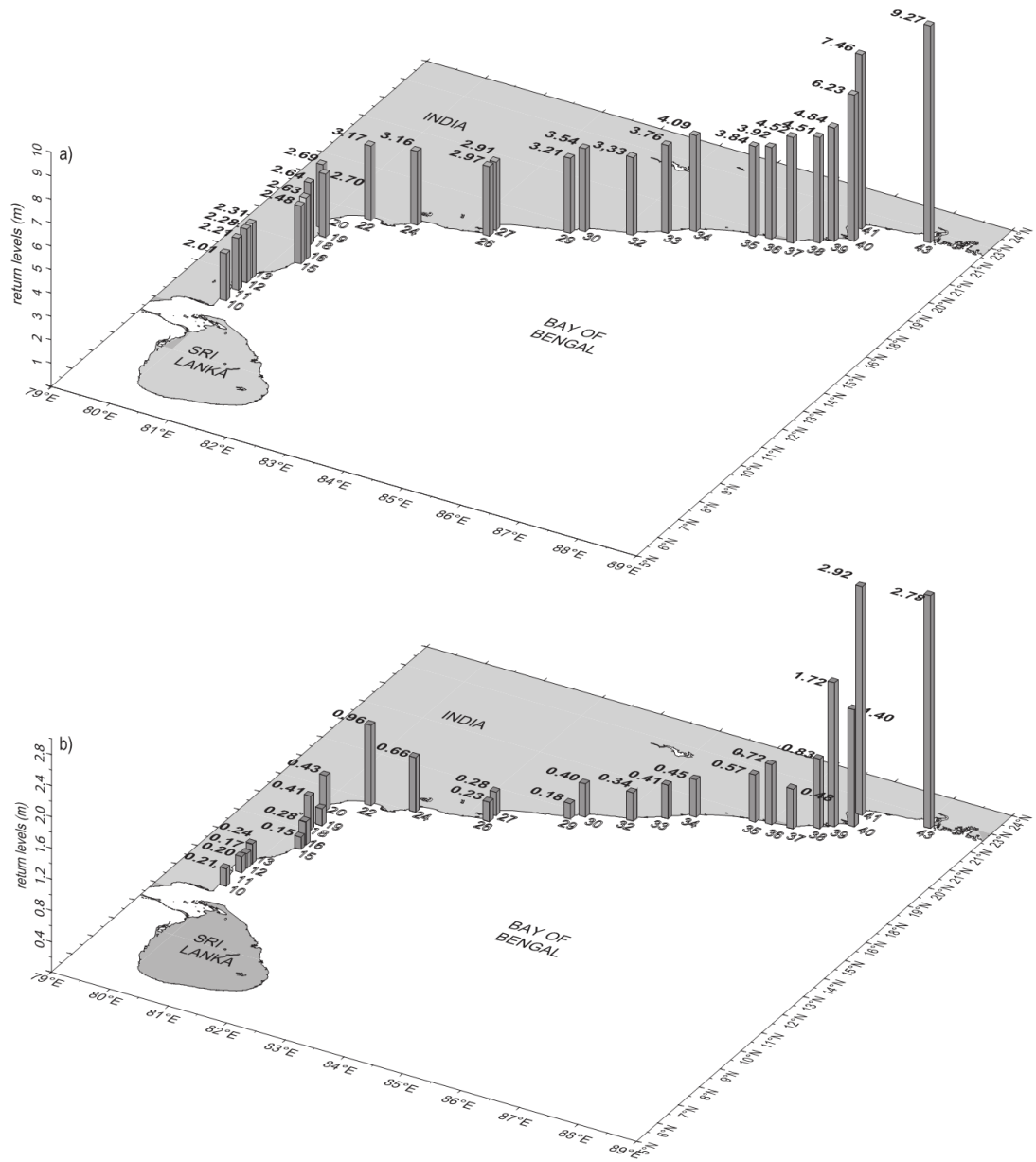


In addition to the 5-year and 50-year return levels, the information on 100-year return levels is also essential for practical purposes, such as design of coastal structures. Therefore, the 100-year return levels for total sea level and surge component, estimated for the 26 stations, are shown in Figure 5.12.

It is noted that the 100-year return level obtained at Chennai, Vishakhapatnam and Paradip are slightly higher than that obtained by Unnikrishnan et al. [2004]. This may be likely due to the fact that they had considered storm surges caused due to cyclones that occurred in a period of 15 years (1974-1988). But in the present study, we have taken into account the cyclones that occurred in the period of 27 years (1974-2000). During this additional period of 12 years, i.e. from 1988-2000, a total number of 64 LPS events occurred in the Bay of Bengal which included the major super cyclones such as the November 1989 SCS that hit Andhra coast and the SCS that hit coast of Orissa and West Bengal in June 1982, April 1991 and October 1999. The simulated storm surge elevations due to these events were also included in the estimation of 5, 50 and 100-year return levels, which are shown in the Figures 5.10, 5.11, and 5.12, respectively.

The 100-year total sea level along the east coast of India is evaluated, on an average, to be 6% higher than the 50-year return levels, with increase being maximum at Nellore where the 100-year return level is higher by 7%. The 100-year return level of surge component is estimated to be higher by 14% than the 50-year levels; the highest increase (15%) is found at Cudallore. The pattern in the distribution of 100-year return level along the east coast of India is similar to that of 5-year and 50-year return levels. The comparison of Figures 5.90 and 5.12b imply that the 100-year return levels of surge component are also affected by the geometrical configuration, shelf width and bathymetry. Along the coast of Andhra Pradesh, the highest 100-year surge level is approximately 1 m, observed at Surya Lanka while along the coast of Orissa, the 100-year surge levels reach as high as 3 m at Chandipur.

**Figure 5.12** The 100-year return a) total sea level and, b) surge level for 26 stations along the east coast of India. The stations are marked as numbers that correspond to the numbers in Table 5.2.



It is therefore shown that, along the east coast of India, the 5-year, 50-year and 100-year return levels of surge components are considerably higher at shallow and wide shelf regions such as Gudur, Kavali, Surya Lanka, Machilipatnam, False Point, Chandipur and Sagar Roads than at deep and narrow shelf regions. Hence accurate bathymetry is a key factor for obtaining accurate model simulation which forms the major advantage of the present work.

## **5.5 Conclusions**

A 2D vertically integrated numerical model was used to simulate storm surge events due to 136 low pressure systems that occurred during the past 27 years (1974-2000) in the Bay of Bengal. The pressure and position of the core at each day of the cyclone development were used in the cyclone model of Holland to derive the wind and pressure field for each of the 136 events. The storm surge model was forced simultaneously with meteorological forcing and tidal forcing, the latter being extracted from the output of global tidal model. The model was also run with tidal forcing alone in order to compute the surge component as the difference between the elevations obtained from the two simulations. A comparison of the simulated total sea level due to some selective events and the observed sea level, obtained from the tide gauges at Paradip, Visakhapatnam and Chennai, showed a good agreement. Moreover, the simulated peak surge components for the same events were also found to agree with the observed peak surge components. The error analysis of simulated surge component corroborated that the model was able to reproduce the observations well.

One of the reasons attributing to the good accuracy achieved by the model could be the use of improved bathymetry data in the simulation. The bathymetry for the model domain was derived from a newly constructed improved ETOPO5 bathymetry dataset which was thoroughly assessed and validated for its accuracy, as described in Chapter 3. The present study, thereby, has the advantage of using a much improved bathymetry dataset for the simulation of storm surges in the Bay of Bengal. In addition, the fine grid resolution of 9 km adopted in the model could also have attributed to the accuracy of the simulated results.

For each year, at least 3 largest events were taken from the simulated total sea level based on the identification of the peak surges. These annual maxima were analysed statistically using r-largest annual maxima method to provide the estimates of return periods of extreme events. Hence, the 5-year, 50-year and 100-year return levels of total sea level and surge component were estimated at 26 stations along the east coast of India.

The return levels (5, 50 and 100-year) of total sea level along the east coast of India show a considerable increase from south to north, with highest value at Sagar Island in West Bengal following the trend of tidal range along Indian coast. However, the return levels of surge components are found to vary spatially depending on the bathymetry, width of continental shelf and orientation of coastline of a region. This is the reason for substantially high return levels at Machilipatnam and Surya Lanka, even though the cyclones developed in the Bay of Bengal generally moves north or north-west, producing more extreme events in the northern part.

The simulation of extreme events of 27 years are considered to be long enough to provide reliable estimates of 5-year, 50-year and 100-year return levels of extreme events along the coast of India. This period includes some of the major super cyclones such as the November 1977 SCS, May 1979 SCS and November 1989 SCS that hit Andhra coast and the SCS that hit coast of Orissa and West Bengal in June 1982, April 1991 and October 1999. Therefore, the present study illustrates that storm surge simulation results can be used to derive the return estimates of extreme events at locations where long period observations of sea level do not exist. The estimated return levels provide useful information for design parameters of offshore and coastal structures.