Modelling coastal flood risk in the data poor Bay of Bengal region

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1. Introduction

In the northern Bay of Bengal, tropical cyclone induced storm surge has resulted in some of the most notable flood disasters in recent history (e.g. Murty et al., 1986). Improvements to mitigating the coastal flood risk of this region have been highlight by the 2007 cyclone Sidr event (see Dube et al., 2009; Lewis et al., 2012), in which the relatively low number of deaths was attributed to the development of an early warning system and cyclone shelter building program (see Paul, 2009). Obvious challenges to reduce flood risk in the Bay of Bengal region includes identifying the magnitude of uncertainty within inundation model based flood risk estimates to direct future research. Further, the development of a computationally efficient inundation model to correctly predict inundation extent in real time as part of an early warning system has been proposed for the northern Bay of Bengal (see Lewis et al., 2012), and thus cyclone forecast uncertainties would need to be included within inundation predictions.

A hydrodynamic model that can simulate inundation extent using the shallow water equations in a discretized form is at the heart of any typical flood risk estimate. Many forms of such inundation models exist, all having benefits and penalties which shall not be discussed further here. However, one major limitation within accurate inundation simulation has been identified as model resolution (e.g. Bates et al., 2005). The nesting of regular grid models (e.g. Madsen and Jakobsen, 2004) or unstructured grid approaches (e.g. Rao et al., 2010) have been successfully employed to improve resolution in regions of interest. Nevertheless, many full shallow water equation models are considered over-specified for gradually varying flooding problems (Neal et al., 2012). Therefore, a computationally efficient modelling approach (at resolution scales appropriate for flood risk assessment) maybe a better way to improve predictive accuracy (Lewis et al., 2012). Moreover, understanding uncertainties within flood hazard mapping is essential because unrealistic expectations of accuracy can result in the misinterpretations of flood hazard to policy makers and the general public (e.g. Hall and Solomatine, 2008).

In "data rich" regions, such as the UK, flood risk uncertainties were found to be high from spatial variability within the water-level forcing scenario (used to force the inundation model), whilst intra-modelling uncertainties were found to be relatively low due to the availability of high quality topographic data such as LiDAR (see Lewis et al., 2011). Therefore, it is hypothesised that "data poor" regions have considerably higher uncertainty with inundation extent predictions, because of the availability of high quality topographic data with which to build a fine resolution Digital Elevation Model (used within an inundation model). Consequently, it is unclear as to the accuracy of previous Digital Elevation Models (DEMs) in the north Bay of Bengal region (e.g. Madsen and Jakobsen, 2004; Karim and Mimura, 2008), or the suitability of products such as SRTM (Shuttle Radar Topography Mission) data (http://srtm.csi.cgiar.org; 2010). Further, a lack of a dense network of high quality tide gauge records (with which to force an inundation model using interpolated extreme water level estimates), and the availability of a much longer cyclone parameter database of historic events (e.g. IBTrACS, www.ncdc.noaa.gov/oa/ibtracs; 2010), has resulted in the use of numerical storm surge models to predict water-levels along the coastline and inundation extent (e.g. Jain et al., 2010a; Rao et al., 2010).

Multiple Bay of Bengal storm surge models exist (e.g. Flather, 1994); however, one successful example is the IIT-D (Indian Institute of Technology – Delhi) storm surge model, which has shown predictive skill (Dube et al., 2009) and attributed to reducing loss of life in the 2007 Sidr event (Paul, 2009). These storm surge models are forced with wind and pressure fields from an idealised cyclone model (e.g. Jelesnianski and Taylor, 1973) using an extreme cyclone scenario (for example the "1 in 50 year cyclone event") based on extrapolation of parameters from a cyclone database (e.g. IBTrACS).

Five parameters are used to create wind and pressure fields within the idealised cyclone model, and thus force the storm surge model (see Azam et al., 2004; Resio et al., 2009):

1) Radius of maximum winds (RMAX), sometime called storm size;
2) Pressure drop (ΔP), defined as the difference between central pressure (CP) of the cyclone and the ambient pressure (we assume 1010hPa);
3) Cyclone track speed (mvspeed), the speed of progression of the cyclone's centre;
4) Cyclone track and landfall location;
5) Angle of attack, the bearing (°N) of the cyclone as it makes landfall.

Observation uncertainty with the cyclone parameters of the 2007 Sidr event were found to have a significant effect upon simulated storm surge height and inundation depth (Lewis et al., 2012). Therefore, it is hypothesised the uncertainty surrounding a 1 in 50 year cyclone event, making landfall at the cyclone Sidr location, would be much greater than that reported in Lewis et al. (2012). In this work we shall examine and compare some of the major intra (DEM) and extra (storm surge height) inundation modelling uncertainties in an effort to direct future research to reduce future loss of life from tropical cyclone inundation events in the northern Bay of Bengal.

The LISFLOOD-FP inundation model is computationally light, and solves a simplified form of the shallow water equations using a local inertia approximation (see Bates et al., 2010). A sub-grid channel routine to simulate rivers with width scales less than grid resolution was employed (see Neal et al., 2012), and a Digital Elevation Model (DEM) was derived from SRTM data (see Lewis et al., 2012). Further details of this northern Bay of Bengal inundation model can be found in Lewis et al. (2012); including model validation to the 2007 cyclone Sidr event. The variability with key cyclone parameters of a 1 in 50 year cyclone making landfall at the 2007 Sidr location (89.8°E on the Bangladesh coastline) was derived and propagated into the IID-T storm surge model (see Dube et al., 2009); hence, the subsequent difference of simulated inundation was compared to the uncertainties within the DEM of the inundation model.

2. The inundation model

The accuracy of SRTM data in low slope regions (such as the delta region of Bangladesh) is thought to be low (Lewis et al. 2012). Instead, the SRTM random vertical noise (~6m at the native 90m SRTM resolution), and impact of vegetation artefacts, were considered to be much larger issues with SRTM data (Lewis et al., 2012). The technique of assigning an SRTM height correction for each vegetation class in the land use data (see Getirana et al., 2009) was not possible in this study because of high SRTM within-class variance; as shown in Figure 1. Instead, “vegetation affected regions” were identified and removed from the SRTM data using the freely available (www.landcover.org, 2011) 1km land use map from the 1981-1994 Advanced Very High Resolution Radiometer (AVHRR) image of Hansen et al. (2000). A nearest neighbour interpolation technique was used to replace the “vegetation affected SRTM regions”, and a 90m UTM projected Digital Terrain Model (DTM) was generated.

The spatial noise of SRTM data, and thus artificial roughness of the 90m DTM, is assumed to reduce linearly in proportion to $1/\sqrt{n}$, where n is the number of pixels averaged (see Rodriguez et al., 2006). Using a smoothing and averaging window, a 900m DEM was generated (Figure 2); as the signal to noise ratio (SNR) was reduced to an acceptable level within the flood plain (Lewis et al., 2012). SRTM data cannot penetrate water, thus bathymetry from the IIT-D storm surge model was interpolated to the DEM, and missing estuary bathymetry was estimated during model calibration (see Lewis et al., 2012). Further, river channel depths can be estimated using hydraulic geometry theory, which relates river depth and width, to river discharge and catchment area. Therefore, a river channel width raster was created from the freely available HydroSHEDS stream network raster file (http://hydrosheds.cr.usgs.gov/hydro.php, 2011); and is shown in Figure 2, and employed within the LISFLOOD-FP sub-grid channel routine of Neal et al. (2012).

The LISFLOOD-FP model of Lewis et al. (2012) was validated to the 2007 cyclone Sidr event, and resulted in an Root Mean Squared Error (RMSE) between 1.89m and 2.13m (due to cyclone parameter uncertainty), with an overall average flood agreement of ~42%. Although cyclone parameter uncertainty was high in the storm surge hind-cast of the Sidr event, DEM uncertainty was also shown to be high due to inundation model resolution and SRTM errors (see Lewis et al., 2012). The standard deviation (s.d.) associated with the mean from each 900m DEM cell was used to build two further 900m DEM grids (minimum = 900m SRTM mean + 1 s.d. and maximum = mean – 1 s.d.) to express the "intra" (topography) inundation model uncertainty. Therefore, by propagating the Sidr 2007 mean forcing water-level condition (see Section 4) into a minimum and maximum DEM grid scenario, DEM uncertainty could be determined in terms of inundation extent and compared to extreme water-level uncertainty.

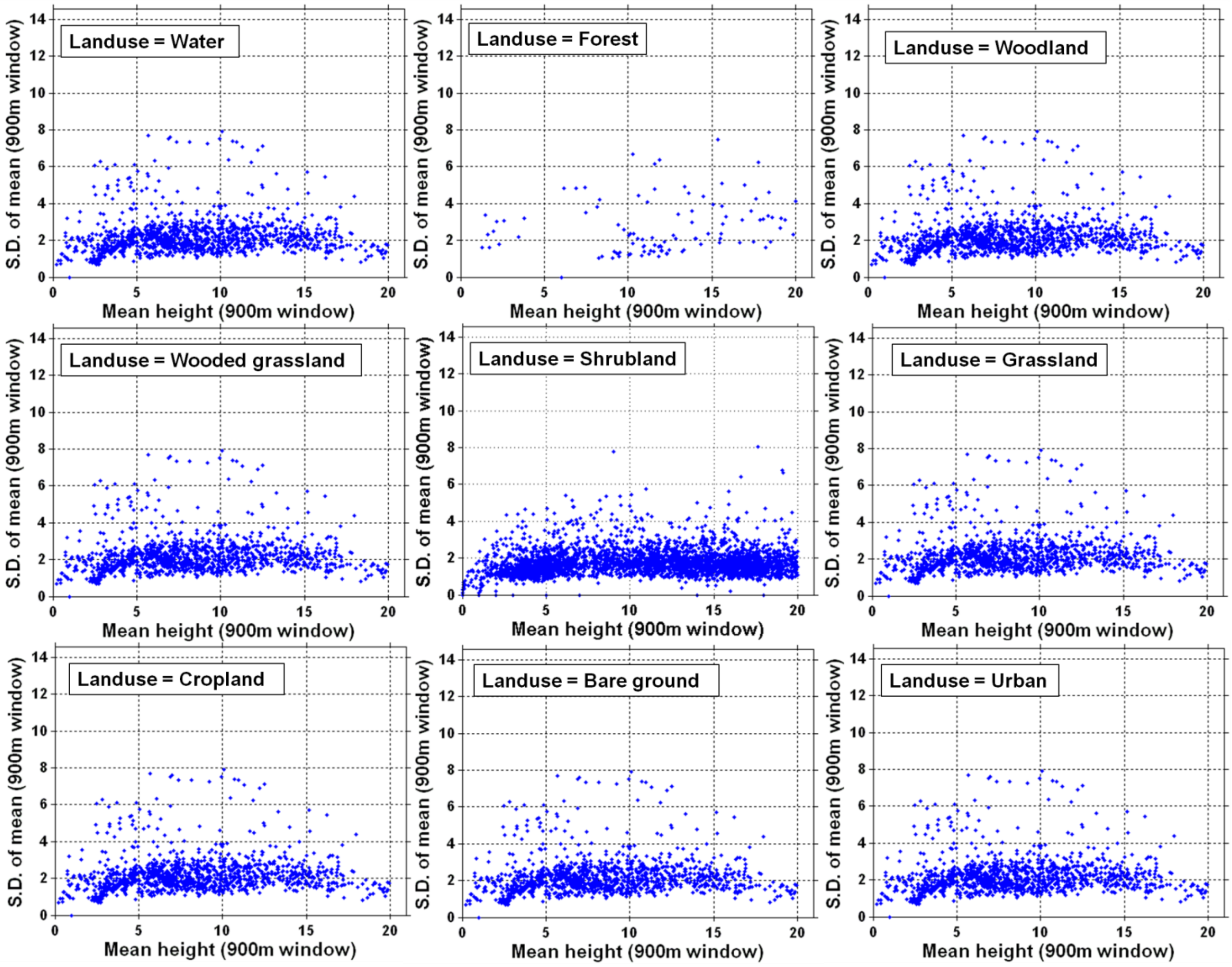

Figure 1. The relationship between the variance of SRTM data (mean 900m compared to the Standard Deviation) for each AVHRR defined land-use (vegetation type) groups in the North Bay of Bengal coastal flood plain (assumed to be SRTM data below 20m).

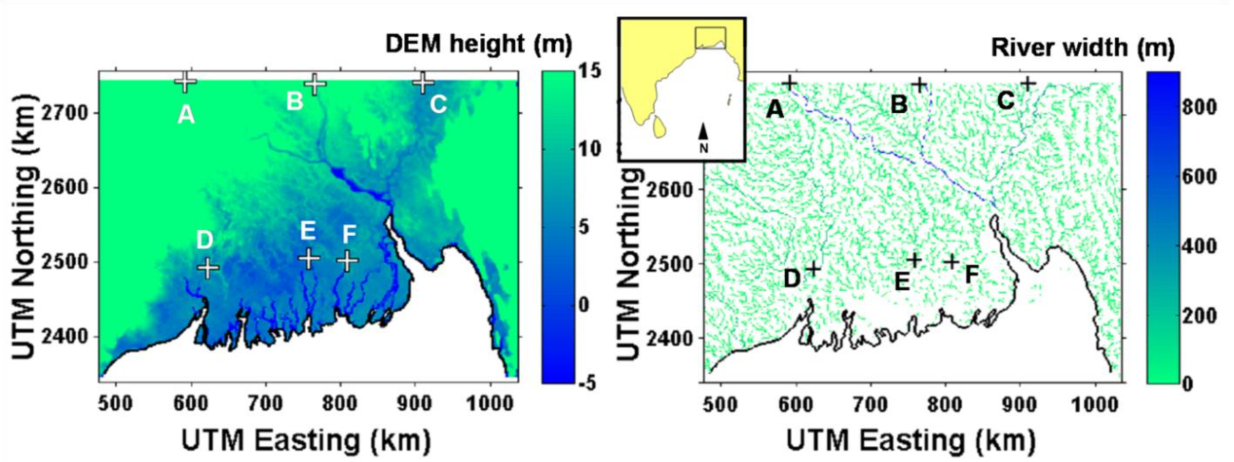

Figure 2. The 900m DEM of northern Bay of Bengal derived from SRTM data (Left Hand Side) with corresponding river widths for the same region (RHS), and six major river point sources within the LISFLOOD-FP model (A to F); from Lewis et al. (2012).

3. Variability within the 1 in 50 year cyclone parameters

The 1 in 50 year cyclone event is a common basis for flood risk modelling in this region (e.g. Jain et al., 2010b); therefore, the uncertainty surrounding an idealised 1 in 50 year cyclone was explored using the IBTrACs (version 2) dataset (http://www.ncdc.noaa.gov/oa/ibtracs/, 2010). Tropical storms were removed from further analysis because these events are likely to behave differently to the cyclone events that cause serious coastal inundation. Previous work indicated spatial similarity of cyclone parameters throughout the Bay of Bengal. Hence, 18 tropical cyclone events were identified in the Bay of Bengal between 1990 and 2008, which met our criteria and quality control measures.

The uncertainty surrounding an extreme storm surge scenario was explored by investigating the natural variability associated within the wind speed (VMAX) and pressure drop (ΔP) relationship of a "1 in 50 year cyclone event"; see Figure 3. Using the standard error within the linear regression of equation 1 (R^2 of 81%, Spearman rank of 0.88 and $P > 0.01$), 68% of the wind speed (VMAX) uncertainty associated with a 1 in 50 year cyclone pressure drop (ΔP) was calculated (points C and D of Figure 3). We assume a ΔP 50-year return period of 68.7hPa, based on Sindhu and Unnikrishnan (2011), which uses a similar methodology for "choosing" cyclone events. Therefore, the uncertainty within the wind-pressure relationship can be propagated through the IID-T storm surge model, and LISFLOOD-FP inundation model, for a "1in 50 year" cyclone event of a similar track to cyclone Sidr: see Section 4.

$$VMAX = 0.4\Delta P + 30.45 \qquad (1).$$

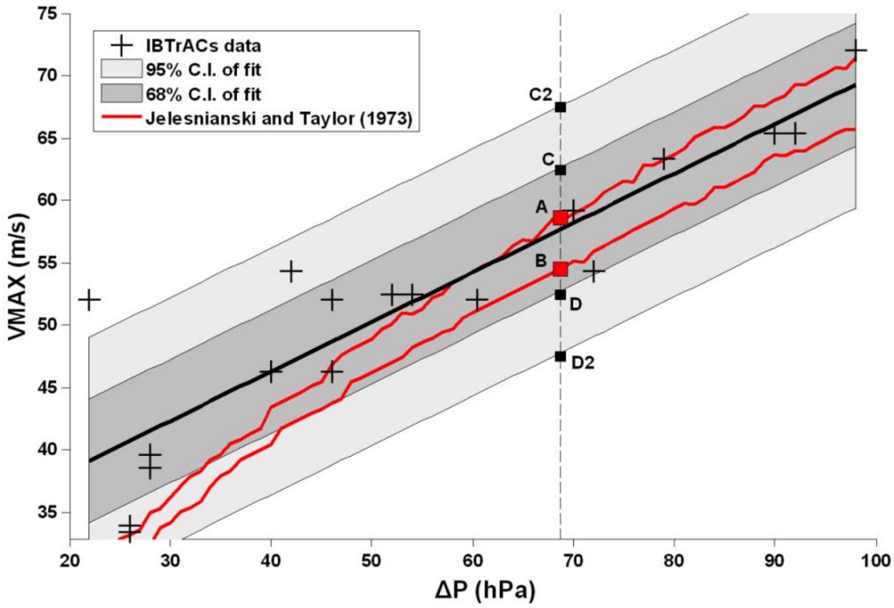

Figure 3. The natural variability of the observed wind (VMAX) and pressure (ΔP) cyclone relationship using the 18 Bay of Bengal cyclones observed between 1990 and 2008, compared to the estimated uncertainty range within the Jelesnianski and Taylor (1973) idealised cyclone model.

4. Storm surge and inundation uncertainty

There is no way to directly explore wind speed uncertainty in the IID-T storm surge model because wind speed (VMAX) is estimated from an idealised cyclone model for computational stability (Jelesnianski and Taylor, 1973). However, the natural variability of the cyclone wind field is much greater than the uncertainty associated with the wind-pressure nomogram in the IID-T storm surge model (see Jelesnianski and Taylor, 1973). Therefore, VMAX uncertainty could be represented in the IID-T model as pressure drop (ΔP) variability by reversing the wind-pressure equation (1): see Table 1. Direct observations of the radius of maximum winds (RMAX) were not available in the IBTrACs database (version 2). Instead, we used the Willoughby et al. (2006) equation (2) to infer RMAX from maximum wind speed (VMAX) and latitude (ψ); hence the variability with VMAX of the 50-year cyclone can be estimated (see Table 1)

$$RMAX = 46.4*\exp(-0.0155*VMAX+0.0169*\psi) \qquad (2).$$

In the Bay of Bengal, extreme water-level estimate studies typically use observed tracks (e.g. Jain et al., 2010a; Rao et al., 2010). To investigate the sensitivity to cyclone track uncertainties, a track can be synthesised by propagating the angle of attack (mean ± s.d.) outward from the coastline for 18 hours (the typical duration of angle of attack observed) and connecting this position to an assumed genesis location.

Table 1. The estimated uncertainty range (mean ±1 standard deviation) of major cyclone parameters associated the "1 in 50 year" cyclone event based on the natural variability of 18 cyclone events observed in the Bay of Bengal (IBTrACs).

Estimated 1:50year cyclone parameter	mean value	minimum scenario	maximum scenario
VMAX (m/s)	57.93	52.98	62.88
ΔP (hPa)	69	56	81
track speed (m/s)	3.8	2.8	4.8
angle of attack	347°N	291°N	43°N

Two genesis locations (a standard "central" Bay of Bengal location at 87.5°E 10°N, and the cyclone *Sidr* genesis location: 93.2°E 9.6°N) were assumed. The uncertainty associated with the angle of attack was calculated as the mean and standard deviation (s.d.) from 10 of the 18 observed events (due to an appropriate landfall location); see Table 1. The mean cyclone track speed (mvspeed), and associated uncertainty (± 1 standard deviation), was calculated from the 18 events (see Table 1). Hence the cyclone parameters and track associated with a 1 in 50 year cyclone making landfall at the 2007 cyclone Sidr location (89.76°E 21.75°N, ± 26km to include average landfall variance) was calculated based on the natural variability observed within 18 Bay of Bengal cyclone events. Therefore, by holding all other cyclone parameters at their "mean" value, the uncertainty of storm surge magnitude could be simulated using the IID-T model for a number of key cyclone parameters; the results of which are shown in Table 2.

Table 2. Sensitivity test cyclone parameters and resultant simulated peak surge using the IID-T model for the estimated uncertainty within the idealised 1 in 50year cyclone making landfall (LF) at the Sidr 2007 position with the exception of the landfall test when the position is shift 26km east and west along the coastline.

Sensitivity test	Peak cyclone parameter scenario		Cyclone track scenario			**Surge difference (m)**
	ΔP (hPa)	RMAX (km)	mvspeed (m/s)	Angle of attack	Genesis position	
genesis position	69	25	3.8	347°N	central	**0.51**
	69	25	3.8	347°N	Sidr	
angle of attack	69	25	3.8	291°N	central	**0.07**
	69	25	3.8	43°N	central	
track speed (mvspeed)	69	25	4.8	347°N	central	**1.39**
	69	25	2.8	347°N	central	
RMAX peak	69	23	3.8	347°N	central	**0.00**
	69	27	3.8	347°N	central	
ΔP (pressure drop)	56	25	3.8	347°N	central	**2.77**
	81	25	3.8	347°N	central	
landfall (LF) position (±26km from Sidr)	69	25	3.8	347°N	central	**0.89**
	69	25	3.8	347°N	central	

Uncertainty in cyclone strength (ΔP) was found to have the greatest effect upon storm surge height, which is reasonable since ΔP has a dual influence on the storm surge via both the inverted barometer effect and the cyclostrophic pressure gradient (thus wind speed). Storm size (RMAX) uncertainty resulted in no change to the simulated maximum storm surge; however the RMAX spread was derived indirectly and errors maybe present. Cyclone track uncertainty (genesis location, landfall, mvspeed and angle of attack) also had an effect on simulated storm surge magnitude, although the influence upon the spatial distribution of the peak storm surge was much greater (important for estimating coastal flood hazard).

The spatial pattern of the simulated storm surge uncertainty was propagated into the LISFLOOD-FP inundation model, assuming a mean spring tide sinusoidal time series interpolated along the northern Bay of

Bengal coastline (see Lewis et al., 2012); the results of which can be seen in Figure 4. The inundation difference due to the ΔP uncertainty within the 1 in 50 year cyclone event was calculated as 279 km². Uncertainty due to the relative timing of storm surge and tidal peaks (i.e. maximum surge height at low water or high water) resulted in a bigger inundation difference of 441 km². Although the sensitivity of angle of attack uncertainty reported a small storm surge difference in Table 2, a much larger inundation difference of 1179 km² was obtained when propagated through to inundation extent (see Figure 4). Moreover, the inundation extent uncertainty from these individual storm surge differences (Figure 4) is comparable to the inundation extent uncertainty (1416 km²) which arises from DEM uncertainty based on the variance of the 900m SRTM data (mean ± 1 s.d.); see Figure 5.

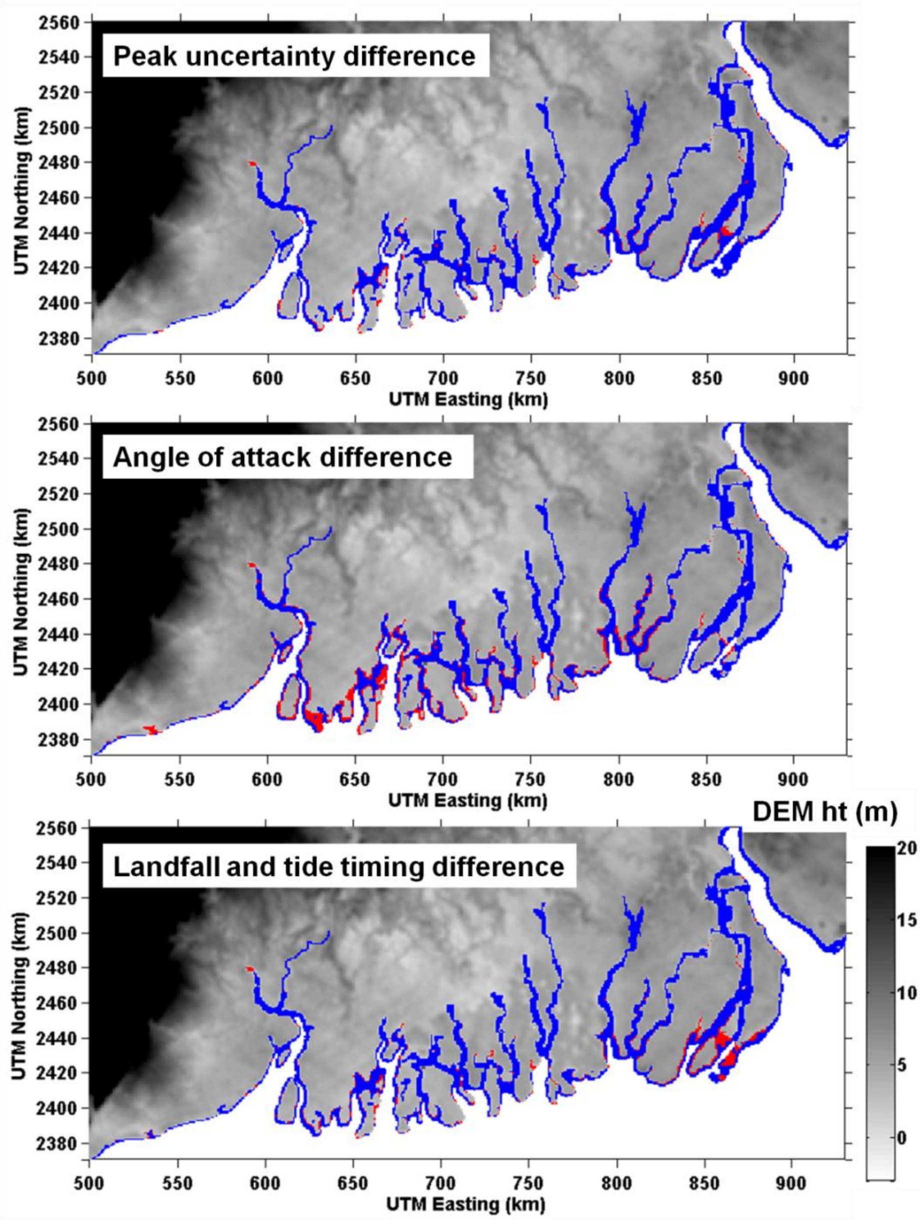

Figure 4. The inundation extent difference (maximum shown as red, minimum extent over-plotted in blue) within a "1 in 50 year" cyclone (making landfall at the Sidr location), for the combined uncertainties of (1) peak cyclone parameter, (2) angle of attack, and (3) cyclone landfall and tide timing uncertainties, based on the observed natural variability of 18 cyclone events in the Bay of Bengal.

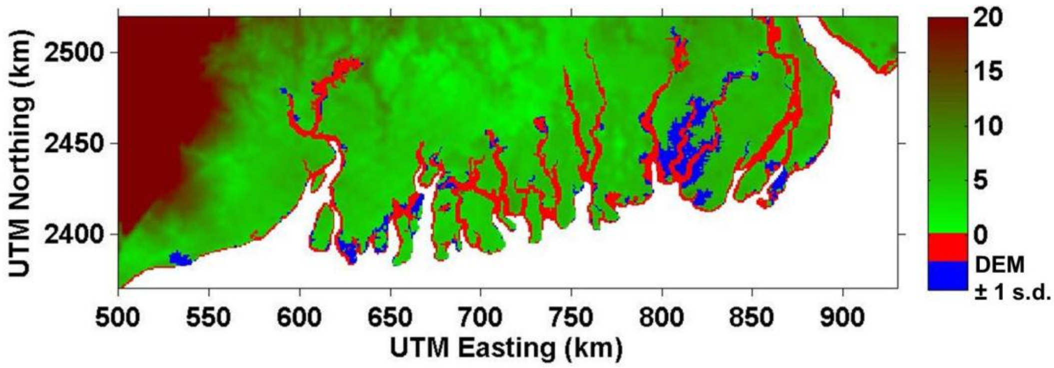

Figure 5. The inundation extent difference (maximum shown as blue, minimum extent over-plotted in red) from the 2007 cyclone Sidr storm surge hind-cast (see Lewis et al., 2012), due to topography uncertainty assumed to be represented by one standard deviation (s.d.) of the mean SRTM height used to create the 900m Digital Elevation Model.

5. Conclusions

Accurate high quality topographic data sources, used to construct DEMs at resolutions necessary for accurate inundation simulation, are not readily available in the Bay of Bengal. Instead, Shuttle Radar Topography Mission (SRTM) topography data were used to generate the Digital Elevation Model (DEM). Considerable DEM error and uncertainty was present at the 900m resolution necessary for processing the SRTM data, which resulted in significant inundation extent uncertainty. Higher quality data sources (e.g. LiDAR) would significantly reduce inundation model uncertainty in data poor regions, such as aid-funded (e.g. http://www.dfid.gov.uk) LiDAR surveys for the Bangladesh region. Furthermore, as the LISFLOOD-FP inundation model developed here is computationally light, DEM uncertainty could be quantified using a probabilistic approach (e.g. Zerger et al. 2002). Therefore, SRTM and other publically available data can be of use to flood risk management in data poor regions if better SRTM processing techniques are developed to produce finer scale DEMs (Lewis et al. 2012).

The natural variability within individual parameters of a 1 in 50 year cyclone was shown to significantly affect simulated storm surge height along the coastline. Hence, storm surge uncertainty appears to have a much greater effect to predicted inundation extent when compared to the DEM uncertainty. Furthermore, although cyclone track uncertainty resulted in small changes to peak storm surge height, this uncertainty resulted in significant inundation extent differences. Therefore, a Joint Probability Method for extrapolating and characterising the natural variability within an extreme cyclone event (e.g. Irish et al. 2011), appears to be the best approach for a robust extreme water-level estimate in the Bay of Bengal.

Uncertainties within cyclone development, cyclone peak parameter characteristics and inundation modelling, resulted in significant difference to the simulated inundation extent of a specific cyclone scenario ("the 1 in 50 year cyclone"). Therefore, a computationally efficient inundation model, which can be used as part of an ensemble probabilistic approach to reducing flood risk (see Lewis et al., 2011), could be of great use to flood risk managers in the Bay of Bengal; such as the LISFLOOD-FP model discussed here (see Lewis et al., 2012). Instead, future work should focus on way to characterise the spatial and temporal uncertainties within extreme water-levels in the northern Bay of Bengal.

6. References

Azam, MH, Samad, MA & Kabir, M (2004), "Effect if cyclone track and landfall angle on the magnitude of storm surges along the coast of Bangladesh in the Northern Bay of Bengal", Coastal Engineering Journal, vol. 46(3), pp 269-290.

Bates, PD. Dawson, RJ, Hall, JW, Horritt, MS, Nicholls, RJ, Wicks, J & Hassan, MAAMH (2005), "Simplified two-dimensional numerical modelling of coastal flooding and example applications", Coastal Engineering, vol. 52, pp 793-810.

Bates, PD, Horritt, MS, & Fewtrell, TJ (2010), "A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling", Journal of Hydrology, vol. 387 (1-2), pp 33-45.

Dube, SK, Jain, I, Rao, AD & Murty, TS (2009), "Strom surge modelling for the Bay of Bengal and Arabian Sea", Natural Hazards, vol. 51, pp 3-27.
Flather, RA (1994), "A storm surge prediction model for the Northern Bay of Bengal with application to the cyclone disaster in April 1991", Journal of Physical Oceanography, vol. 24, pp 172–190.
Getirana, ACV, Bonnet, MP & Martinez, JM (2009), "Evaluating parameter effects in a DEM 'burning' process based on land cover data", Hydrological Processes, vol. 23, pp 2316–2325.
Hall, J & Solomatine (2008), "A framework for uncertainty analysis in flood risk management decisions", International Journal of River Basin Management, vol. 6(2), pp 85 - 98.
Hansen, MC, Defries, RS, Townshend, JRG & Sohlberg, R (2000), "Global land cover classification at 1 km spatial resolution using a classification tree approach", International Journal of Remote Sensing, vol. 21 (6-7), pp 1331-1364.
Irish, JL, Song, YK & Chang, K (2011), "Probabilistic hurricane surge forecasting using parameterised surge response functions", Geophysical research letters, vol. 38. L03606, 5pp.
Jain, I, Rao, AD, Jitendra, V & Dube, SK (2010a), "Computation of expected total waterlevels along the east coast of India", Journal of Coastal Research, vol. 26(4), pp681-687.
Jain, I, Rao, AD & Ramesh, KJ (2010b), "Vulnerability assessment at village level due to tides, surges and wave set-up", Marine Geodesy, vol. 33 (2-3), pp 245-260.
Jelesnianski, CP & Taylor, AD (1973), "A preliminary view of storm surges before and after storm modification. Washington", D.C. Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Technical Memorandum, WMPO-3, pp. 23–33.
Karim, MF & Mimura, N (2008), "Impacts of climate change and sea level rise on cyclonic storm surge floods in Bangladesh", Global environmental change, vol. 18, pp 490-500.
Lewis, M, Horsburgh, K, Bates, P & Smith, R (2011), "Quantifying the uncertainty in future coastal flood risk estimates for the UK", Journal of Coastal Research, vol. 27 (5), pp 870-881.
Lewis, M, Bates, P, Horsburgh, K, Neal, J, Schumann, G (2012), "Storm surge inundation model of the Northern Bay of Bengal using publically available data", Quarterly Journal of the Royal Meteorological Society. QJ - 12 - 0069.R1. Online ahead on print: doi: 10.1002/qj.2040
Madsen, H & Jakobsen, F (2004), "Cyclone induced storm surge and flood forecasting in the northern Bay of Bengal", Coastal Engineering, vol. 51(4), pp 277-296.
Murty, TS, Flather, RA & Henry, RF (1986), "The storm surge problem in the Bay of Bengal", Progress in Oceanography, vol. 16, pp 195–233.
Neal, J, Villanueva, I, Wright, N, Willis, T, Fewtrell, T & Bates, P (2012), "How much physical complexity is needed to model flood inundation?", Hydrological Processes, vol. 26 (15), pp 2264 – 2282.
Paul, BK (2009), "Why relatively fewer people died? The case of Bangladesh's Cyclone Sidr", Natural Hazards, vol. 50, pp289-304.
Rao, AD, Jain, I, Murthy, MVR, Murty, TS & Dube, SK (2008), "Impact of cyclonic wind field on interaction of surge-wave computations using Finite-element and Finite-difference models", Natural Hazards, vol. 49 (2), pp 225-239.
Resio, DT, Irish, J & Cialone, M (2009), "A surge response function approach to coastal hazard assessment – part 1: basic concepts", Natural Hazards, vol. 51, pp 163-182.
Rodriguez, E, Morris, CS & Belz, JE (2006), "A global assessment of the SRTM performance", Photogrammetric Engineering and Remote Sensing, vol. 72(3): pp 249–260.
Sindhu, B & Unnikrishnan, AS (2011), "Return period estimates of extreme sea level along the east coast of India from numerical simulations", Natural Hazards, vol. 61, pp 1007 – 1028
Willoughby, HE, Darling, RWR & Rahn, ME (2006), "Parametric representation of the primary hurricane vortex. Part 2: A new Family of sectionally continuous profiles". Monthly Weather Review, vol. 134, pp 1102 - 1120.