Numerical Simulation of Storm Surges Associated with Severe Cyclones Land Falling Pakistan Coast during 1999-2010

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Abstract

A tropical cyclone is one of the most powerful and destructive weather phenomena that cause heavy loss of human lives and property around the world. The impact of tropical cyclones has been proving to be three-pronged – the torrential rain, strong ravaging winds & storm surges with storm surge being the cause of highest death toll out of these three. Pakistan coastal area is quite vulnerable to cyclones and storm surges. In this study the simulations of storm surges, generated by the severe tropical cyclones which developed in the Arabian Sea and crossed Pakistan coast during the last 11 years (1999-2010), have been carried out by using the Indian Institute of Technology, Delhi storm surge model (IIT-D Model).

Key words: Storm surges, Tropical cyclones, Arabian Sea, IIT-D model.

Introduction

Tropical Cyclones (TC) like floods, droughts and tornados are one of the most destructive weather phenomena, which cause innumerable damages to human lives & infrastructure across the entire globe every year. The Pacific, Atlantic & the Indian Oceans are the major areas which experience the formation and impact of tropical & extra-tropical cyclones every year. Amongst the three major world oceans the Pacific is the one where the higher frequency of TC formation (averaging 20 per year) is observed, (Lutgens and Tarbuck, 2010). Whereas in the North Indian Ocean region only 6-7% of the worlds' total TC production takes place with Bay of Bengal being 3 times more prone compared with the Arabian Sea with one TC per year reaching the hurricane intensity in the North Indian Ocean, (Gupta, 2006). There are two major TC seasons pre-monsoon (April-June) and post-monsoon (October-November) as far as the Bay of Bengal and the Arabian Sea are concerned, (ibid). Tropical cyclones affect/impact the coastal regions in three ways i.e. very strong/ gale force winds, torrential rain and storm surges.

Pakistan coastal area stretching over about 1000 Km east/southeast – westwards (Figure 1) remains under tropical cyclone threat during May-June (pre-monsoon) and October-November (post-monsoon) with May being the host of highest TC formation in the Arabian Sea (SMRC, 1998). The available data reveals that Pakistan's coastal area has been affected by the TCs in the years 1895, 1902, 1907, 1948, 1964, 1985, 1999, 2001, 2007 and 2010 (source: PMD and SMRC, 1998). The TCs, having impacted Pakistan's coast, were investigated earlier by many for their formation, movement, landfall and damages inflicted with no real attempt having ever been made for calculating/ simulating the storm surges generated by TCs.

A storm surge, generated principally by strong winds and low pressure, is an abnormal rise of sea level along shore as a cyclone approaches and crosses it, (Lutgens and Tarbuck, 2010). Storm surges account for a high proportion (about 90%) of the deaths associated with tropical cyclones around the world, (ibid). In 1970, a severe tropical cyclone struck the coast of Bangladesh (the then East Pakistan) killing over 300,000 people primarily due to the storm surge that flooded low-lying islands in the Ganges Delta (Islam, 2006, Hossain et al., 2008). TC Sidr (2007) again struck Bangladesh triggering 6m high waves and killed more than 2000 people. Sidr was accompanied with 260 km/h ravaging winds and storm tide as high as 7m that swept about 20 km inland.

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Figure 1: Pakistan Coastal Area (courtesy: Googleearth.com)

The impact can be worse if the storm surge arrives following a high tide. A 'storm tide' is the combined effect of the two "a storm surge and "normal (astronomical) tide". In such a case the storm tide can reach areas that might otherwise considered safe. The sea water flooding may inundate along the coast for over 100 kilometres, with water pushing several tens of kilometres inland if the coast is low lying. The combined effects of the storm tide and wind waves have potential to bring buildings down, wash away roads and run ships over the coastal land.

During past 11 years (1999 – 2010) the Pakistan coast has been battered by the four severe cyclones TC 02A (1999), TC 01A (2001), TC Yemyin (2007) and TC Phet (2010). TC 02A caused about $6 million worth damages with about 700 people went missing (source: PMD and JTWC, actr-99), TC Yemyin inflicted $560 million worth damages with about 950 casualties and TC Phet resulted in 44 people's death with $780 million worth damages across Oman, Pakistan and some parts of India. These events have been studied by doing a post-event analysis/investigation in systems' development, intensification, movement and land falling with only limited attempts in determining the surge prior to a cyclone landfall (Dube et. al, 1994, 1997, 2009; Jain et. al, 2007). This is the scenario which prompts to simulate the "would-be surge" generated by a cyclone because to know the maximum surge height prior to cyclone hitting a particular coastal location is of crucial importance for forewarning the public of the potential risk as the surge of few meters can push the huge amount of water inland especially in low lying deltaic areas and result in coastal inundation and flash floods.

In the present paper IIT-D Storm Surge Model has been used for simulation of storm surges associated with the four severe cyclones which hit Pakistan coast during past 11 years. The model has been tested and being implemented to simulate/ forecast the storm surge with predicted cyclone path in all the regional countries, India, Bangladesh, Thailand, Myanmar and Sri Lanka. The Model-simulated surge results have been validated with the post-storm survey and IMD abridged report 1999 (Dube et al., 1985, 1997 and 2004) for India coast, for Bangladesh coast (Chittibabu. P., 1999) and for Myanmar coast (Sinha et al., 2005) and were found reasonably in agreement with the available data. For Pakistan no such surge data is available but statements of local people from the affected areas and aforementioned results from other regional countries suggest that the model can confidently be applied to simulate and predict the storm surge associated with approaching storm which can contribute a lot in issuance of early warning and mitigating the potential loss to human lives and property.

Data and Methodology

Data of the four significant cyclones (TC 02A, 1999; TC 01A, 2001; TC Yemyin, 2007 and TC Phet, 2010) which have affected the Pakistan coast has been downloaded from the UNISYS website (http://www.weather.unisys.com/hurricane/n_indian/index.html) and verified with data available with the PMD and the cyclone data archives maintained by the Regional Specialized Meteorological Centre (RSMC), Delhi, India. The verification revealed that all five data parameters (Tables 1-4) used in the model as input files of the four cyclones understudy were by and large same from the three sources.

The input data required to run the IIT-D model consists of the track of cyclone, duration, pressure drop and radius of maximum sustained winds. This data is used to compute the wind stress forcing using the dynamic storm model developed by Jelesnianski and Taylor (1973). This data is used as input in the IIT-D storm surge model to compute the surge. The IIT-D Storm Surge Model is a stair step model for the Pakistan coast and Gujarat coast, India covering the analysis region from 19.24 °N to 25.52 °N and 64.05 °E to 73.0167 °E and with grid resolution of 3.7x3.7 km. The bathymetry for the model is derived from the Earth-Topography-Two-Minute module (ETOPO2) from the National Geophysical Data Center database and is interpolated at the model grid points by using cubic spline interpolation scheme. The details of formulation of the IIT-D Model and its numerical solution scheme are given in Dube et al., (1985). The model is run for different scenarios (with varying bathymetry i.e. shallow and deep water depths, storm landfall angles from north/south, wind stress forcing, changing storm central pressure, varying radius of maximum winds and storm duration over water) and the results were found in agreement with the Unisys Weather Information Services. The results of the storm surge simulations generated by the aforementioned cyclones are given in the next section (Figures 2b-5b).

Table 1: Location (Lat and Long), observation time, pressure drop and radius of maximum winds of TC 02A

S. No	Latitude (N)	Longitude (E)	Time (hr)	Pressure drop, DP (mb)	Radius (R_{max}) of maximum winds
1	19.6	67.2	0.0	52.0	30.0
2	20.4	67.1	6.0	58.0	30.0
3	21.1	67.1	6.0	58.0	30.0
4	21.8	67.3	6.0	58.0	30.0
5	22.5	67.6	6.0	58.0	30.0
6	23.1	67.9	6.0	58.0	30.0
7	23.6	68.2	6.0	58.0	30.0
8	24.0	68.3	6.0	57.0	30.0
9	24.4	68.7	6.0	57.0	30.0
10	24.7	69.1	6.0	37.0	30.0

Table 2: Location, observation time, pressure drop and radius of maximum winds of TC 01A

S. No	Latitude (N)	Longitude (E)	Time (hr)	Pressure drop DP (mb)	Radius (R_{max}) of maximum winds
1	19.0	67.6	0.0	19.0	30.0
2	19.5	67.7	6.0	16.0	30.0
3	19.9	67.7	6.0	16.0	30.0
4	20.2	68.2	6.0	10.0	30.0

5	21.0	68.4	6.0	10.0	30.0
6	21.8	67.9	6.0	13.0	30.0
7	22.3	67.7	6.0	08.0	30.0
8	22.8	68.2	6.0	06.0	30.0
9	23.4	68.8	6.0	13.0	30.0

Table 3: Location, observation time, pressure drop and radius of maximum winds of TC Yemyin

S. No	Latitude (N)	Longitude (E)	Time (hr)	Pressure drop, DP (mb)	Radius (R_{max}) of maximum winds
1	22.9	67.3	0.0	12.0	30.0
2	23.5	66.4	6.0	12.0	30.0
3	24.2	66.3	6.0	14.0	30.0
4	25.1	65.2	6.0	17.0	30.0
5	25.7	64.2	6.0	12.0	30.0

Table 4: Location, observation time, pressure drop and radius of maximum winds of TC Phet

S. No	Latitude (N)	Longitude (E)	Time (hr)	Pressure drop DP (mb)	Radius (R_{max}) of maximum winds
1	22.9	64.1	0.0	17.0	30.0
2	23.5	65.6	6.0	15.0	30.0
3	24.6	67.3	6.0	13.0	30.0
4	25.9	70.5	6.0	10.0	30.0

Results

Tropical Cyclone 02A (16-20 May 1999)

Tropical cyclone TC 02A developed at around latitude 12 °N and longitude 72 °E on May 16, 1999 in the east central Arabian Sea, moved northwestwards up to 18 °N then northwards up to 21 °N and finally it took the northeastwards course and crossed the Pakistan coast near Lat 24 °N and Long 68 °E on May 20, 1999 – Figure 2a, (source: www.weather.unisys.com and PMD, TCWC). TC 02A was the most intense and severe cyclone in the history of the Arabian Sea (until 2007) with maximum winds of 105 Kts. The input file of TC 02A (Table-1, data and methods section) was used in the model to simulate the surge generated by TC 02A, which gave the maximum surge of 3.4m (Figure 2b). On comparison with Unisys Weather Information Services' tropical cyclones intensity and associated range of surge heights it is found that the maximum computed surge height of 3.4m is close enough to the highest value in the range of surge estimates provided by Unisys (1999).

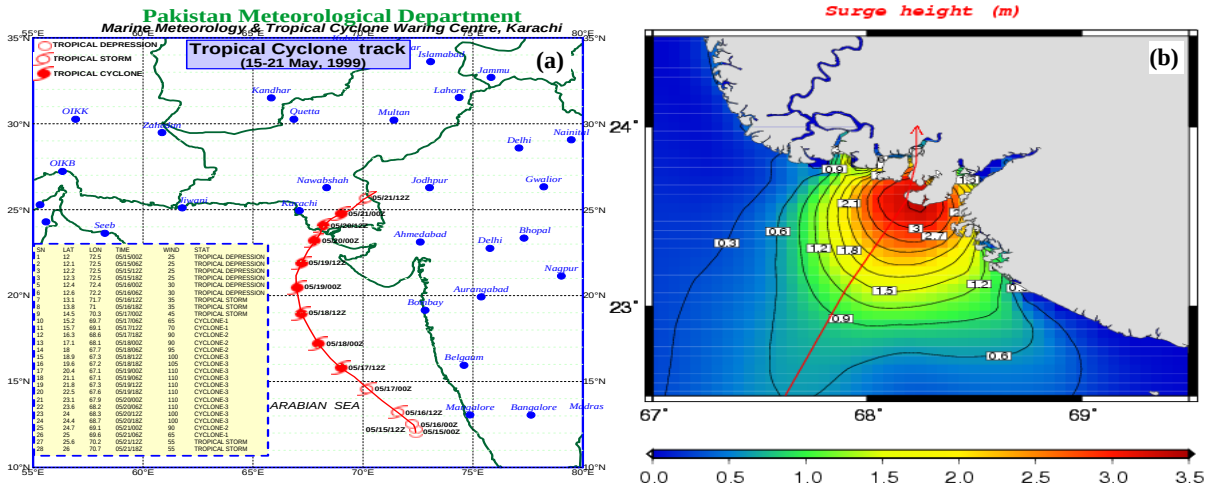

Figure 2: (a) depicts the actual track followed by 02A and landfall at Pakistan's southeast coast (data courtesy: weather.unisys.com). **(b)** shows the model-simulated surge contours with maximum surge height of 3.4 m near India-Pakistan coast

Tropical Cyclone 01A (21-28 May 2001)

Tropical cyclone 01A developed also in the east central Arabian Sea on 21st May 2001 at around latitude 14 °N and longitude 70 °E. Initially it moved eastward towards Indian coast, then re-curved towards north/northwest and reached the maximum intensity on May 24, 2001. Further it moved west/northwestwards and weekend into a depression on May 28 and re-curved northeastwards but had slightly re-intensified again into a cyclone before making landfall at Indian-Gujarat coast on 29 May 2001(source: RSMC, Delhi, India). Figure 3a shows the TC 01A actual track.

Using the input file (Table-2, data and methods section) for TC 01A surge simulations in the model the simulated surge has come out to be 1.03 meters at Indian Gujarat coast (Figure 3b). TC 01A posed a persistent threat to the Pakistan – India coast for about a week though no casualties or damages were reported. The maximum computed surge height of 1m is comparable to the estimated surge value provided by Unisys (2001).

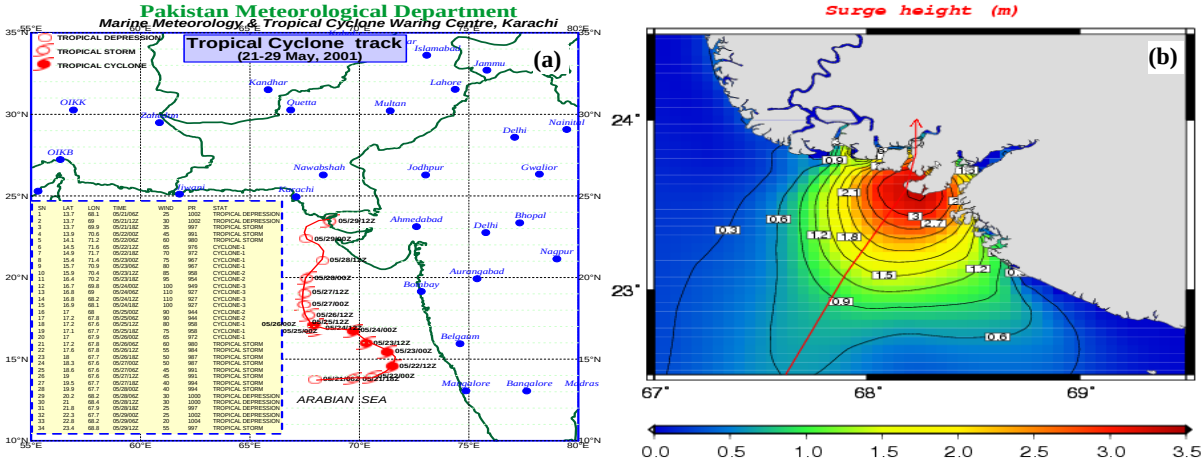

Figure 3: (a) depicts the TC 01A actual followed track (courtesy: weather.unisys.com, TCWC- PMD). **(b)** depicts the model-simulated surge contours with maximum surge value = 1.03 m.

Tropical Cyclone Yemyin (21-26 June, 2007)

The 3rd tropical cyclone considered in this study was the Yemyin, 03B (21 – 26 June, 2007). It initially originated in the afternoon of 21st June 2007 near the Bay of Bengal and after a brief span

landed on 22 June at the Andhra Pradesh coast with inundating the city of Kurnool, Andhra Pradesh, where exceptionally high torrential rainfall of 400 mm was recorded in little more than 24 hours. TC 03B triggered the flooding from Andhra Pradesh west to Maharashtra and Karnataka and Mumbai (source: http://www.usno.navy.mil/JTWC/). After entering the north Arabian Sea it redeveloped as a cyclone on 25 June 2007 at 0600 UTC with centre around lat. 22.9 °N, long. 67.3 °E and was named "Yemyin". Moving northwest TC Yemyin finally landed at the Balochistan coast on early morning of 26 June 2007 (Figure 4a) resulting in torrential rains in southern districts of Kech, Gwadar, Pasni, Turbat, Panjgur and Lasbella etc. For simulation of the surge generated by Yemyin the input file used in the model is given in Table-3 (data and methods section). The simulated maximum value of the peak surge was 0.37 meters (Figure 4b). The maximum computed surge height of about 0.4 m is comparable to the estimated surge value provided by Unisys (2007).

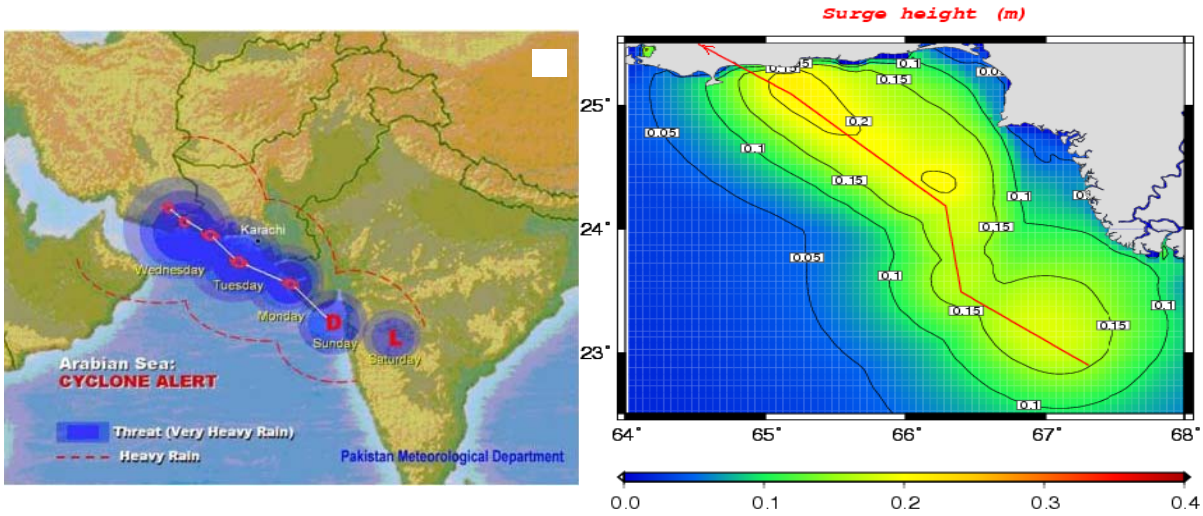

Figure 4: (a) The Yemyin track with affected area (courtesy: PMD); **(b)** shows the model-simulated surge contours with the maximum value being 0.37 m.

Tropical Cyclone "Phet" (1 – 6 June 2010)

The tropical cyclone "Phet" developed in the early hours of 1st June 2010 in the east central Arabian Sea at around 15.7 °N – 63.8 °E about 1100 Km south-southwest of Karachi (source: PMD, http://www.usno.navy.mil/JTWC/). Having moved in a northwesterly direction it further intensified first in to a severe tropical cyclone and then a very severe tropical cyclone, a category-4 cyclone on the following days. The Phet keeping northwestwards track struck the northeastern tip of Oman coast on 3rd June, inflicted huge damages and then re-curved towards northeast (Figure-5a). With its east and northeastwards movement it started impacting the Makran (Balochistan, Pakistan) coastal cities of Gwadar, Jiwani, Pasni and Ormara, which got torrential rains of up to 60 - 370 mm in about 24 hours. The entire area was inundated with 15 casualties reported besides 24 in Oman and five in India, (source: http://in.reuters.com/article/idINIndia-49106920100607).

The model was run by using the input file (Table-4, data and methods section) for surge simulation and the maximum value of peak surge simulated is 1.17 meters. The graphical depiction follows in Figure. 5(b).

The model-simulated surge results show that the TC 02A (1999) had generated the highest surge (3.4m) and Yemyin produced the least surge (0.37m). More elaboration on this is given in the next discussion section.

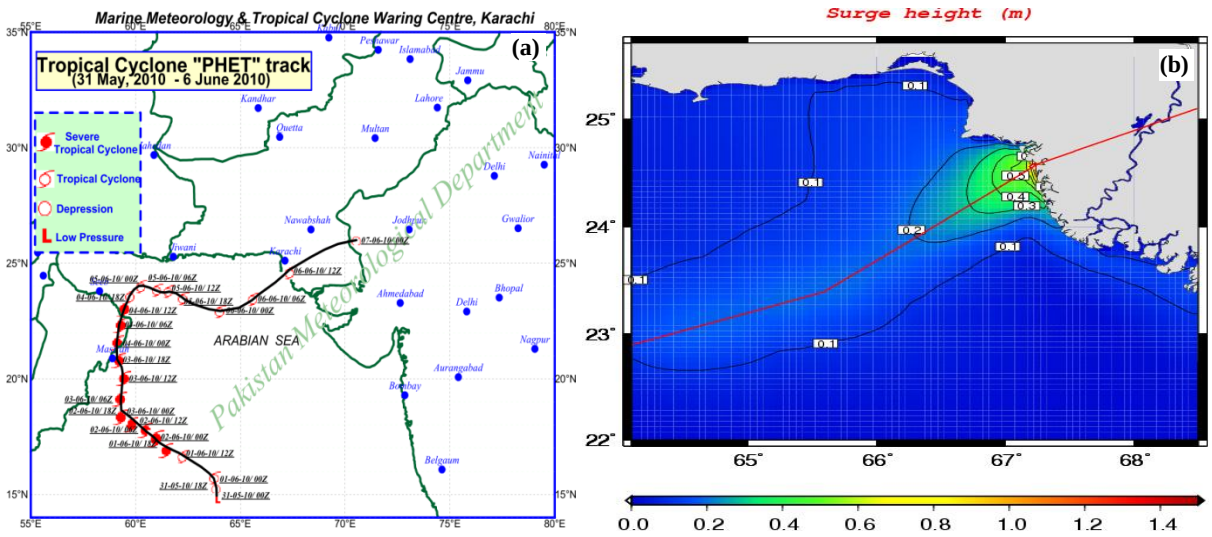

Figure 5: (a) Phet track depicting its movement and intensity, (courtesy: TCWC-PMD)
(b) shows the model-simulated surge contours with a maximum value being 1.17 m

Discussion

The results of IIT-D Model-simulated surges for the four tropical cyclones during the period 1999-2010 show that the TC 02A had generated the highest surge (3.4 meters) followed by the TC Phet-generated surge of 1.17 m, TC 01A-generated surge of 1.03 m and TC Yemyin-generated surge of 0.37m. These results were found in agreement with Unisys Weather Information Services' (1999, 2001, 2007) values which estimate the intensity of tropical cyclones and associated range of surge heights based on the post-analysis of all the available satellite images, surface data, upper air data and radar data.

It is believed that the high surge of 3.4m generated by TC 02A would have caused much of the damage (total damage being $6 million plus 700 casualties) by inundating the coastal shelf of the two southern districts Thatta and Badin after its landfall at southeast Sindh (south of Karachi) as confirmed by Arif Suleman, one of many local fishermen that "The waves were 12 feet high and the sea water was pouring into our homes. Nearly everything we had was destroyed" (Source: http://news.bbc.co.uk/2/hi/south_asia/348438.stm). Until 2007, the TC 02A remained the most intense tropical cyclone having developed in the Arabian Sea with maximum winds attained 105 kts which was eventually surpassed by a super tropical cyclone Gonu (with maximum sustained winds of over 120 kts) developed in June 2007 which hit the Oman coast inflicting damages of $200 million to country's oil export (source: Joint Typhoon Warning Centre).

TC Yemyin though having generated a very low surge of only 0.37m still proved to be the 2nd highest destroyer cyclone for Pakistan with damages worth $560 million accompanied with 790 human lives (140 in India, 213 in Karachi and 80 in Afghanistan - due to torrential rains'- caused floods). The death toll in Karachi was mainly due to the high-speed winds generated by tornado-like phenomena occurred prior to Yemyin redevelopment in the north Arabian Sea. The surface wind data shows that a wind of 50 - 66 kt blown from the northeast direction for about 30 minutes with a maximum gust of 67.74kt accompanied by a temperature of 44.3ºC and 78% relative humidity (courtesy: PMD, NMCC). This half-an-hour persistent high wind brought down most of the billboards and hoardings along roadside of the city with collapsing about 30,000 muddy houses as a result killing about 215 people. The system after redeveloping as a cyclone "Yemyin" in the north Arabian Sea moved northwestwards and crossed the Makran coast near Lat 25.1ºN and Long 65.2ºE creating havoc in coastal cities of Pasni, Ormara, Turbat and Kech with some southern areas of Afghanistan also received a heavy downpour. TC Yemyin has therefore proved to be a

killer with high ravaging winds and torrential rains which affected about two million people besides killing about 2 million worth livestock.

The 3rd cyclone understudy TC 01A having generated a surge of 1.03 meters though did not result in any damage but posed a persistent threat for about a week. And the impact of TC "Phet" too was not in surge but torrential rains that created havoc across the Makran coast (Balochistan, Pakistan) in addition to the considerable damages in Oman where Phet initially hit its coast. The Makran coastal city Gwadar received as much as 370 mm of rain in 24 hours when Phet got nearer to the Pakistan southwest coast. This is the highest 24-hour rain produced by any cyclone in any Pakistan coastal city so far. The damage was of big proportion to the Kutcha houses and loose structures much of which collapsed. In Oman about $780 million worth damages were caused by Phet with 44 casual fatalities, 24 in Oman, 15 in Pakistan and 5 in India. The affected countries were Oman, Pakistan and India.

On model results' validation, as far as Pakistan is concerned the unavailability of actual surge data is a bit drawback but, however, the simulated results were nearly in agreement with the local people's statements published in post-storm reports. The validation results from other regional countries are encouragingly in agreement with that reported in post-storm survey and IMD abridged reports, (1999). For the Indian coast Andhra (1988 Khulna cyclone), Orissa (1989 Balasore cyclone) and Gujarat the model predicted a peak surge of about 5m, 7.8m and 5m respectively close to the landfall, which agrees well with the post - storm survey reports, and the reported surge (IMD Report, Feb. 1999). For Bangladesh 1985 Chittagong Cyclone the model simulated a maximum surge of 3m with surge values at Chittagong and Cox's Bazar being 1.8m and 2.2m respectively whereas Roy et al., (1999) reported astronomical tide at the location as 1m at the time of landfall. Thus the total water level being about 2.8m at Chittagong was close enough to the observations reported, Dube et al., (2004). For another Bay of Bengal country Myanmar the model-computed sea levels were found to be in agreement with the available estimates/observations, Sinha et al., (2005). Across Myanmar, for Mala cyclone (May 2006) peak storm surge of about 4m was reported by the Department of Meteorology and Hydrology, whereas the simulated surge of 3.6m to the right of the landfall point near Goa, and the peak surge at Pathein were about 2m, (ibid).

Conclusions and Future Plan

The only drawback is that for the Pakistan coastal region we do not have the actual sea level rise data after the crossing of cyclone for verification of the model-simulated surge height though the model-simulated maximum surge height of 3.4m for TC 02A was verified by some local people of Keti Bandar, Sindh. The scale of damages inflicted by TC 02A (1999) compared to that by TCs Yemyin and Phet also indicate that high surge generated by TC 02A has been a prime killing factor.

Across other regional countries, as mentioned in discussion, the model-simulated surge data was by and large in close agreement with post-storm surveys and observations. While the storm surge prediction for India in particular, and for the North Indian Ocean region in general, is generally satisfactory, improvements are needed both in storm surge model as well as meso-scale NWP model to further enhance the storm surge forecasting capability in the region. Keeping this in view the IOC-UNESCO/JCOMM organized two Advisory Workshops (http://www.jcomm.info/SSindia) at Indian Institute of Technology Delhi, on 14-17 July 2009 and 11-15 February 2010, wherein the international experts on storm surges have worked with the regional modelling experts to review the current status/performance of an operational storm surge forecasting model (IIT-D Model) for the North Indian Ocean region and addressed requirements for upgrading and improving the model performance. Workshops also discussed initiatives of the National Meteorological and Hydrological Services to improve infrastructure required for an improved prediction of cyclone and associated surges (IOC-UNESCO, 2009 and IOC-UNESCO, 2011). This is a line of activities following the recommendations made at the 1st JCOMM Scientific and Technical Symposium on Storm Surges (October 2-6, 2007 Seoul, Korea: http://www.surgesymposium.org). This activity is designed and conducted under the framework of

the UNESCO project on "Enhancing regional capabilities for Coastal Hazards Forecasting and Data Portal Systems".

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