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Numerical storm surge model for India and Pakistan

Indu Jain · P. Chittibabu · Neetu Agnihotri · S. K. Dube · P. C. Sinha · A. D. Rao

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Abstract The northeastern sector of the Arabian Sea, which covers the Gujarat coast of India and western coast of Pakistan, is a region vulnerable to extreme sea levels associated with tropical cyclones (TCs). Although the frequency of tropical cyclones in the Arabian Sea is not high, the coastal regions of India and Pakistan suffer in terms of loss of life and property caused by the surges. In view of this a location-specific fine resolution model is developed for the Gujarat coast of India and adjoining Pakistan coast. The east–west and north–south grid distance is about 3.0 km. Using this model, numerical experiments are carried out to simulate the surges generated by 1999 and 2001 cyclones which struck the Pakistan coast. The model computed surges are in agreement with the available observational estimates.

Keywords Numerical model · Storm surge · Tropical cyclone · Pakistan coast

I. Jain · N. Agnihotri · A. D. Rao
Center for Atmospheric Sciences, IIT Delhi,
New Delhi 110 016, India

P. Chittibabu (✉)
Baird & Associates, 1145 Hunt Club Road,
Suite 1, Ottawa, Canada K1V 0Y3
e-mail: cpadala@baird.com

S. K. Dube
Indian Institute of Technology, Kharagpur,
West Bengal 721302, India

P. C. Sinha
Institute of Oceanography,
University College of Science & Technology,
21031 Kuala Terengganu, Malaysia

1 Introduction

The most feared and deadly weather systems on Earth, tropical cyclones, are intense atmospheric vortices that develop over the warm tropical oceans. Severe tropical cyclones (TCs) produce destructive winds, high surges, torrential rains and severe floods, usually resulting in serious property damage and loss of life. The Arabian Sea is a potential genesis region for cyclonic storms. Cyclones in the Arabian Sea hit the west coast of India but sometimes they change their track and strike the coast of Pakistan. A geographical map of the study area is shown in Fig. 1. Very limited modelling efforts have been undertaken for location-specific storm surge simulation in the region to date (Dube et al. 1997; Chittibabu et al. 2000). Earlier, Dube et al. (1985) simulated the surge associated with 1975 Porbandar cyclone by using a vertically integrated model covering the entire west coast of India with a coarse grid resolution of about 33 km. In view of this a location specific fine resolution (3 km × 3 km) model is developed for the coastal regions of Pakistan and Gujarat in India.The analysis area of the model extends from 19.18° N to 25.5° N and 64° E to 73° E. There are two open boundaries located at 19.18° N and 64° E. At the open boundaries a radiation boundary condition is used. The bathymetry for the model is derived from the Earth-Topography-Two-Minute module (ETOPO2) from the National Geophysical Data Center database (Smith and Sandwell 1997).

2 Basic equations

In the formulation of the model a system of rectangular Cartesian co-ordinates are used. The origin, O, is within the equilibrium level of the free surface, Ox points towards the west, Oy towards the south and Oz is directed vertically upwards.

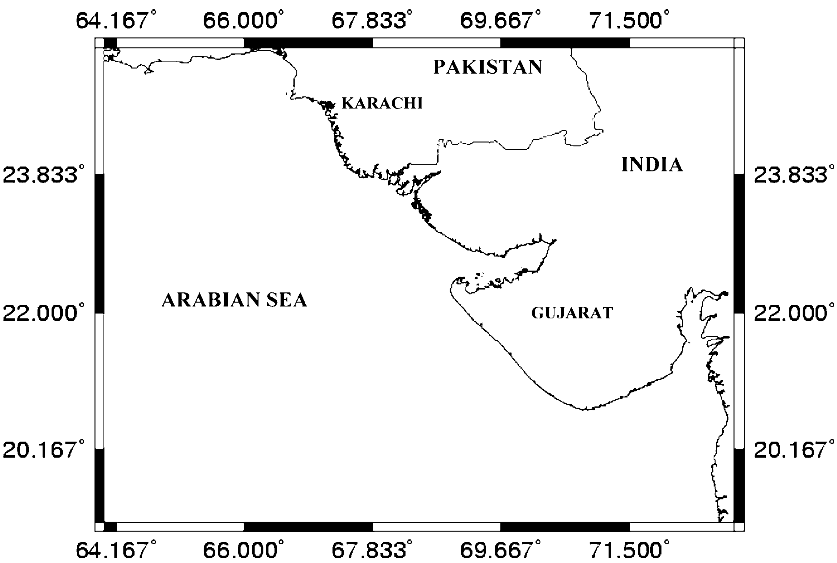

Fig. 1 Map of the analysis area

The displaced position of the free surface is given by $z = \zeta(x, y, t)$ and the position of the sea floor by $z = -h(x, y)$.

The depth averaged equations of continuity and momentum for the dynamical processes in the sea are given in the flux form by Dube et al. (1985) and Chittibabu et al. (2000)

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} = 0 \tag{1}$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial}{\partial x}(u\tilde{u}) + \frac{\partial}{\partial y}(v\tilde{u}) - f\tilde{v} = -g(\zeta + h)\frac{\partial \zeta}{\partial x} + \frac{F_s}{\rho} - \frac{c_f\,\tilde{u}}{(\zeta + h)}(u^2 + v^2)^{\frac{1}{2}} \tag{2}$$

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial}{\partial x}(u\tilde{v}) + \frac{\partial}{\partial y}(v\tilde{v}) + f\tilde{u} = -g(\zeta + h)\frac{\partial \zeta}{\partial y} + \frac{G_s}{\rho} - \frac{c_f\,\tilde{v}}{(\zeta + h)}(u^2 + v^2)^{\frac{1}{2}} \tag{3}$$

where

$$(\tilde{u}, \tilde{v}) = (\zeta + h)(u, v)$$

u, v: averaged component of velocity (m s^{-1}) in the direction of x, y respectively,
ζ: sea surface elevation (m) above the mean water level,
h: water depth (m),
t: time (s),
ρ: density of the sea water,
f: Coriolis parameter ($=2\omega\sin\phi$),
g: acceleration due to gravity,
F_S, G_S: x and y components of the surface wind stress,
c_f: Bottom friction coefficient ($=2.6 \times 10^{-3}$)

The surface stresses are parameterized using a conventional quadratic law (Johns et al. 1985)

$$(F_S, G_S) = c_d \rho_a (u_a^2 + v_a^2)^{\frac{1}{2}} (u_a, v_a)$$

where $c_d = 2.8 \times 10^{-3}$ is the surface drag coefficient, ρ_a is the density of the air and u_a, v_a are the x and y components of the surface wind.

3 Boundary conditions

The boundary and initial conditions take the form (Dube et al. 1985)

$$\begin{aligned} \tilde{u} &= 0 \quad \text{at the meridional boundaries} \\ \tilde{v} &= 0 \quad \text{along the latitudinal boundaries} \end{aligned} \tag{4}$$

and

$$\zeta = u = v = 0 \text{ for } t \leq 0$$

At the open sea boundaries a radiation boundary condition (Heaps 1973) is applied which leads to

$$v - \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = 0 \quad \text{at } y = L \text{ (southern open sea boundary)} \tag{5}$$

$$u - \left(\frac{g}{h}\right)^{\frac{1}{2}} \zeta = 0 \quad \text{at (on the western open sea boundary)} \tag{6}$$

Application of a radiation condition, as mentioned above, at the open sea boundary of a model allows the propagation of energy (disturbances) only outwards from the interior in the form of a simple progressive wave. It also helps to eliminate the transient response more quickly, as a result of the frictional dissipation in the system. Concerning its effectiveness Flather (1976) notes that the application of such a radiation condition in the numerical model may remove the unrealistically large currents and grid-scale oscillations in the vicinity of the open boundary, which may possibly be produced by the application of conventional open-sea boundary conditions.

4 Numerical experimentation

The model has been used to compute the surge associated with the 1999 and 2001 cyclones hitting the Pakistan coast. The storm surge model requires the wind stress forcing as the basic input to the model. For this purpose the wind stress is computed by using a dynamic storm model of Jelesnianski and Taylor (1973). To obtain a dynamic wind profile in the storm model, initially a stationary symmetric model wind profile is taken, and then correction is applied to approximate the asymmetry due to the storm motion. The storm model represents a balance between pressure gradient, centrifugal, Coriolis and surface frictional forces for a stationary storm.

A conditionally stable semi-explicit finite difference scheme with a staggered grid is used to solve the governing equations. With a fine resolution grid specification of 3 km × 3 km it is found that computational stability is achieved with a time step of 90 s.

5 Results and discussion

5.1 1999 Pakistan cyclone

A depression (17–27 knots) developed over the eastern Arabian Sea on 15th May 1999 at 0000 UTC near 12° N, 72.5° E and continued until 1800 UTC of the same day. It intensified into a deep depression (28–33 knots) by 16th May at 0000 UTC and further intensified into a cyclonic storm (34–37 knots) by 1200 UTC. The system gained further strength to become a severe cyclonic storm (48–63 knots) by 17th May at 0600 UTC. The system continued to gain strength and attained a maximum wind speed of 57 m s^{-1} on 19th May at 0000 UTC, which it maintained through to the early hours of 20th May. The cyclone made landfall at 0600 UTC on 20th May near Wari creek at about 23.6° N and 68.2° E.

In this experiment, the cyclone track (Fig. 2) and the relevant data are taken from Unisys Weather Information Services (1999). Using these data numerical

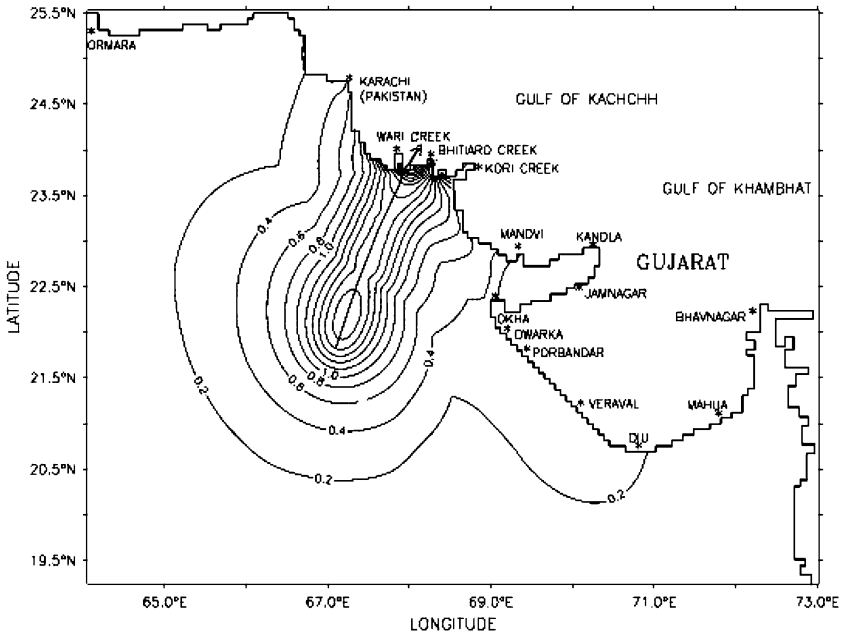

Fig. 2 Surge contours (m) associated with 1999 Pakistan cyclone

experiments are carried out with a pressure drop (the difference between the central and ambient pressures) of 40 hPa and radius of maximum winds of 30 km. The surge contours computed by the model at the time of landfall are shown in Fig. 2. It may be seen that a maximum surge of 3.8 m is predicted near the Bhitiaro creek and the surges at Wari creek and southern Kori creek are 3.4 m and 2 m, respectively. The surge of about 0.5 m can be seen near southern part of Karachi. Unisys Weather Information Services estimates the intensity of tropical cyclones and the associated range of surge heights based on the post-analysis of all available satellite images, surface data, upper air data and radar data. It is found that the maximum computed surge height of 3.8 m is comparable with the highest value in the range of surge estimates provided by Unisys (1999).

5.2 2001 Pakistan cyclone

A depression formed over the Arabian Sea on 21st May 2001 at 0600 UTC near 13.7° N and 68.1° E. The system intensified into a deep depression followed by a cyclonic storm on the same day at 1800 UTC. On the morning of 22nd May it intensified into a severe cyclonic storm with central winds topping 31 m s^{-1}. The system intensified further by 1200 UTC on 22nd May and continued until the early morning of 26th May with maximum winds of 55 m s^{-1}. Thereafter, the system started weakening and crossed the coast in the morning of 29th May.

The track of the cyclone (Fig. 3) and the relevant data are taken from the Unisys Weather Information Services (2001). Numerical experiments are carried out with a

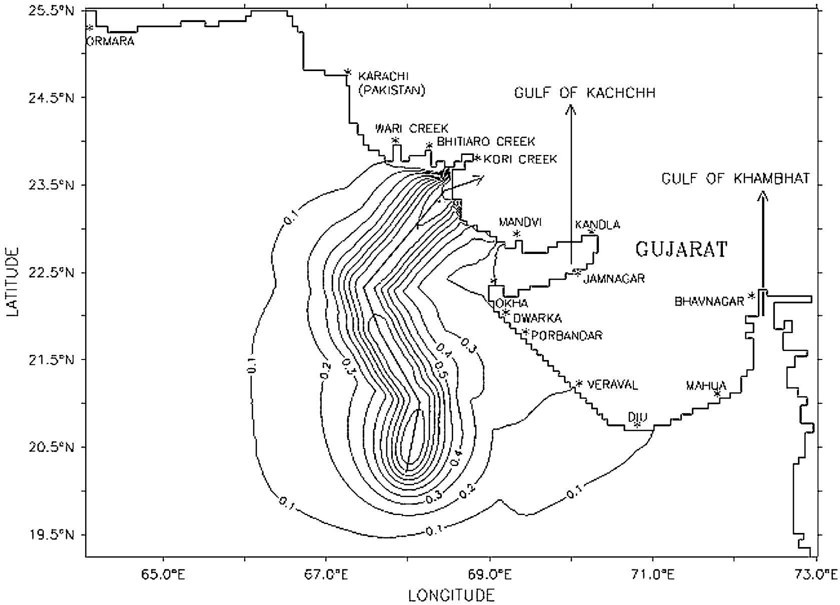

Fig. 3 Surge contours (m) associated with 2001 Pakistan cyclone

pressure drop of 22 hPa and a radius of maximum wind of 20 km. The model is integrated ahead in time for 48 h.

Figure 3 shows the model computed surge contours. It may be seen that a maximum surge of 1.0 m occurred close to the landfall point and south of Kori creek. Near Bhitiaro creek the surge was found to be less than 40 cm. The maximum computed surge height of 1 m is comparable to the estimated surge value provided by Unisys (2001). A comparison between the computed and estimated range of surge heights at the time of landfall for both the 1999 and 2001 Pakistan cyclones is given in Table 1.

6 Conclusions

Numerical experiments were carried out with a location specific high-resolution model using the data of 1999 and 2001 cyclones hitting the Pakistan coast. The model is able to simulate surge heights which are in broad agreement with the estimated values provided by Unisys. The present study further emphasizes the need for a

Table 1 Estimated range of peak surge has been taken from Unisys Weather Information Services

Name of the cyclone	Pressure drop (hPa)	Computed peak surge height (m)	Estimated range of surge height (m)
1999 Pakistan cyclone	40	3.8	2.7–3.7
2001 Pakistan cyclone	22	1.0	<1.0

location specific fine resolution model for different regions along the Indian coast as well as coastal regions of Pakistan, to be used for prediction on a real time basis.

In the present study, the cyclonic storm is the sole driving force for the dynamical processes in the sea. However, the tides have not been included in the present study. Therefore, the non-linear interaction of surge and the tide has not been studied. Such an interaction may be significant if the occurrence of the surge coincides with that of the high tide. The model may be used on a real time basis for predicting surges generated by a severe cyclonic storm which may strike the coast.

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