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ORIGINAL ARTICLE

Climate change, flooding in South Asia and implications

M. Monirul Qader Mirza

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Abstract South Asia is one of the most flood vulnerable regions in the world. Floods occur often in the region triggered by heavy monsoon precipitation and can cause enormous damages to lives, property, crops and infrastructure. The frequency of extreme floods is on the rise in Bangladesh, India and Pakistan. Past extreme floods fall within the range of climate variability but frequency, magnitude and extent flooding may increase in South Asia in future due to climate change. Flood risk is sensitive to different levels of warming. For example, in Bangladesh, analysis shows that most of the expected changes in flood depth and extent would occur between 0 and 2°C warming. The three major rivers Ganges, Brahmaputra and Meghna/Barak will play similar roles in future flooding regimes as they are doing presently. Increases in future flooding can cause extensive damage to rice crops in the monsoon. This may have implications for food security especially of poor women and children. Floods can also impact public health in the flood plains and in the coastal areas.

Keywords Climate change · Flooding · South Asia · Crop damage · Food security

Introduction

From a hydro-meteorological perspective, South Asia is a very important region in the world. It encompasses many large river systems: Ganges, Brahmaputra, Meghna, Indus, Godavari, Mahanadi and Narmada (Fig. 1). Water availability in this region is driven by monsoons. Two monsoon systems operate in South Asia: the Southwest or summer monsoon and the northwest or winter monsoon. The summer monsoon accounts for 70–80% of the annual rainfall over most of South Asia during June to September, except for Sri Lanka and Maldives where the northeast monsoon is dominant. Apart from the monsoons, the northern part of South Asia receives considerable precipitation from Western disturbances, and in the Southern parts (especially in Sri Lanka), from weather associated with the ITCZ (Inter-Tropical Convergence Zone). The Himalayan Rivers receive water from snow and glacier melt and have continuous flow throughout the year.

Flooding is a regular hazard in South Asia where it causes enormous damages to lives, property, crops and infrastructure. While there is no discernible trend in increase in peak flood discharge in the major rivers in South Asia, damage is on the increase (Mirza et al. 2003). The frequency of extreme floods is also apparently on the rise. Bangladesh experienced five large floods from 1987 to 2007. Frequency of increases in flooding is also evident in India and Pakistan. In addition to this, there is a tendency of expansion of flood-prone areas. For example, in western India where droughts are very frequent, floods are now also occurring frequently. In July 2005, in Gujarat, floods engulfed a large region and killed 132 people (Dartmouth University 2005). Although these events are within the range of climate variability, based on the future climate scenarios from the global climate models (GCMs), scientists are concerned that the frequency, magnitude and extent of flooding may increase in South Asia. In this paper, an attempt is made to quantify these with the aid of hydrologic models. Possible effects of increased flooding

M. M. Q. Mirza (✉)
Adaptation and Impacts Research Section (AIRS),
Environment Canada, Department of Physical and
Environmental Sciences, University of Toronto at Scarborough,
1265 Military Trail, Toronto, ON M1C 1A4, Canada
e-mail: monirul.mirza@ec.gc.ca

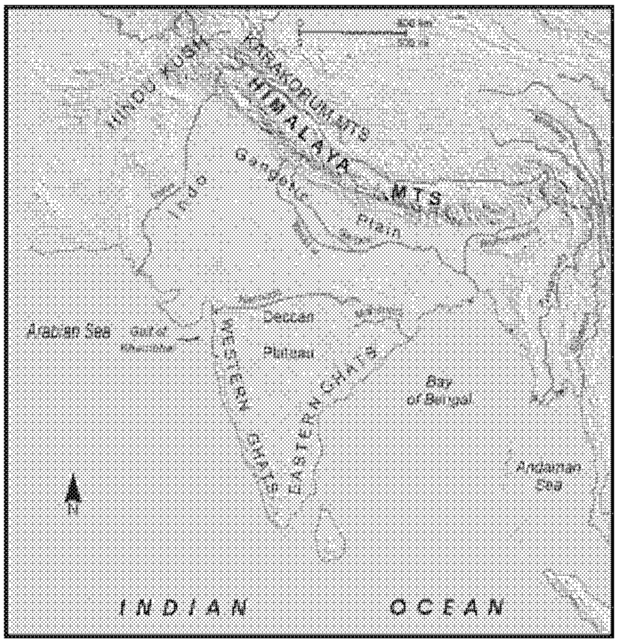

Fig. 1 Major rivers of South Asia

on some economic sectors (food, public health, etc.) are also discussed.

Flood hazard in South Asia

In the monsoon months, flood is a common hazard in South Asia. In Nepal, floods and landslides occur almost every year. In July 1993, Nepal experienced the worst natural disaster on record. Three days of torrential rainfall in central Nepal triggered disastrous landslides and caused debris flows and major flooding in main streams and the Terai plains. Nepal is also vulnerable to Glacier Lake Outburst Floods (GLOFs). In India, $40°10^6$ ha of land are annually vulnerable to floods. The northeastern part of India through which the Brahmaputra river system flows is highly vulnerable to flooding. Uttar Pradesh, Bihar and West Bengal states in the Ganges basin are also regularly flooded. The eastern coast of India is vulnerable to storm surge flooding. On July 26, 2005 the India's financial capital Mumbai received a record 944 mm of rain in 1 day (Kumar et al. 2008), causing severe urban flooding that affected daily lives of millions people with 405 casualties. In August 2008, the Koshi River, which originates in Nepal, broke through a flood control embankment in the State of Bihar in eastern India. Flood waters engulfed hundreds of villages in the state and displaced over three million people (Action Aid 2008). The downstream delta in Bangladesh, which drains vast areas of the Ganges, Brahmaputra and Meghna rivers, is always at risk of flooding. Bangladesh experienced five large floods in 1987, 1988, 1998 and 2004, 2007 over about a 20-year period. The human and economic damage caused by these floods were also very high. The south and southeastern coasts of Bangladesh often experience flooding from storm surges. The most recent devastating flood occurred in November 2007. The category 4 cyclone Sidr hit the Bangladesh coast, affecting 8.7 million people and claimed 3,295 lives (United Nations 2007). Previously, in April 1991, another disastrous cyclone claimed 138,000 lives and also shattered the coastal social and economic structure. In Sri Lanka, floods are not very common. However, in 2003, Sri Lanka experienced the worst flooding in more than half a century, which left a trail of destruction and claimed 150 lives. Floods are also recognized as a major natural calamity in Pakistan. In June 2007, the tropical cyclone Yemyin hit the coastal area of Pakistan in Sindh and Baluchistan provinces. The cyclone dumped huge rains that caused severe flooding, affecting about 2.5 million people and claimed 330 lives. Human lives lost in floods in Bangladesh, India and Nepal from 1953 to 2007 are shown in Table 1.

Causes of floods in South Asia

Mirza (2003) grouped the causes of floods with particular reference to Bangladesh (Fig. 2). However, these causes are also common in the wider South Asia context. They are the following: common causes (precipitation, snow melt, etc.), continental (El Niño Southern Oscillation, ENSO) and acceleratory factors (e.g., infrastructure, backwater effect, synchronization of flood peaks, siltation of rivers and channels and deforestation). Among these causes, precipitation is by far the most important factor in causing floods in the countries of South Asia which is under high influence of the monsoon weather system. Southwest monsoon dominates the South Asian climate from June to September. More than 80% of the rainfall occurs during the monsoon months. River basins in South Asia experience intensive rainfall in July and August when most of floods occur. However, there are spatial differences in rainfall. The highest rainfall occurs in the eastern India, eastern Gangetic basin in India, northeast of Bangladesh, Bhutan and in the Terai region of Nepal. The distribution of precipitation in the Ganges, Brahmaputra and Meghna/Barak basins is shown in Table 2.

The continental factor ENSO phenomenon has strong relationships with monsoon rainfall and flooding situation in the Indian subcontinent (Chowdhury 2003; Mirza 2003; Chowdhury and Ward 2004). In the Ganges, Brahmaputra and Meghna (GBM) basins, rainfall shows a strong connection to the Southern Oscillation Index (SOI) extremes. In the negative phase of the SOI, the entire basin experiences less than normal rainfall, while during a positive SOI

Table 1 Number of deaths due to floods in India, Bangladesh and Nepal during the period 1953–2007

Year	India	Bangladesh	Nepal
1953	37		
1954	279	112	60
1955	865	129	
1956	462		
1957	352		
1958	389		
1959	619		
1960	510		
1961	1374		
1962	348	117	
1963	432	30	
1964	690		
1965	79		
1966	180	39	
1967	355		
1968	3497	221	276
1969	1408		
1970	1076	87	350
1971	994	120	
1972	544	50	
1973	1349	427	
1974	387	1987	
1975	686		
1976	1373	103	
1977	11316	13	
1978	3396	17	130
1979	3637		
1980	1913	655	
1981	1376		750
1982	1573		92
1983	238	245	186
1984	1661	1200	200
1985	1804	300	46
1986	1200	150	22
1987	1835	3680	358
1988	2050	2379	27
1989	1097	180	
1990	203	231	25
1991	1024	450	51
1992	572	15	
1993	1862	366	2307
1994	2845	43	
1995	1479	900	140
1996	1506	55	768
1997	2526	179	
1998	2131	1050	311
1999	500	48	170
2000	2159	100	144
2001	216	9	
2002	732	10	472
2003	235	252	
2004	1138	730	
2005	1202		
2007	2827	3944	

Source Updated from Mirza et al. (2001), http://www.mapreport.com and UN (2007)

phase (both in strong and moderate La Nina years), the GBM basins experience severe flooding due to significant increase in rainfall (Chowdhury 2003) (Fig. 3). However, Chowdhury (2003) identified a unique feature of rainfall within Bangladesh during a moderate ENSO year when it is significantly different from the GBM basin areas located in upstream India. The Ganges and Brahmaputra basins experience +13.6 to 20.4% increases in rainfall, respectively, while rainfall in the Meghna basin decreases by 4%.

Mirza (2003) analyzed three recent large floods that occurred in Bangladesh in 1987, 1988 and 1998 with particular reference to ENSO. From September 1987 onwards, the central equatorial pacific began retreating from the warming phase to the colder phase and entered into the colder phase in March 1988. By July, the La Niña phase began and continued until December 1988. Due to this phenomenon, heavy monsoon rainfall occurred in the upper basin areas in India and caused heavy flooding in downstream Bangladesh. In 1998, a La Niña event similar to that of 1988 brought huge rains to the region and was the main cause of floods in Bangladesh (Mirza 2003) (Fig. 3). In 1998, part of the Ganges basin in India experienced higher rainfall than normal in Bihar Plateau, Bihar Plain, East Uttar Pradesh and West Uttar Pradesh from late August to the middle of September. The external contribution to the flood discharge of the Ganges River in Bangladesh came from Bihar (including Nepal) and Uttar Pradesh. Upstream of the Brahmaputra basin in India, high rainfall was concentrated in the North Assam meteorological subdivision and a significant departure is noticeable (Fig. 5). For 1998, Dhar and Nandargi (2003) reported 14 flooding events at Dhubri gauging site in Assam. Rainfall distribution (excess or deficit compared to normal) is shown in Figs. 4, 5.

Singh and Dash (2004) analyzed atmospheric features in relation to Indian summer monsoon in ENSO years. During ENSO years with deficient rainfall, they identified major centers of positive divergence anomalies and negative anomalies over the central and East Pacific and Indian Ocean and West Pacific, respectively. Droughts that often occur during ENSO years could be related to the

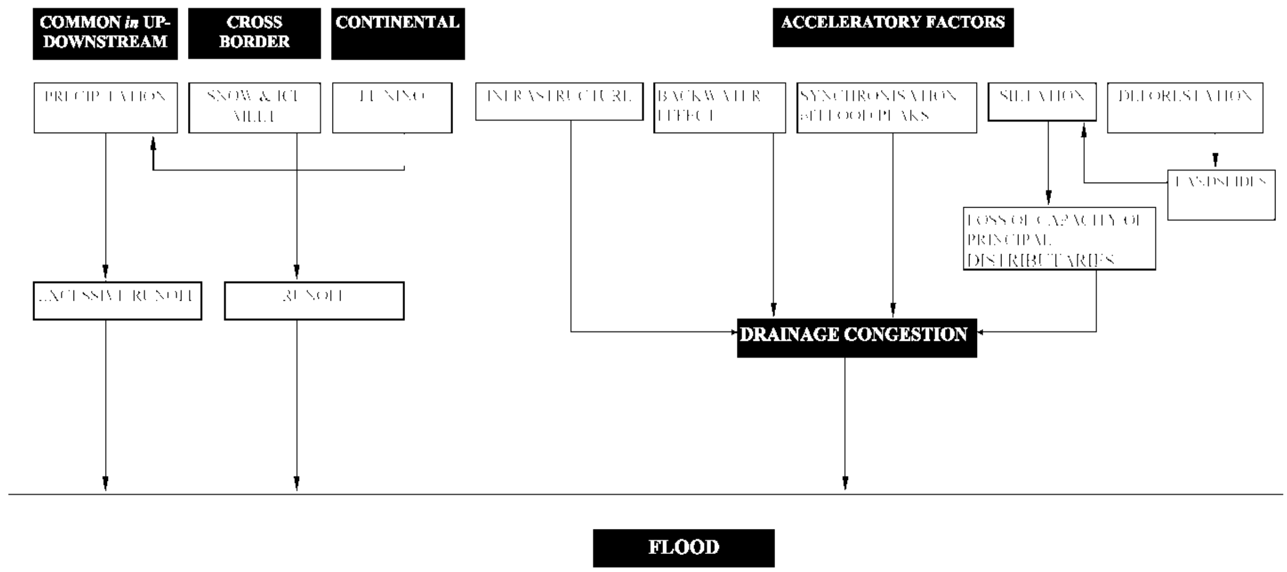

Fig. 2 Causes of floods in South Asia (modified from Mirza 2003)

Table 2 Precipitation in the Ganges, Brahmaputra and Meghna/Barak basins

Basin	Country	Mean annual precipitation (mm)
Ganges	India	450–2000
	Bangladesh	1568
	Nepal	1860
Brahmaputra	India	2500
	Bangladesh	2400
	China (Tibet)	400–500
	Bhutan	500–5000
Meghna/Barak	India	2640
	Bangladesh	3574

Source Mirza (1998)

southeastward shift of divergent circulation in response to warm sea surface temperature (SST) anomalies. Omega fields at 500 hPa show ascending motion over central and eastern Pacific and descending motion over India in the drought years.

Climate change and atmospheric features

Relatively small climate change can cause large problems in the flood vulnerable areas in South Asia. Mirza (2007) discussed extreme weather (including floods) variables reported in the IPCC Fourth Assessment Report (Table 3). Climate change can affect a large number of physical and atmospheric variables that are associated with flooding in South Asia.

First, the onset and departure dates of monsoon may be shifted. Presently, the monsoon arrives in the Kerala coast of India on June 1 and the retreat begins in early September. The onset date over Kerala has a standard deviation of about 7 days. With a slow northward movement along the western coast and northwestwards across central India, the monsoon covers the whole India by 15th July. During the last 50 years, the earliest monsoon onset over Kerala was on 14th May in 1960 and the most delayed onset was on 18 June in 1972. In future, there is a possibility of enhanced variability in the date of onset of summer monsoon in a warmer atmosphere.

Second, there is a possibility of changes in extreme rainfall. Cruz et al. (2007) projected an increase in extreme precipitation over the South Asia Region, consistent with projections since the early 1990s. Climate model experiments suggest that rainfall intensity and number of wet spells are likely to increase with increases in greenhouse gas concentrations (McGuffie et al. 1999). Gordon et al. (1992) and Whetton et al. (1993) indicate that global warming may produce changes in the frequency of intense rainfall because of possible changes in the paths and intensities of depressions and storms, and possible increases in convective activity. Lal et al. (2000) found that there is also an increase in intra-seasonal precipitation variability and that both intra-seasonal and inter-annual increase are associated with increased intra-seasonal convective activity during the summer in South Asia. However, current GCMs lack accuracy at smaller resolutions (regional and sub-regional) and therefore involve high uncertainties in projecting local weather extremes (Kattenberg et al. 1996). Recently, scenarios from the high resolution HadRM2 model show regional variations in rainy day intensity in India. The model projects an overall increase in the rainy day intensity by 1–4 mm day^{-1}, except for small areas in

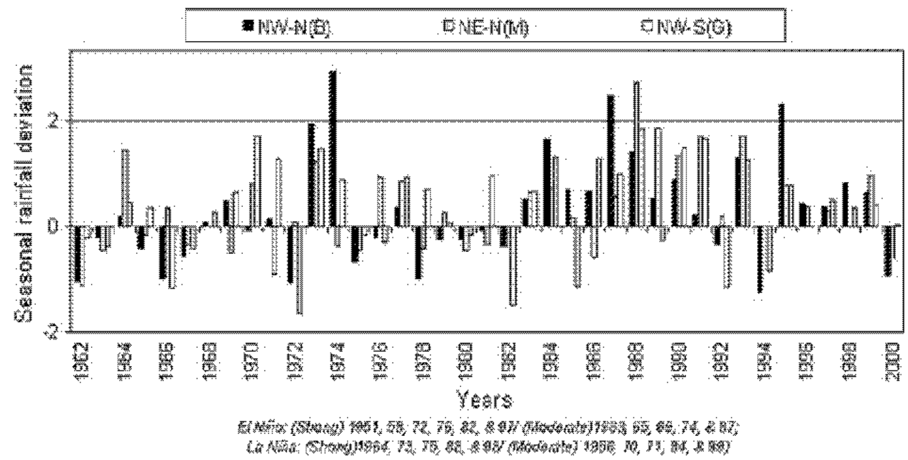

Fig. 3 Year–year standardized deviation of seasonal (JJAS) rainfall in the GBM basins in India during 1950–1998 (Chowdhury 2003). *NW-N(B)* Brahmaputra; *NE-N(M)* Meghna; and *NW-S(G)* Ganges. Data (2.5 × 2.5° gridded data) *Source* Climatic Research Unit (CRU), University of East Anglia. Data from 2001 are not available

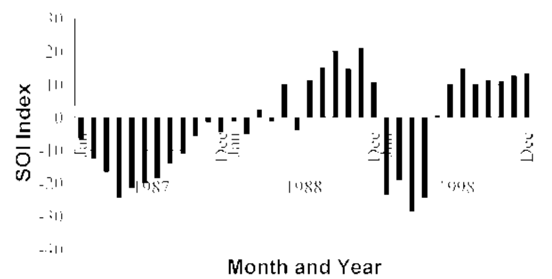

Fig. 4 The southern oscillation index (SOI) for 1987, 1988 and 1998 (Mirza 2003)

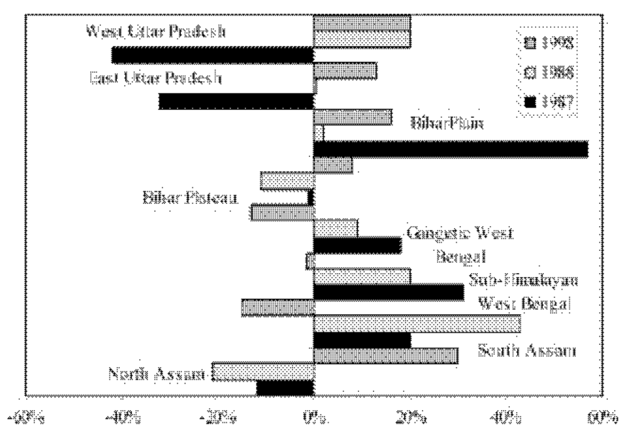

Fig. 5 Deviations (%) of rainfall from normal in some meteorological subdivisions in the GBM basins in India (Mirza 2003)

northwestern India, where the rainfall intensities may decrease by 1 mm day^{-1}. The model results also indicate that there will be an overall increase in the highest one-day rainfall over a major part of the Indian region. This increase could be as high as 20 cm day^{-1} (Government of India 2004). Intense rain occurring over fewer days implies increased frequency of floods during the monsoon (Cruz et al. 2007).

Third, climate change may affect the frequency and intensity of cyclones and consequent flooding in the Arabian Sea, Indian Ocean and the Bay of Bengal region (AIB). Eastern parts of India and the south and southeastern coastal districts are highly vulnerable to cyclonic storms and associated storm surge flooding. Srivastava et al. (2000) examined the cyclone data for India for the period of 1891–1997 and found a significant decrease (at 99% confidence level) in the frequency of cyclones. They also found the steepest decrease from 1960 to 2000. Lal (2001) found a significant increase in cyclone intensity in the AIB region. His findings are supported by recent findings from other regions of the world.

Climate change and flooding in South Asia

Climate change scenarios

Most climate models estimate that precipitation will increase during the summer because the air over land will warm more than air over oceans in the summer, resulting in an intense monsoon. The critical aspect of climate change in Bangladesh is possible changes in monsoon precipitation which drives the country to water-related disasters. Agrawala et al. (2003a) noted that the estimated increase in summer precipitation appears to be significant, larger than the standard deviation across models. With the aid of ECHAM4 and HadCM3 models, Kumar et al. (2003) constructed precipitation scenarios for 30-year time slices centered around the 2030, 2050 and 2080 s relative to the 1960–1990 climatology for India. The simulations show an increase in the rainfall over a large area of land and ocean, which covers the core monsoon region. The two models show an increase exceeding 50% over a large area. In other areas, changes are expected to be in the range of 0–25%. For Nepal, climate models also show an overall increase in annual precipitation with high standard deviation. The high standard deviations may be due to limitations inherent in the climate models, which are still not efficient enough to simulate precipitation in the mountainous regions.

Table 3 Extreme weather (including floods)-related variables reported in the IPCC AR4

Climate and atmospheric systems	Terrestrial systems	Economic and social systems	Vulnerability and adaptation	Mitigation and stabilization
Extreme temperature	High and low flows	Anthropogenic pressure	Risk and its perceptions	Mitigation of greenhouse gases
Total precipitation	Water levels-Water storage	Multiple stressors (e.g., economic globalization)	Degree of exposure	Stabilization scenarios
Intensity and duration of precipitation	Infiltration capacity	Water related diseases and public health	Adaptation practices	
Wind speed (hurricanes/cyclones/typhoons)	Water quality	Income and public health	Coping capacity	
ENSO	Flow variability and impacts on ecosystems	Insurance and other policy incentives	Adaptive capacity	
Sea level rise	Erosion and sedimentation	Gender and social classes	Governance	
Storm surge heights		Environmental refugees	Mainstreaming	
			Opportunities and constraints	

Source Mirza (2007)

Therefore, the results for annual precipitation were advised to be interpreted with caution (Agrawala et al. 2003b). In terms of seasonal precipitation, precipitation in the summer monsoon months are expected to be more pronounced than the winter months. Generally, climate models are in agreement on increases in precipitation across South Asia.

Impacts on future flooding

In this paper, climate change impacts on future flooding are reported for India and Bangladesh who share many river basins. Note that the climate change impacts on future flooding for other countries of South Asia have not been investigated in similar depth.

India

Gosain and Rao (2003) investigated impacts of climate change on flooding in the Mahanadi and Brahmani river basins in India. They constructed climate scenarios for 2041–2060 from the HadRM2 model for the IS92a scenarios and then applied the scenarios in the SWAT (Soil Water Assessment Tool) distributed hydrologic model. The vulnerability assessment to flooding was conducted using the daily outflow discharge from four sub-basins. Maximum daily peak discharge was identified for each year and for each sub-basin. Table 4 shows the number of years where the flood will likely to exceed the two arbitrary fixed thresholds for two of the sample sub basins for each of the river basins, respectively. It demonstrates the possibility of a substantial increase in the incidences of flooding.

Bangladesh

The geographical location of Bangladesh (Fig. 6) in the Ganges, Brahmaputra and Meghna (GBM) basins has made it special in terms of extreme hydrological events. Bangladesh drains out approximately 92.5% of the water that is generated in the GBM basins (an area of 175°10^6 ha). Mirza et al. (2003) investigated impacts of climate change on the magnitude, extent and depth of flooding in Bangladesh. A sequence of empirical models and the MIKE11-GIS hydrodynamic model were used. Climate scenarios were constructed from the results of four climate models: CSIRO9, UKTR, GFDL and LLNL. Changes in

Table 4 Events exceeding arbitrary thresholds in Mahanadi and Brahmani basins

Discharge (m^3/s)	Control (1961–1990)	Climate change (2041–2060)	Control	Climate change
Mahanadi Sub basins	Sub15	Sub15	Sub 21	Sub21
Discharge > 20,000	2	4	9	13
Discharge > 30,000	0	0	1	7
Brahmani Sub-basins	Sub9	Sub9	Sub16	Sub16
Discharge > 10,000	6	9	0	4
Discharge > 15,000	0	6	0	1

Source Gosain and Rao (2003)

magnitude, depth and extent of flood vary considerably between the GCMs.

The MIKE11-GIS model results show that the current mean flooded area is 3.77×10^6 ha based on the mean discharge of 52,680, 64,866 and 14,060 $m^3 s^{-1}$ for the Ganges, Brahmaputra and the Meghna Rivers, respectively, together with local rainfall in the river basins. The mean flooded area produced by the MIKE11-GIS model seems to be very reasonable in relation to observational records.

With regard to the mean flooded area, the model results indicate three main outcomes:

- the largest change in flooded area occurs between 0 and 2°C changes in global mean temperature (for the modeling purpose, standardized precipitation scenarios were developed with respect to per degree change in global mean temperature change. The simulated change in climate at a grid point between the GCM control and $2 \times CO_2$ simulations is divided by the respective GCM's model sensitivity global to produce a standardized value.) (For details, see Hulme et al. 2001);
- there is a clear difference in flooded area outcomes from the UKTR and GFDL models when compared with the CSIRO9 and LLNL models; and
- the Brahmaputra and Meghna Rivers will play a major role in future flooding.

Surprisingly, the model results indicate that most changes in the mean flooded areas occur between 0 and 2°C in relation to the increases in the peak discharges of the Ganges, Brahmaputra and Meghna Rivers (Table 5; Fig. 7) rather than at higher temperature increases. In the range of 0–2, 2–4 and 4–6°C increases in temperature, increases in flooded area for per degree warming is $0.44–0.55 \times 10^6$, $0.015–0.09 \times 10^6$ and $0.015–0.075 \times 10^6$ ha, respectively. In general, increases in peak discharge between 0 and 2°C will engulf most of the flood vulnerable areas. Therefore, at higher temperature increases, proportionate increases in discharge will not be able to increase the spatial extent of flooding as it will possibly be limited by the elevation of the lands. There is a clear distinction between the outputs from the UKTR and GFDL models and those from the CSIRO9 and LLNL models. The former two models show greater discharge, and thereby higher flooded area, than the latter (Table 5).

Table 5 Area (in million ha) inundated under 2, 4 and 6°C temperature increases for the four GCMs

Model	Mean				20-year			
	0°C	2°C	4°C	6°C	0°C	2°C	4°C	6°C
CSIRO9	3.77	4.65	4.68	4.71	5.18	5.18	5.20	5.22
UKTR	3.77	4.87	5.08	5.24	5.18	5.35	5.50	5.61
GFDL	3.77	4.84	5.02	5.17	5.18	5.33	5.36	5.48
LLNL	3.77	4.68	4.73	4.78	5.18	5.20	5.25	5.29

Although there is little difference in results between the UKTR and GFDL models, the UKTR model gives the largest increases in the mean peak discharge for 2, 4 and 6°C temperature changes. Consequently, the MIKE11-GIS model yields the highest changes in the mean flooded area for the UKTR model. For a 2°C temperature increase, the expected change in the mean flooded area is +29%. This is perhaps caused by higher increases in the peak discharge of the Ganges River. This helps increase the flooded area in the Brahmaputra basin by slowing down drainage of its water at Baruria Transit. The change is expected to be +39% for a 6°C temperature rise. For the GFDL model, the changes are 28 and 37% in the flooded area, respectively.

The third point to emerge from the analysis of flooded areas is that the Brahmaputra and Meghna peak discharges play a major role in flooding. The role of the Ganges River in flooding is somewhat catalytic. The peak discharge of the Ganges slows down the drainage of the Brahmaputra River through the Baruria transit. This helps to increase the areal extent, depth and duration of flood in the Brahmaputra basin because the Brahmaputra water cannot be drained out quickly. Further downstream in Chandpur, the combined flow of the Ganges and Brahmaputra obstructs drainage from the Meghna basin. This phenomenon creates problems in the Meghna basin similar to those of the Brahmaputra.

Effects on the economic sectors in Bangladesh

Floods cause considerable damage in South Asia and four main economic sectors, agriculture, housing, industry and transportation infrastructure are particularly vulnerable. In this chapter, Bangladesh is being considered as a case study. The loss caused by floods in Bangladesh in a normal year is about US$ 175 million. In extreme cases, the damage may exceed two billion dollars, as estimated during the 1998 flood when more than 70% of the country went under water. In 2007, Bangladesh was hit by successive riverine and storm surge floods. Estimated loss from the riverine flood was $1.4 billion. The floods also caused food loss of 1.2×10^6 t which put the country into a state of severe food insecurity. Flood-related damage puts considerable strain on the economy of Bangladesh. This is particularly true in terms of diversion of resources to recovery activities and the loss in growth of gross domestic products (GDP). For example, during the 2007/2008 fiscal year in Bangladesh, GDP growth declined to 6.1% from 6.4% of the previous year due to the devastating floods and cyclones. Larger GDP losses were registered during flood

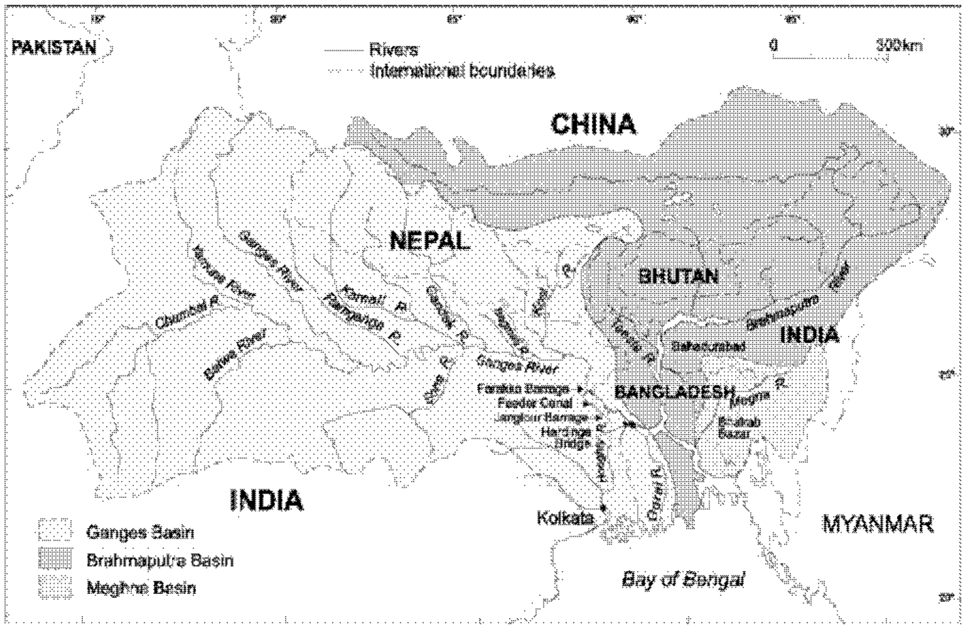

Fig. 6 The boundary of the Ganges, Brahmaputra and Meghna basins used for the flood modeling (Mirza 2003)

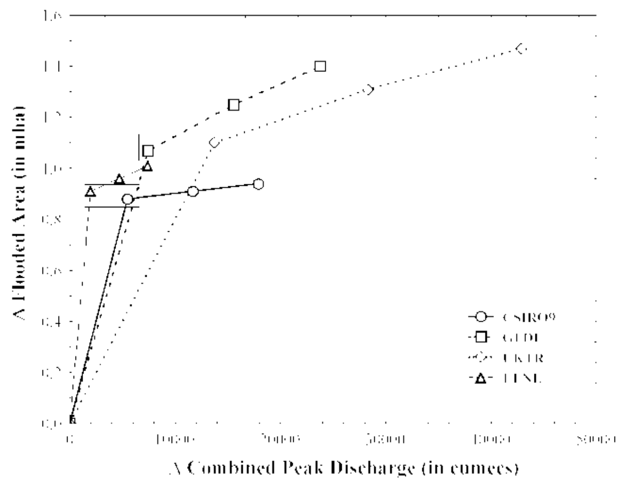

Fig. 7 Changes in the combined mean discharges of the Ganges, Brahmaputra and Meghna Rivers (under control and climate change scenarios) and the mean flooded areas. Values within boxes indicate changes for a 2°C rise in global mean temperature

years of 1974, 1987, 1988 and 1998. Reduced GDP growth due to floods from 1973–2008 is shown in Fig. 8.

Flooding and crop damage

Bangladesh is a highly populated country with a present population of 140 million over only 148,000 km^2 area. Arable lands are around 9°10^6 ha or 61% of the country. Present cropping intensity is 182%, which is a substantial increase from 150% in the early 1980s (MOA 2007). Bangladesh's economy is highly agrarian, with agriculture contributing 50–60% to the national GDP during 1970–1980s. Over the years, this contribution declined gradually as the country adopted industry and services sector-based development strategies for rapid economic growth. The agriculture sector is still the single most important economic sectors contributing about 23.5% to

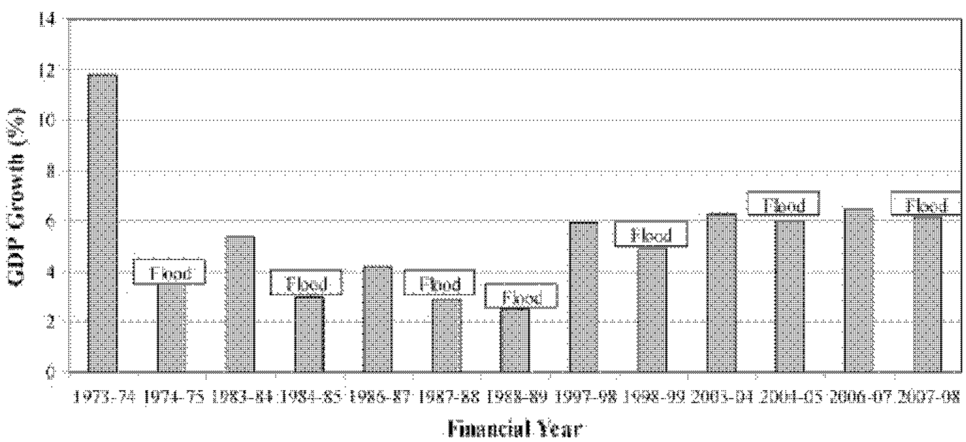

Fig. 8 Floods in Bangladesh and loss in GDP (%)

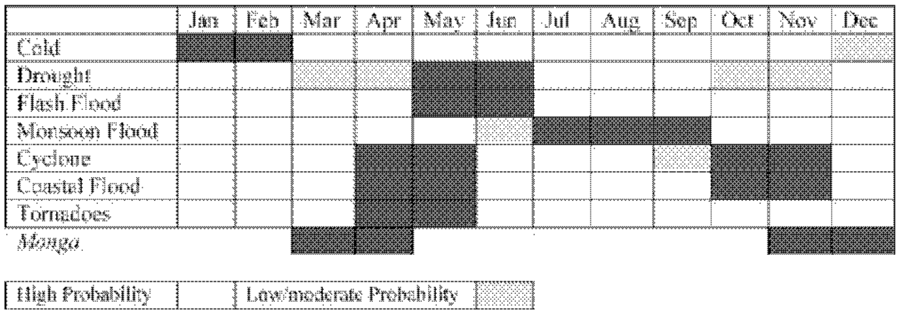

Fig. 9 Natural hazards calendar of Bangladesh

Table 6 Damage potentials of rice in flood waters at different growth stages

Crop growth stages	Clear water				Muddy water			
	Days of submergence							
	3	7	10	15	3	7	10	15
	Percent yield reduction							
10 days after transplant (DAT)	10	15	20	30	25	45	50	60–70
Maximum Tillering	10	15	25	40	25	45	55	70–90
Panicle initiation	0	0	30	40	15	15	60	70–90
Heading	0	0	30	40	15	15	60	70–90
Early grain filling	0	0	30	40	20	20	60	70–90
Maturity	0	25	40	40	15	15	70	70–100

Source Bangladesh Agricultural Research Council (pers. communication 2004 with Dr S.G. Hussain, BARC, Dhaka, Bangladesh)

the national GDP and constitutes more than 60% of the rural employment. The crop sector has the largest share in agriculture and food grain (rice and wheat) claims about 80% share of total acreage and 75% share in total gross value production (Sahabuddin 2000).

In Bangladesh, there are two main cropping seasons (*kharif* and *rabi*) and three-growing seasons (*aus*, *aman* and *boro*). The *kharif* season coincides with the rainy season and the *rabi* season with the dry season. Both seasons can be divided into two parts: *Kharif-I* includes the pre-monsoon season and most of the monsoon while *kharif-II* includes the later part of the monsoon and post-monsoon time. The *rabi* season includes the cool winter period when dry season crops (such as wheat) are grown, and a second part, which includes the hot pre-monsoon, during which *boro* paddy is grown (Fig. 9).

Crops in Bangladesh are susceptible to climate variability and extremes. Usually, crop damage occurs due to high rainfall induced flooding, flash foods, riverine flooding and moisture stress during a drought. *Aman* rice crop that is planted in the monsoon is very much more vulnerable to flood waters. However, the magnitude of the damage is dependent on various growth stages and the magnitude of flood levels, duration and condition of flood waters (clear or muddy) (Table 6). It is seen that the muddy waters can substantially increase damage potentials. Rivers in Bangladesh carry a huge amount of sediments from the upstream areas during the flood season and usually the state of flood water is so muddy that it destroys rice and other monsoon crops. Mustafi and Azad (2003) assessed crop loss caused by the devastating floods in 1998. They carried out a survey in 9 districts in Bangladesh which include: Chapai Nawabgonj, Rajshahi, Narsinghdi, Sirajgonj, Gazipur, Chandpur, Tangail, Comilla and Kishoregonj. They found that long duration and depth of floods destroyed the crops (Table 7). Crops are also damaged by droughts, cyclones and associated surges and hailstorms.

In a warmer climate in future, crop yields in Bangladesh could be affected by increases in temperature, dryness of soil, increased flooding (magnitude, depth, extent and duration), pest infestation and CO_2 fertilization. Based on

Table 7 Extent of duration and depth of flooding in selected districts in Bangladesh in 1998

Districts	Date of flood initiation	Date of receding	Duration (days)	Water depth (meter)
Chapai Nawabgonj	29 July	24 October	87	6.4
Rajshahi	21 July	5 October	75	6.1
Narshingdi	28 June	21 September	79	6.2
Sirajgonj	1 July	12 September	72	4.9
Gazipur	9 July	25 September	78	4.7
Chandpur	24 June	15 September	84	5.2
Comilla	14 July	20 September	66	4.5
Tangail	14 July	24 September	71	4.9
Kishoregonj	20 July	10 September	51	4.2

Source Mustafi and Azad (2003)

Table 8 Estimated crop damage for future 20-year flood under various warming scenarios

GCM	ΔT	Future mean flood (m^3/s)			Combined discharge (m^3/s)	Estimated crop damage (×1000 tons)
		Ganges	Brahmaputra	Meghna		
CSIRO9	2	57790	64853	15171	137814	634
	4	62900	64840	16267	144007	785
	6	68010	64827	17378	150215	935
HadCM2	2	50963	70308	16017	137288	621
	4	49240	75757	17971	142968	759
	6	47523	81199	19927	148649	897
GFDL	2	55419	67487	16844	139750	681
	4	58159	70107	19614	147880	879
	6	60898	72728	22412	156038	1077
LLNL	2	52996	65385	15958	134339	550
	4	53312	65904	17842	137058	616
	6	53628	66423	19740	139791	682

Source Mirza (1998) and Mirza et al. (2003)

results from the experimental plots in the International Rice Research Institute (IRRI), Manila, the Philippines, Peng et al. (2004) reported that in the dry season, grain yield reduces by 10% for each degree increase in nighttime temperature. Karim et al. (1996; 1998) investigated the impacts of various levels of CO_2 concentrations and temperature change on rice and wheat yields in Bangladesh. They also considered the case of moisture stress, sea level rise and salinity effects. Although temperature (2°C), moisture stress (30%), sea level rise and salinity all have negative impacts on yield, CO_2 fertilization showed a net +5% compensatory effect by 2030. However, by 2050, the higher CO_2 fertilization effect will not be able to compensate for the negative effects of higher temperature (4°C), moisture stress, sea level rise and salinity intrusion, with a possible 8% overall yield reduction. Note that these studies did not consider flood-related inundation scenarios.

Mirza (2003) developed an empirical relationship between flood discharge of the Ganges, Brahmaputra and Meghna rivers and annual crop damage in Bangladesh, which explained about 65% of the variations. For a current mean flood, crop damage in Bangladesh is estimated to be at 0.48×10^6 t. Note that there are other factors, which affect crop damage, but the relationship was found to be useful. The empirical relationship has also been used to estimate future crop damage due to changes in mean floods under various warming scenarios. The estimated flood discharge for the three rivers and corresponding estimated crop damage is shown in Table 8. The highest crop damage is expected for the GFDL model, followed next by the CSIRO9 model. The lowest crop damage is estimated for the LLNL GCM. The crop damage was found to be proportional to future inundated area. Note that crop damage may be significantly increase by floods of higher return periods. For example, Mirza (2003) reported 2.6–2.9 times higher crop damage for 20-year floods.

Under a 2°C temperature increase, Bangladesh's overall crop production may remain the same as the base period (1990–1991), due to the expected positive effects of CO_2 fertilization. However, there are uncertainties such as the availability of adequate water in the rivers in the dry season, magnitude of soil stress, extreme floods, irrigation efficiency and upstream water uses. The food deficit in Bangladesh will certainly increase as a result of increases in population and income. Assuming 175 million population in 2030, and 0.47 kg grain consumption person^{-1} day^{-1}, annual grain requirement will increase to 30×10^6 t, implying a 0.25×10^6 t deficit at 2007/2008 production level without considering losses from natural hazards and other causes. According to one estimate (Gill 2003), grain production should increase at a rate of 3% when compared to the current 2%. Beyond 2050, Bangladesh will experience a larger deficit which will result from climate change and population growth.

Food security in Bangladesh

In developing countries, food security of the poor is highly dependent on employment, wage, number of earners in the family, their buying capacity, family size, food supply in the market, inflation rate, market control mechanisms, government policy toward the agriculture system, social and family equity, climate variability and extremes, etc. In Bangladesh, around half of the population live below the upper poverty line (2,122 kcal day^{-1}) and a third below the lower poverty line (1,805 kcal day^{-1}). Although food consumption among the poor is increasing, under malnutrition indicators remain alarmingly high, and the rich–poor gap is growing. The most vulnerable are women and girls (intra-household discrimination) and those who live in areas vulnerable to climatic shock (Gill 2003).

There are two seasonal dimensions to food insecurity. The first is the high exposure to climatic shock at certain times of year, as shown in Fig. 9. The other arises from the cycle of food production and consequent seasonal variation in food availability and prices. There are two lean seasons, March–April and October–November. Locally known as '*Monga*' (near famine situation), the second season is particularly severe for the rural landless in the northern Bangladesh, when food stocks run out and job opportunities lay absent until the main *aman* rice harvest in December. It is very difficult for the millions of poor in this area to survive during this period. Both Government of Bangladesh (GOB) and Non-Governmental Organizations (NGOs) have adopted emergency measures to provide relief assistance in the *monga* stricken areas. But it is widely alleged that the support is not adequate. According to the GOB information, at least eight hundred thousand households in this area are now receiving supply of food grains under the VGF (Vulnerable Group Feeding) program. In addition to this program, expansion in irrigation and hence winter rice production has reduced intra-year variation in rice production and therefore prices, and this has lowered the vulnerability of the poor to seasonal price fluctuation in rice (Gill 2003).

Climate variability, change and extremes can certainly create food insecurity among the poor in Bangladesh. Bangladesh's success with poverty reduction is encouraging which reduced from 74% in 1974 to 40% in 2005. However, at the current rate, complete alleviation of poverty may take five more decades unless governance, corruption and equity situations are drastically improved. Natural hazards will remain a big challenge as the frequency and magnitude of climate-related hazards may increase in future. The country will have to divert resources from social sectors to disaster management which will eventually reduce the pace of poverty reduction. A large number of people may be displaced in the coastal districts by sea level rise and which could make the poverty situation worse.

Floods and public health

Floods affect public health in South Asia. The downstream area of the Ganges, Brahmaputra and Meghna basins used to be severely affected by cholera during flood and drought seasons. Miller et al. (1982) noted that since the early times, climatic variables such as rainfall were used to explain cholera patterns. Floods and droughts can affect not only the concentration of the bacterium in the environment, but its survival through the effect of salinity, pH or nutrient concentrations, as well as human exposure to pathogens, sanitary conditions and susceptibility to disease. Changes in the patterns of monsoon winds have coincided with summer plankton blooms and the occurrence of cholera in Bangladesh. It appears that cholera can increase with an increase in ocean surface temperature, a fundamental characteristic of climate change. Pascual et al. (2002) argued that additional knowledge on the ecology of the pathogen was required to unravel the causal pathways linking climate to disease prevalence.

Most of the diseases such as diarrhea, dysentery and dengue prevalent in the flood season are water related. People are infected by the pathogens either through drinking polluted water or contact. In the rural areas, hand tube wells get drowned during an extreme flood. Then the only water source is the flood water. Due to lack of fuel wood, flood water cannot always be purified by boiling. However, only a limited supply of water purifying tablets is available to the flood-affected people. Diarrhea-affected people are treated with oral saline so that they do not die from dehydration. Despite these efforts, diarrhea remains as the single largest killer in a flood event. Poor, women and children are major victim of flood water–related diseases in South Asia.

Displacement of large coastal populations will have an impact on public health in terms of increased distribution of diseases, fatalities and ill health. A 45 cm rise in sea level would inundate approximately 11% of Bangladesh. Rises in sea level combined with other likely outcomes of climate change and variability—increased riverine flooding, increasingly severe cyclones in the region together with deadly storm surges—will likely affect sewage systems, water supply, waste water disposal and the structural integrity of buildings and other structures. In addition to the localized health impacts of such changes, sea level rise could also lead to "climate refugees", pushing those refugees to other regions of Bangladesh.

Concluding remarks

It is highly likely that the frequency, magnitude and extent of flooding will increase in South Asia in a warmer climate. Vulnerability will increase in river basins which are already vulnerable to floods. As a result, the likelihood of damage to lives, property, crop agriculture and infrastructure will also increase. Analysis from the Bangladesh data shows that most of the changes in extent and depth of flooding will occur between 0 and 2°C global mean temperature changes. Therefore, with respect to flooding, a 2°C rise in global mean temperature (from 1990 level) could be termed "dangerous climate change" for Bangladesh in particular and South Asia in general. Although the scenarios used in the modeling studies now are several years old, new SRES-based scenarios are broadly in agreement with the direction and magnitude of changes in temperature and precipitation in South Asia (for details see Lal 2005). However, it is nevertheless necessary to conduct modeling experiments with the new scenarios.

Increased flooding will have cascading effects on the lives of millions of people and economy of the South Asian countries. Flood losses will likely increase many times due to increases in wealth, expansion of human settlements and increased risk of flooding. Although food security is a complex issue to address, unless crop yields are increased, per capita food availability will decrease, posing a threat to millions of poor people especially to women and children. Public health will also likely to be impacted in the flood plains and in the coastal areas. Formulation and implementation of adaptation measures in a coordinated fashion are necessary for the South Asian countries because most of them share large river basins.

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