Sea Level Changes in Bangladesh: Observational Constraints on Human, Geologic and Weather-Climate Variability Related Factors

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Introduction

Bangladesh is a nation prone to flooding due to its geographical location. Situated on the Bay of Bengal, Bangladesh is the floodplain of the Ganges River which is fed by other major rivers including the Meghna and the Brahmaputra Rivers (Figure 1). Since much of Bangladesh lies in the flat, coastal delta of the Mouths of the Ganges, it is easily susceptible to flooding from both coastal storms as well as spring meltwater. As Bangladesh does not have flood control structures on the Ganges River, the increase in river flow resulting from rain and snowmelt from the Himalayas of both India and Nepal often floods the country. Indeed, the Indian highlands are among the regions of the world with the heaviest annual precipitation. Moreover, tropical storms which frequent Indian Ocean during the high sun season – when highland rains are greatest and the flow of the Ganges is highest – often drive storm surges into the low-lying country.

Somewhat ironically, flooding is required for Bangladeshi survival and flood control measures are relatively primitive. A number of different rice varieties feed the population and they are differentially susceptible to different climate-related factors (Mahmood and Hayes 1995), including El Niño and La Niña events. For example, while Boro rice is grown in the low-sun (dry) season and Aman rice is grown in the rainy

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monsoon, a decided shift from Aman to Boro rice has occurred over the past thirty years to diminish the impact of potential failures of the high-sun monsoon rains (R. Mahmood, personal communication). Approximately 75% of Bangladesh lies below 10m in sea level and nearly 20% of the country is usually flooded during the Monsoon season from June to September (FAO, 2007). During severe floods, as much as three-quarters of the country can be inundated; major floods occurred six times in the 19th Century and eighteen times in the 20th Century.

Sea Level Rise and Its Potential Impact on Bangladesh

Given the occurrence of flooding in Bangladesh and its low-lying lands, it is not surprising that the potential for sea level rise would be of considerable concern to Bangladeshi officials and the citizens of Bangladesh. Repeated episodes of coastal flooding and seawater inundation of the Ganges-Brahmaputra-Meghna Delta plain (Pate et al. 2009; Sarkar et al. 2009) and the increased salinity in the Sundarbans mangrove forest system (Wahid et al. 2007; Sandilyan et al. 2010) of the Bangladesh have been well documented. Thus, the rise of sea levels, which have continued at a fairly regular pace over the past eighty years (Chao et al. 2008), have already affected Bangladesh and will likely continue to do so in the future. Recently, however, questions have been raised as to whether sea level rise and the development around the Bengal Bay basin are caused or exacerbated by anthropogenic global warming such that reduction in CO2 emissions will reduce the risk of coastal flooding and biological threats to the mangrove ecosystem in Bangladesh.
The Intergovernmental Panel on Climate Change (IPCC; Cruz et al. 2007) has argued that by 2050, sea levels could rise by an additional 1 meter due to anthropogenic global warming. As a result, Bangladesh could lose up to 20% of its land area with the concomitant displacement of up to 20 million refugees and loss of 32% of its production of rice and 8% of its production of wheat (Cruz et al. 2007). But note too that the floods of the Ganges-Brahmaputra-Meghna River system brings agriculturally-beneficial sediments that offsets coastal subsidence which often afflicts flood plains in developed countries (e.g., the Mississippi River Delta in Louisiana). Most notably, Bangladesh has been gaining land at the rate of about 20 km\(^2\) per year from 1973 to 2005 due to the sedimentation and siltation of the Ganges River (see Figure 1 of Inman 2009), although it must be remembered that this ‘new land’ is largely unusable for many years until it is properly compacted and settled.

Furthermore, it is difficult to ascertain whether sea level trends can be explained by anthropogenic global warming from CO\(_2\). Satellite altimeters (see, for example, Figure 2 of Nicholls and Cazenave 2010) show that global sea level rise exhibits a high degree of spatial variability. Despite the difficulty in tying sea level rise and fall in the Indian Ocean to anthropogenic levels of CO\(_2\), Han et al. (2010) contend that the “SST warming trend in the Indo-Pacific warm pool during the past few decades [is caused] primarily by anthropogenic forcing.” One wonders how they can possibly make such a claim. As Mörner (2010a) notes, rapid rates of sea level rise (by van de Plassche et al. 2003 in Connecticut, USA) and fall (by Mörner 1999 in the Baltic region) can be explained by the natural effect of meteorological and climatic factors rather than changes in glacial mass volumes. Moreover, Kokler and Hameed (2007) show that sea levels are
affected “by non-tidal, short-term local sea-level variability that is orders of magnitude greater than the trend” and argue for a meteorological cause for trends in sea levels.

It cannot be stressed enough that satellite altimeter-derived estimates of global changes in sea level are grossly overestimated. For example, Nicholls and Cazenave (2010) estimate the global rise is 3.3 mm yr\(^{-1}\) from 1993 to 2009 while Wunsch et al. argue for a much smaller value of 1.6 mm yr\(^{-1}\) from 1993 to 2004. Chao et al. (2008), after accounting for the large impact of artificial reservoir water impoundments, found that global sea levels have been rising at a constant rate of 2.5 mm yr\(^{-1}\) over the past 80 years. Cautions raised by Wunsch et al. (2007:5889,5905) are telling:

“The widely quoted altimetric global average values may well be correct, but the accuracies being inferred in the literature are not testable by existing in situ observations. Useful estimation of the global averages is extremely difficult given the realities of space-time sampling and model approximations. Systematic errors are likely to dominate most estimates of global average change: published values and error bars should be used very cautiously. … It remains possible that the database is insufficient to compute mean sea level trends with the accuracy necessary to discuss the impact of global warming–as disappointing as this conclusion may be.” [emphasis added]

Mörner (2010a) further notes the difficulties and problems in confirming sea level change even at individual tide-gauge locations. He notes a complex range of factors including shoreline morphology, tectonic movements, zone of active compactions, geoid
deformation, as well as hydro-, sediment and glacial isostasy must be taken into account to accurately measure sea level changes. Mörner (2010a) also suggests that analyses must span at least the full 18.6-year tidal cycle to prevent aliasing. Note too that Wunsch et al. (2007) has argued that detecting changes in sea level of 1 mm per year require an observational precision of the measurement of oceanic volume to 0.000001%, a temperature change of 0.0015°C, and a change in salinity to $10^{-5}$ on the practical salinity scale per year (see Fofonoff 1985).

So what can be concluded about sea level rise on the Ganges-Brahmaputra-Meghna Delta plain that will help quantify the future threats facing Bangladesh? Sea levels vary on scales ranging from seconds to millions of years and cover a wide variety of geological and meteorological processes (Harrison 2002). If the results from the Gravity Field and Steady-state Ocean Circulation Explorer (GOCE) satellite are used, the Indian Ocean/Bay of Bengal region sits approximately 40 to 100 meters below the surface of a reference ellipsoid – the lowest of anywhere on the globe (BBC 2010). This determines the relative effect of gravity and helps explain that global sea level would be lowest in the Bay of Bengal (and the Maldives) region if there were no tides, winds, or ocean currents.

Next, the natural setting of the region under the tectonically active zones with the Indo-Burman collision zone to the east and the Himalayan to the north must be considered. Goodbred et al. (2003) note that tectonics and the high sediment supply of the Ganges River controls the development of the Mouths of the Ganges more than anywhere else in the world. For example, the 1950 earthquake in Assam (magnitude of 8.7 on the Richter scale) changed the course and morphology of several Brahmaputra
tributaries and introduced an unquantified (but suspected to be large) amount of sediment via slope failures into the Ganges-Brahmaputra-Meghna Delta River system. This had the consequence of rapidly widening the Brahmaputra River at a rate greater than 127 m yr\(^{-1}\) from 1973 to 1996 (Goodbred \textit{et al.} 2003). As seismic activity has a roughly 30-year recurrence period, large tectonic events may affect the development and sedimentation of the Ganges-Brahmaputra-Meghna Delta River system and, in particular, the development of its floodplain.

In addition, the Ganges-Brahmaputra-Meghna Delta may be subject to a tectonically-driven subsidence (in contrast to the compaction of sediments in the Mississippi River Delta; see Tornqvist \textit{et al.} 2008) at a rate ranging from 4 mm yr\(^{-1}\) (Goodbred and Kuehl 2000) to 15 mm yr\(^{-1}\) (Mörner 2010b). Note that this rate exceeds the predicted global sea level rise of a few mm yr\(^{-1}\) under the anthropogenic warming scenarios posited by the IPCC. Goodbred \textit{et al.} (2003) further suggests that the rate of current sediment discharge is about equal to the average over the last 16 thousand years although in the past, it has varied both higher and lower by about a factor of two. A more detailed study by Goodbred (2003) documented that discharge to the Ganges-Brahmaputra-Mehgina River system is strongly sensitive to the southwest summer monsoon during which the rivers transports 80% to 90% of the water and 95% of the sediment loads.

“The river discharge[s], intimately linked with the summer monsoon, seem to be higher in the interglacial than in glacial time. In addition, the river discharge during recent interglacials seems to be higher than 4 Ma [million years ago]; i.e., before the inception of major glacial-interglacial alternation. Therefore, the summer monsoon seems to be enhanced during glacial-interglacial times of the past [800,000 years] compared to the situation 4 Ma ago. These variations appear to have been triggered by Northern Hemisphere climatic fluctuations through the summer monsoon regime, but not in a simple way.”

Another recent study of sediments from the Ganges-Brahmaputra-Meghna River system has provided further details but with additional quantitative results (Sarkar et al. 2009). Around nine thousand years ago, the low-lying Delta area was inundated, pushing the coastline and mangrove forest about 100 km inland. At this time, the intensification of the summer monsoon increased the sediment discharge by up to eight times the present rate causing a rapid aggradation of both floodplain and estuarine valley fill deposits. Thus, very large and substantial sea level incursions naturally affect the Bangladesh region. Pate et al. (2009:8) adds

“The Holocene and Pleistocene sections [documented in their 123-meter core at Raipur] are sufficiently alike to conclude that delta formation, sequence development, fluvial processes, and marine boundary conditions must also have been remarkably similar at these times. These results help codify the model of a strong South Asian monsoon driving immense sediment flux to the Bengal margin, where tides and coastal circulation
efficiently distribute sediments across a broad delta plain at rates sufficient to offset even rapid rates of sea-level rise. This pattern of behaviour may also yield insights as to how the Ganges-Brahmaputra and other monsoon delta systems could respond to future changes in climate and sea level, whereby a stronger monsoon and sediment flux could mitigate the impacts of rising ocean levels.” [emphasis added]

In particular, Wahid et al. (2007) notes that the annual maximum tidal range has increased by about 0.75 meter in the eastern and central parts of the Sundarbans over the last two decades. Moreover, about 60% of the area retains higher salinity (>20‰) for at least 45 days per year, with seasonal values ranging from about 0.4‰ during the monsoon period to a high of about 28‰ during dry period. Mangrove forests are clearly able to tolerate high variability in salinity levels.

A deeper understanding of the hydraulic interplay between coastal sea levels and rainfall/snow melt runoff and how it affects the mangrove ecosystem of the Ganges-Brahmaputra-Meghna Delta can be obtained by an examination of other river delta systems. Using sediment cores and pollen analysis, Ellison (2008) suggested that thriving mangrove forests around the world, with good peat accumulation, can tolerate or keep pace with a sea level rise of 2 to 10 mm per year. Proske et al. (2010) examined the paleoenvironmental development in the northeastern Vietnamese Mekong River delta – the world’s second largest mangrove forest (after the Ganges-Brahmaputra-Meghna Delta). They concluded that during the mid-Holocene (five to six thousand years ago), the Mekong River Delta was flooded about 2.5 to 4 meters above the present sea level, which caused the coastline to reach inland to almost Phnom Penh, Cambodia (see also
Tamura et al. 2009). During that extensive flooding, Proske et al. (2010:1) found that the mangrove forest ecosystem thrived with “a diverse, zoned and widespread mangrove belt (dominated by Rhizophora) covered the extended tidal flats.” With the subsequent regression and coeval delta progradation, freshwater vegetation with tropical forest prevailed during the late Holocene, although back-mangrove communities dominated by Ceriops and Bruguiera have endured. Thus, mangrove forests are resilient to changing salinity conditions and are likely to be more tolerant of sea level rise than is often claimed.

The Indian/Bangladeshi monsoon is characterized by extreme flooding events often caused by tropical cyclones within the warm ocean waters of the Indian Ocean. Landsea et al. (2006) remarked that the strength of the 1970 Bangladesh tropical cyclone – in which 300,000 to 500,000 people were killed in the world’s worst tropical-cyclone disaster – cannot be quantitatively determined due to limited observations of the storm. Indeed, archived infrared images suggest that many tropical cyclones hit the Ganges-Brahmaputra-Meghna Delta in the 1970s and 1980s than were previously counted. Their reanalysis notes that no systematic increase has occurred in extreme tropical cyclones in the North Indian basin over the last fifteen years. Data on the Accumulated Cyclone Energy Index (ACE – Maue 2009), a combined measure of the frequency and intensity of tropical storms, shows that tropical cyclone activity has been highly variable in the North Indian basin, but with no long-term trend (Figure 2). Such observational results should underscore the lack of correlation between rising atmospheric CO$_2$ levels and the occurrence of tropical storms. Although the prediction of tropical cyclones is considered to be an inexact science, Sugi et al. (2009) have argued that tropical cyclone frequency should be reduced both globally and over the Northern Indian Ocean in particular
(especially in the higher spatial resolution model results) under future enhanced CO₂ warming scenarios.

A broader perspective on rainfall changes and variations around the Ganges-Brahmaputra-Meghna Delta can be obtained by considering the evolution of the Indian summer monsoon and its co-variation with the ITCZ rainbelt for the Holocene. Using a wide range of paleo-proxies across much of the tropics, Fleitmann et al. (2007) suggests that during the early Holocene (10.5 to 9.5 thousand years ago), the mean latitudinal position of the summer ITCZ and its associated rainbelt was shifted northward. Since then, the mean summer ITCZ continuously migrated southward and its rainfall gradually decreased in response to decreasing solar insolation (e.g., Berger et al. 2010). Significant multidecadal and centennial variability in monsoonal rains also was observed and linked to changes in the intrinsic magnetic activity of the Sun (Fleitmann et al. 2003).

However, the rapidly growing Bangladeshi population (from 54 million in 1960 to 160 million in 2008) will be increasingly important in shaping and modifying the Ganges-Brahmaputra-Meghna Delta in the future. Changes in the Delta region will be more affected by human impacts such as dam control of freshwater flow, withdrawal of ground water, and mangrove deforestation by the shrimp industry (see Mörner 2010b). Such effects will substantially change the sediment and nutrient loadings to the Ganges-Brahmaputra-Meghna Delta thereby increasing the salinity of coastal waters. Mörner (2010b) has noted that the rise in salinity in the Sundarbans is progressing from east to west, which indicates that the damming of rivers is a key driving factor for the observed recent trends.
Cazenave and Llovel (2010) have highlighted additional problems that are related to human development which deserve attention. They note:

“Accelerated ground subsidence due to local groundwater withdrawal and hydrocarbon extraction is another problem that affects numerous coastal megacities. For example, during the twentieth century, Tokyo subsided by 5 m, Shanghai by 3 m, and Bangkok by 2 m … Hydrocarbon extraction in the Gulf of Mexico causes ground subsidence along the Gulf Coast in the range of 5-10 mm/yr.” (Cazenave and Llovel 2010:167)

We have set out to sketch the geological and climatic evidence that places in proper context the realistic constraints that affect sea level in Bangladesh and refutes the popular alarmist dogma that anthropogenic global warming is the primary driver of sea level rise in the Ganges-Brahmaputra-Meghna Delta region. We strongly object to the overly simplistic assertion that a serious catastrophe can be averted in Bangladesh simply by channeling funds and efforts to mitigate carbon dioxide emissions. While concern focuses on anthropogenically-induced sea level rise, we note it is negligent not to admit to a 4 to 6 cm rise in sea level over the next two decades due simply to the cyclical effect of the 18.6 year lunar nodal cycle on the Bay of Bengal (see Gratiot et al. 2008). Even more relevant is the fact that the tide-surge interaction can often lead to a devastatingly high tidal range with water levels rising by as much as 4.5 meters in the Meghna estuary (e.g., As-Salek and Yasuda 2001), thus making the surge arrival time and its duration so critical. This is why the results of Webster et al. (2010) are so important, where they demonstrate an impressive capability to make extended-range probabilistic forecasts of the Ganges and Brahmaputra floods in Bangladesh with a lead
time of up to ten days. New reanalyses by Kikuchi and Wang (2010:475) also offer additional insights and capabilities into the prediction of tropical cyclones in the Bay of Bengal in that

“Over the northern Indian Ocean (NIO), a substantial number (~60%) of tropical cyclones (TCs) form in association with significant intraseasonal oscillation (ISO) events (*i.e.*, Nargis [2008]). …It was found that over 70% of ISO-related genesis is associated with the northward propagating BSISO [Boreal Summer Intraseasonal Oscillation] mode and up to 30% with the eastward propagating MJO [Madden-Julian Oscillation] mode. The BSISO mode primarily affects TC formation in May-June-and September-November, while the MJO mode affects TC formation primarily from November-December…The results imply that monitoring the evolution of the two types of ISO modes, especially the BSISO, may provide a useful medium-range forecast for NIO cyclogenesis.”

**Sea Level and Rainfall Variability in the Ganges-Brahmaputra-Meghna Delta**

Sea level data for Bangladesh are regularly measured at four locations along the Ganges-Brahmaputra-Meghna Delta coastline – Khepupara, Charchanga, Hiron Point, and Cox’s Bazar – and the data are archived from 1977 to 2003 by the Permanent Service for Mean Sea Level (Figure 3). With regard to the Hiron Point station, Mörner (2010b:244) notes

“This tide gauge has a very unstable position on a landing bridge resting on delta clay. Hence any analysis with respect to trends of sea level
changes must be considered unsafe and risky, if not directly misleading.

Furthermore, the record seems to include different factors (cycles, episodes, independent segments, etc) preventing meaningful linear trend analysis.”

Thus, the Hiron Point station will not be considered in further discussion.

Sea level trends at all three stations are increasing with annual rates of 1.48 m, 0.7 m, and 0.27 m at Khepupara, Charchanga, and Cox’s Bazar, respectively. These rates are much greater than the 0.16-0.25 m global sea level rise over the past century as estimated by Chao et al. (2008). However, note that the annual range in sea level variability is 0.8-1.0 m; quite large with respect to the annual rate of increase.

Mörner (2010b:245), however, indicates that estimates of sea level rise are hampered by both the instability of the gauge and the application of trends “over incomplete cycles, signals of different origin, and segments that need independent treatment.” With regard to gauge instability, Mörner (2010b) provides numerous photographs of the Bangladesh coastline to illustrate the existence of strong coastal erosion on the order of 0.8 m in elevation which argues strongly that the erosion rates greatly exceed the sea level rise. Mörner (2010b) even suggests the rate of sea level rise in Bangladesh is negligible with the creation of both erosional and depositional landforms. Mörner (2010a) further discusses the impact of shore morphology and multiple causes of coastal erosion as contaminants to sea level rise determination.

A second issue with trend estimation relates to the statistics of periodicities and data contamination with multiple signals. Mörner (2010a) gives a detailed assessment of the problems that are associated with the statistical determination of trends from sea level
data. This includes the existence of the 18.6 year tidal cycle and how it impacts gauge records. Short temporal analyses, such as the approximate 20 year records shown in Figure 3, are problematic in that data records must extend over several of these cycles to be able to adequately estimate and remove the effect of the well-known 18.6 year tidal cycle to prevent aliasing from affecting estimates of mean sea level rise. Such lunar tidal effects are denoted particularly well by the recent detection of the 18.6 year cycle in clay mineralogy records from the Cariaco Basin (Venezuela). These records have demonstrated the effects of lunar-tidal cycles on coastal and sedimentary processes for at least the past 8 centuries (Black et al. 2009). El Niño and La Niña cycles, in particular, affect estimates of sea level rise along the eastern Indian Ocean can adversely impact reliable analyses.

Considerable climatic variability has been present in this region during and since the Last Glacial Maximum (LGM – circa 22,000 years ago). Rainfall varied considerably causing wild fluctuations in both the summer and winter monsoons (Williams and Clarke 1984; Sarkar et al. 2009) while arid conditions have caused retreat of Himalayan valley glaciers despite a decrease in temperatures by as much as 5°C (Goodbred 2003). Sarkar et al. (2009) further note the dominance and expansion of C4 plants (i.e., plants that utilize the C4 carbon fixation pathway where the first photosynthesized organic compound has 4 carbon atoms) on the exposed low-stand areas of the Ganges-Brahmaputra-Meghna Delta (Galy et al. 2008; Sarkar et al. 2009) as well as the continental interior of the Central Himalayas (Mampuku et al. 2008) during the arid glacial period and low water table conditions of the LGM. Since then, the transition to C3 mangrove vegetation (i.e., vegetation that utilize the C3 carbon fixation pathway
where the first photosynthesized organic compound has only 3 carbon atoms) in the Ganges-Brahmaputra-Meghna Delta region occurred in the early Holocene, which was followed by a further transition from mixed C3 and C4 vegetation biomes during the mid-Holocene to a dominance of C4 vegetation in the late Holocene (i.e., a transition from an even mix of C3 and C4 plants to the present level of 70% C4 plants). Thus, it seems reasonable that the origin of agriculture and the domestication of plants and animals are likely linked to the wetter and more climatically conducive conditions of the early Holocene (Gupta 2004). While we are not suggesting that a warm and wet climate is preferable for Bangladesh, we simply note that an accurate geologic and climatic perspective is necessary for a proper discussion of future climatic trends in Bangladesh.

**Final Discussion**

It is well noted that current conditions in and around Bangladesh are harsh and unforgiving. The adverse impact of natural hazards is commonplace and this only serves to exacerbate the economic and social difficulties that plague the country. It has to be recognized, however, that floods and droughts, storm surges and high winds associated with tropical storms, and other naturally-caused catastrophes have always affected this region. Such variations have occurred despite any possible effects of anthropogenic CO₂ and indeed are likely to occur again in the future, regardless of any steps taken to mitigate the effects of anthropogenic CO₂ emissions.

Thus, the tendency by self-indulged politicians, rent-seeking advocates, and scaremongers in the popular press to downplay the current difficulties present in the climate of Bangladesh and hype future disasters postulated from a rise in global sea levels is clearly
counterproductive for the Bangladeshi citizens. It serves to divert efforts from proper planning, mitigation, and adaptation strategies that are vital to saving lives now. However, the future of Bangladesh is not bleak as attention is paid to helping the Bangladeshi people develop realistic controls on river flow and discharge and provide timely dissemination of warnings of environmental hazards (e.g., cyclones and flooding) while simultaneously protecting the Ganges-Brahmaputra-Meghna Delta landscape and the continued destruction of the mangrove forest ecosystem. Only by properly addressing current problems can Bangladesh be prepared for future changes in the climate, regardless of the source – natural or anthropogenic.

Moreover, one has to recognize that in other tidal wetland systems such as the Kirkpatrick marsh land (Maryland, USA) around the Chesapeake Bay (off the USA Atlantic coast, bounded by Maryland and Virginia), evidence exists that enhanced levels of atmospheric CO\(_2\) may actually stimulate marsh vegetation thereby providing an effective counter to sea level rise and ocean water encroachment. Langley et al. (2009:6182) notes:

“Here, we present experimental evidence that plant response to elevated atmospheric [CO\(_2\)] stimulates biogenic mechanisms of elevation gain in a brackish marsh. Elevated CO\(_2\) (ambient + 340 ppm) accelerated soil elevation gain by 3.9 mm yr\(^{-1}\) in this 2-year field study, an effect mediated by stimulation of below-ground plant productivity. Further, a companion greenhouse experiment revealed that the CO\(_2\) effect was enhanced under salinity and flooding conditions likely to accompany future [sea level rise]. Our results indicate that by stimulating biogenic contribution to marsh
elevation, increases in the greenhouse gas, CO₂, may paradoxically aid some coastal wetlands in counterbalancing rising seas.”

It also is likely that increased CO₂ will enhance vegetation growth in the Ganges-Brahmaputra-Meghna Delta region and help offset rises in sea level, regardless the cause.

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Figure 1: Satellite imagery of the coastline of Bangladesh. White lines denote the border with India and Myanmar. (From Google Maps – http://maps.google.com)
Figure 2: Accumulated Cyclone Energy (ACE) index values for the North Indian Ocean. (Ryan Maue, personal communication)
Figure 3: Tide data (in meters) for four stations along the Ganges-Brahmaputra-Meghna Delta in Bangladesh. (Data from the Permanent Service for Mean Sea Level – http://www.pmsl.org)