# EXTENDED-RANGE PROBABILISTIC FORECASTS OF GANGES AND BRAHMAPUTRA FLOODS IN BANGLADESH

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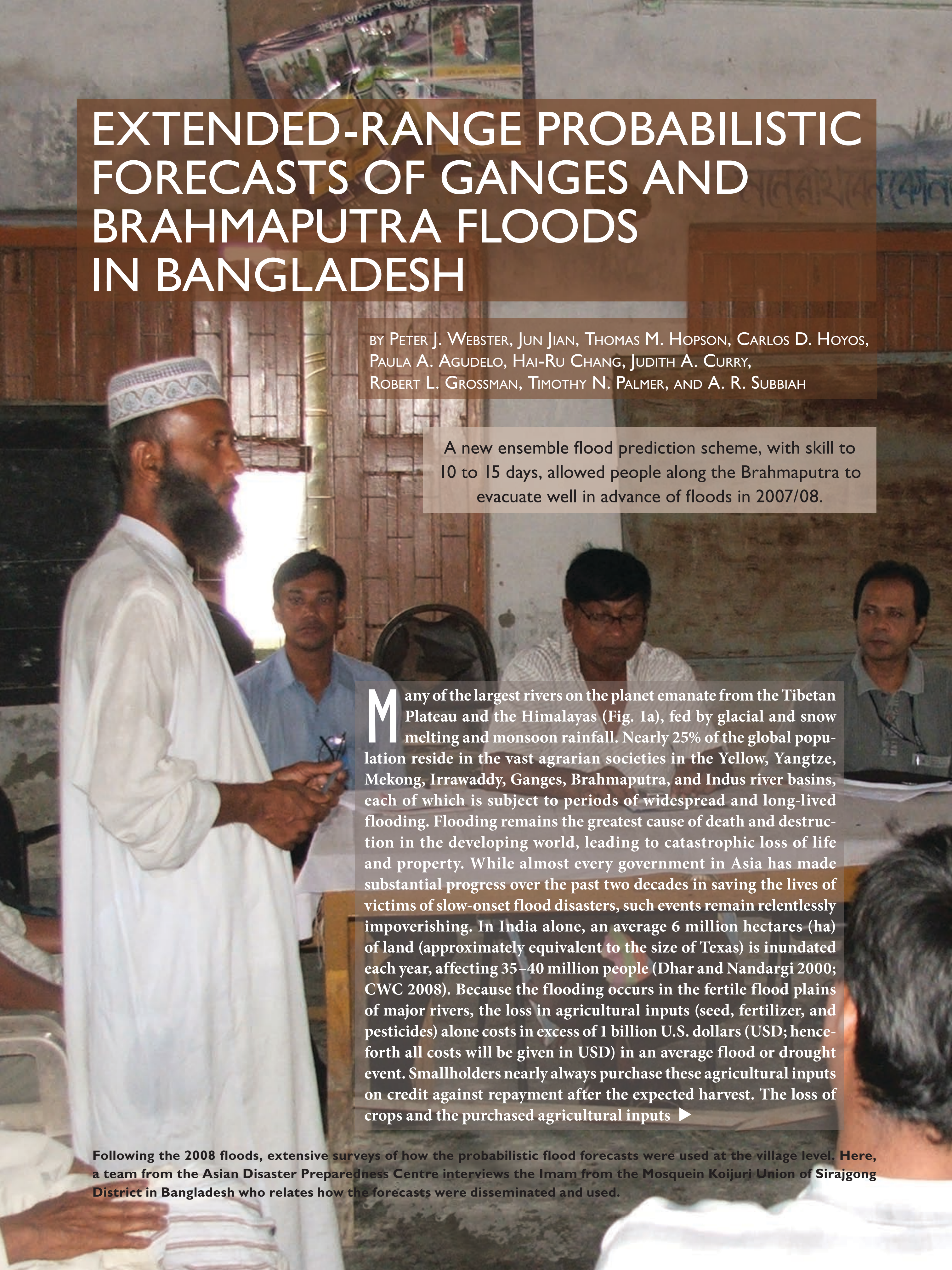
A new ensemble flood prediction scheme, with skill to 10 to 15 days, allowed people along the Brahmaputra to evacuate well in advance of floods in 2007/08.

Many of the largest rivers on the planet emanate from the Tibetan Plateau and the Himalayas (Fig. 1a), fed by glacial and snow melting and monsoon rainfall. Nearly 25% of the global population reside in the vast agrarian societies in the Yellow, Yangtze, Mekong, Irrawaddy, Ganges, Brahmaputra, and Indus river basins, each of which is subject to periods of widespread and long-lived flooding. Flooding remains the greatest cause of death and destruction in the developing world, leading to catastrophic loss of life and property. While almost every government in Asia has made substantial progress over the past two decades in saving the lives of victims of slow-onset flood disasters, such events remain relentlessly impoverishing. In India alone, an average 6 million hectares (ha) of land (approximately equivalent to the size of Texas) is inundated each year, affecting 35–40 million people (Dhar and Nandargi 2000; CWC 2008). Because the flooding occurs in the fertile flood plains of major rivers, the loss in agricultural inputs (seed, fertilizer, and pesticides) alone costs in excess of 1 billion U.S. dollars (USD; henceforth all costs will be given in USD) in an average flood or drought event. Smallholders nearly always purchase these agricultural inputs on credit against repayment after the expected harvest. The loss of crops and the purchased agricultural inputs ▶



**Following the 2008 floods, extensive surveys of how the probabilistic flood forecasts were used at the village level. Here, a team from the Asian Disaster Preparedness Centre interviews the Imam from the Mosquein Koijuri Union of Sirajgong District in Bangladesh who relates how the forecasts were disseminated and used.**

typically place a farming family in debt for several years, by which time the cycle is generally repeated, condemning successive generations to the treadmill of poverty.

In 1987, 1988, and 1998, extensive flooding occurred throughout Bangladesh when both the Ganges and the Brahmaputra crested simultaneously well above flood level. It is estimated that in 1988 and 1989, 3,000 people lost their lives, millions of homes were destroyed, and more than 200,000 cattle drowned. In 1998, more than two-thirds of the country was submerged for three months and an estimated 1,000 people drowned, with millions left homeless (Mirza 2003a,b; Del Ninno et al. 2001). In addition to extensive river flow, the sea level at the head of the Bay of Bengal was elevated by about 30 cm throughout the summer, restricting river outflow. The sea level rise was probably associated with the phase of the Indian Ocean dipole (Webster et al. 1999; Saji et al. 1999), with warm sea surface temperature (SST) and elevated sea surface height in the eastern Indian Ocean and the reverse in the western sectors.

In 2004, 2007, and 2008, shorter-term flooding occurred along the Brahmaputra. Although not as devastating as the earlier prolonged floods, these widespread inundations impacted millions of people. However, societal vulnerability associated with these floods has increased because of a rapidly growing population (e.g., Streatfield and Karar 2008) that has forced many people to farm the fertile chars (river islands) prone to chronic flooding and even disappearance following a flood.

The overall catchment area of the Ganges system (approximately $10^6$ km$^2$) extends across the great Indo-Gangetic plain of northern India and southern Nepal and the Nepal Himalaya (Fig. 1b). The Brahmaputra basin, roughly half the size of the Ganges catchment, extends northward through Assam and Bhutan and then westward between the Himalaya and the Tibetan Plateau (Fig. 1b). Whereas the combined catchment area of the two rivers ranks tenth in size globally, only the Amazon and the Congo Rivers surpass the combined discharge of the Brahmaputra and the Ganges. The Ganges–Brahmaputra delta, which makes up 80% of the area of Bangladesh, is the largest river delta in the world (Chowdhury et al. 1996). Figure 1c portrays the Ganges–Brahmaputra delta as a labyrinth of interconnected rivers and channels around the two major braided rivers. The terrain is very flat and once these rivers reach flood stage, floodwaters spread out rapidly across the extensive floodplains.

Most flood forecasting systems in developing countries have a short time horizon of only 1–2 days, typically using simple statistical methods that extrapolate upstream river flow to lower parts of the river basin with qualitative adjustments for short-term precipitation forecasts (e.g., CWC 2008). Implementation of such statistical schemes often suffers from the lack of upstream data, which are either not measured or unavailable, owing to transboundary political reasons and also from the lack of quantitative precipitation forecasts (QPFs). For example, in India hydrological data are collected by the individual states and rarely shared internationally or even interstate (Jain et al. 2007). In many parts of the world, intercountry exchanges of river flow data are limited and serve as impediments to flood forecasting. Bangladesh receives no upstream data from India at all.

Over a decade ago, Bangladesh incorporated MIKE II, a sophisticated routing model (www.mikebydhi.com/), into its flood forecasting system. Daily deterministic forecasts were made throughout Bangladesh using river discharge data collected at the India–Bangladesh border by Bangladeshi authorities at Hardinge Bridge on the Ganges and Bahadurabad on the Brahmaputra (Fig. 1c) and other staging stations within Bangladesh. However, even this advanced hydrological model provided little lead time in the north and west of the country where the major rivers enter the country and provided only a 2–3-day horizon in the south, matching the flowthrough time scale of the rivers through Bangladesh (Ahmad and Ahmed 2003).

Such limitations on flood forecast lead times are costly. Economic analyses by the Bangladeshi Center for Environmental and Geographic Information Services (CEGIS 2006) have estimated that a 7-day flood forecast has the potential of reducing postflood

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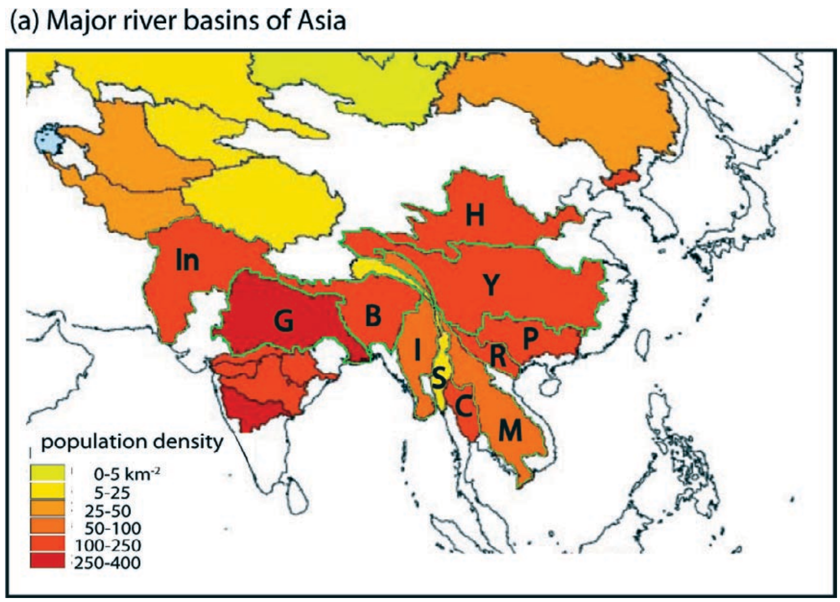
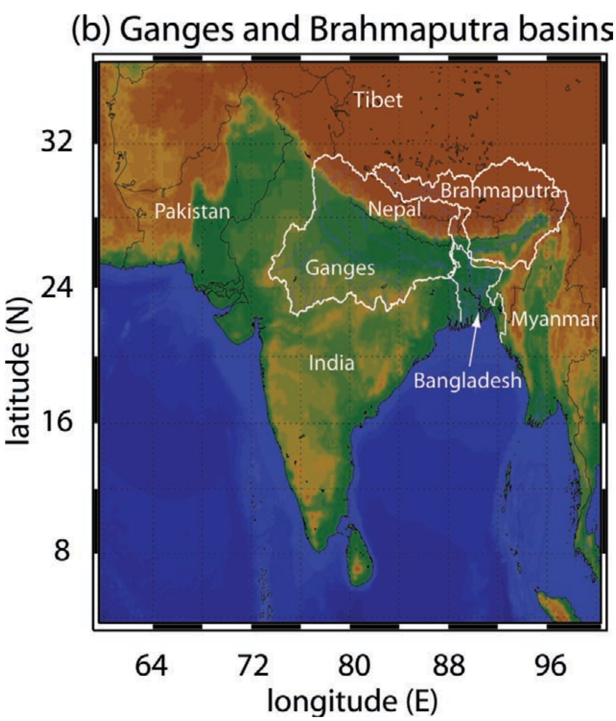


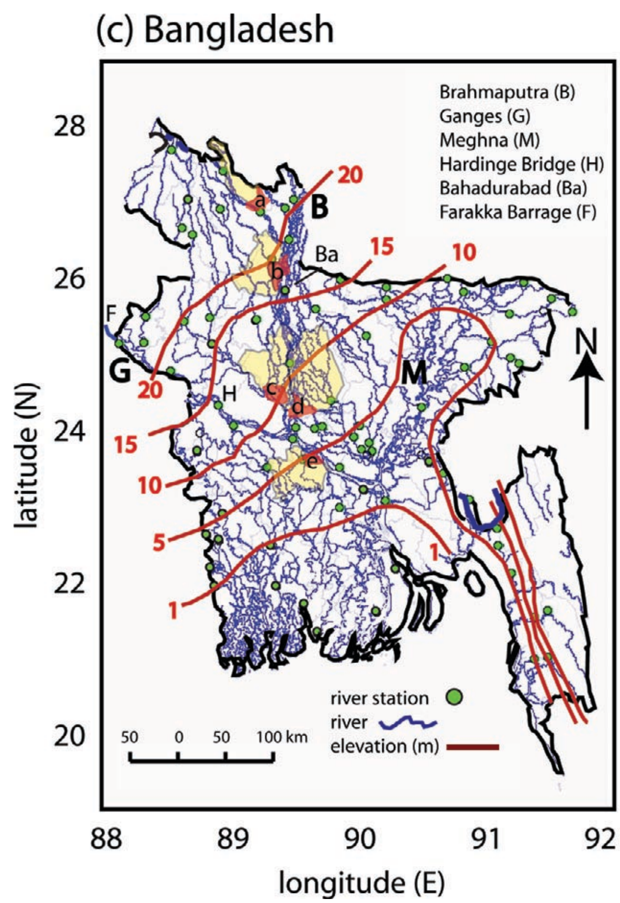




**Fig. 1. (a) Major river basins of Asia emanating out of the Tibetan Plateau and the Himalaya (Ganges G, Brahmaputra B, Irrawaddy I, Mekong M, Red R, Pearl P, Yangtze or Chang Y, Huang or Yellow H, Salween S, Chao Phraya C, Indus In). Colors indicate population density. In total, these rivers support more than 25% of the global population. (b) Detail of the Ganges and Brahmaputra river basins outlined in white. Bangladesh lies at the confluence of the Ganges and Brahmaputra rivers. More than 85% of river flow originates across its border. (c) Detailed map of Bangladesh showing elevation (red contours: m), rivers (blue lines), and river staging stations (green circles). The delta is flat with elevation gradients from the coast northward of 1 m per 50 km. The major rivers, the Ganges, Brahmaputra, and Meghna, are denoted G, B, and M, respectively. The entrance points of the Ganges and the Brahmaputra into Bangladesh are located near Hardinge Bridge (H) and Bahadurabad (Ba). The five unions chosen for dissemination and application of the CFAB forecasts in 2007 and 2008 are colored yellow and labeled a–e.**

household and agricultural costs in Bangladesh by a much as 20% compared to 3% for a 2-day forecast. Thus, there are clear and tangible benefits for increasing the forecast horizon of river discharge. Specifically, forecasts of river flow of these major rivers have the potential to provide critical information to facilitate water resource management, optimization of agricultural practices, disaster mitigation, and relief work, all of which are conducive to reducing the burden of poverty.

There is a long history of flood forecasting in more developed countries. Large networks of streamflow gauges and the availability of QPFs (e.g., Hamill and Whitaker 2006; Hamill et al. 2006) have allowed progress beyond short-term statistical schemes toward generating probabilistic streamflow predictions using ensemble precipitation forecasts to drive hydrological models (e.g., Young 2002; Clark et al. 2005; Werner et al. 2005; Hunt 2005; Gouweleeuw et al. 2005; Chen and Yu 2007; Cloke and Pappenburger 2009; Thielen et al. 2009; Dietrich et al. 2009). Schaake et al. (2007) report on an international program, the Hydrologic Ensemble Prediction Experiment (HEPEX), that was organized to "... bring the international hydrological and meteorological communities together to demonstrate how to produce and utilize reliable hydrological ensemble forecasts to make decisions for the benefit of public health and safety, the economy, and the environment" (Schaake et al. 2007).

The catastrophic Bangladesh flooding in 1998 prompted the U.S. Agency for International Development's Office of Foreign Disaster Assistance (USAID-OFDA) to fund an exploratory project [Climate Forecast Applications in Bangladesh (CFAB); http://cfab2.eas.gatech.edu). The primary goal of CFAB was to provide advanced warning of flooding in Bangladesh on daily to seasonal timescales on the presumption that extended-range streamflow and precipitation forecasts would be of value in the densely populated and heavily farmed river basins of Bangladesh. CFAB decided early in the project to issue probabilistic forecasts to support risk management that allowed cost–benefit analyses to be made relative to the probability of the occurrence of an event. CFAB envisioned a seamless probabilistic prediction system ranging from daily to seasonal forecasts (Table 1).

Seasonal forecasts can enable strategic decisions to be made, such as the selection of crops and seed varieties and long-term disaster preparation and possibly mitigation. A number of studies have sought an association between global sea surface temperature patterns, rainfall over India, and Ganges and Brahmaputra streamflow. A statistically significant relationship between the seasonal Ganges discharge and the phase of the El Niño–Southern Oscillation (ENSO) phenomenon has been found (e.g., Whitaker et al. 2001; Chowdhury and Ward 2004; Jian et al. 2009), consistent with the long-established relationship between total Indian rainfall and ENSO (e.g., Shukla and Paolino 1983). On the other hand, the Brahmaputra discharge does not appear to have any direct relationship with the central–eastern Pacific SSTs, a result substantiated by Shaman et al. (2005). Furthermore, when the exceptional year of 1998 is removed from the record, there is little precursor information from Indian Ocean SSTs (Jian et al. 2009). However, Jian et al. (2009) found a persistent relationship between springtime northwest Pacific SSTs and Brahmaputra summer discharge that is consistent with the results of Shaman et al. (2005) and Kamal-Heikman et al. (2007), suggesting that the seasonal Brahmaputra discharge may be related to Himalayan snow depth during the previous spring.

Intermediate forecasts on the time scale of 2–4 weeks can enable tactical adjustments to the strategic decisions that have been made based on the longer-term forecasts. Webster and Hoyos (2004) argued that forecasts of precipitation on this intermediate time scale are critical for the optimization of planting and harvesting. Predictions on the 1–10-day horizon would support tactical decisions regarding the timing of fertilizer and pesticide applications, as well as transplanting and harvesting. Further, the short-range forecasts would support timely evacuations of at-risk communities that would save not only lives but also grain stores, livestock, household items, and other critical economic assets. Table 1 describes the envisioned overlapping three-tier forecast system.

CFAB developed an international consortium led by the Georgia Institute of Technology[1] in collaboration with the European Centre for Medium-Range Weather Forecasts (ECMWF) in the United Kingdom, the Bangladesh Meteorological Department (BMD; www.bmd.gov.bd; www.bdonline.com/bmd/), the Bangladesh Flood Forecast and Warning Centre (FFWC; www.ffwc.gov.bd) in Bangladesh, and the Asian Disaster Preparedness Centre (ADPC; www.adpc.net) in Thailand. The principal aim of CFAB was to assess the feasibility of developing a forecast

[1] During the 2001–03 period, the lead institution was the Program in Atmospheric and Oceanic Sciences at the University of Colorado, Boulder, where the principals resided at the time.

**Table 1. Basic CFAB strategy for the development of an overlapping tiered flood forecasting system for Bangladesh. Forecast periods are chosen to allow a systematic approach to decision making, starting with tactical decisions at the beginning of the season followed by tactical adjustments to these decisions using intraseasonal forecasts and further tactical adjustment based on short-term forecasts. Probabilistic forecasts are made to allow cost–benefit analyses.**

| Forecast period | Type | Frequency | Type | Decisions |
|---|---|---|---|---|
| Seasonal | 1–6 months | Monthly | Probabilistic | Strategic |
| Intraseasonal | 15–30 days | Weekly | Probabilistic | Strategic/tactical |
| Shortterm | 1–10, 1–15 days | Daily | Probabilistic | Tactical |

system described in Table 1 and, if possible, to develop an operational system to produce such forecasts and identify a means of disseminating these forecasts to user communities.

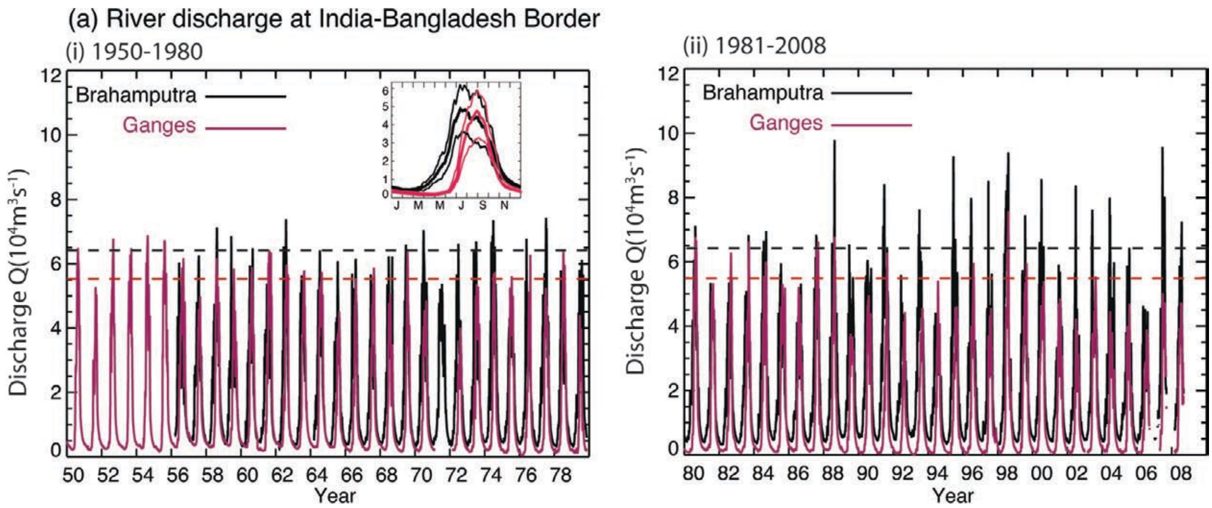
In the next section, we describe the hydrological and meteorological phenomenology of the Ganges–Brahmaputra delta and the issues of data availability. Section 3 provides a brief description of the forecasting modules. Results of medium-range forecasts (1–10 days) made in real time for the years 2003–09 are summarized in section 4, as well as examples of extensions to 15 days, together with a discussion of the feasibility of 30-day and seasonal forecasts. Section 5 discusses the use of the operational 1–10-day Brahmaputra flood forecasts in mitigating the adverse impacts of flooding in 2007 and 2008. Finally, we discuss the applicability of these schemes to other river basins and also make suggestions of how international scientific and technical collaborations can be improved to be more useful and successful in the future in terms of supporting the adoption and sustained transfer of technology to developing countries.

**HYDROMETEOROLOGY OF THE GANGES AND BRAHMAPUTRA BASINS.** Figure 2a displays the 59-yr time series of the streamflows of the Ganges (Hardinge Bridge: 59 years) and the Brahmaputra (Bahadurabad: 52 years) collected daily. The mean annual streamflow of the Ganges and Brahmaputra is $1.14 \times 10^4$ m$^3$ s$^{-1}$ and $2.01 \times 10^4$ m$^3$ s$^{-1}$, respectively, with flood levels occurring at $5.5 \times 10^4$ m$^3$ s$^{-1}$ and $6.4 \times 10^4$ m$^3$ s$^{-1}$.

There is a very strong and repeatable annual cycle (see the inset to Fig. 2a), with the Brahmaputra streamflow rising a month earlier than the Ganges. Snowmelt from the Tibetan Plateau–Himalayan complex contributes to the early flow of both rivers well before the onset of the monsoon rains (Shaman et al. 2005; Kamal-Heikman et al. 2007). The relative lag in the rising of the Ganges at Hardinge Bridge is due to the upstream drawing down of the river by an extensive irrigation system supporting the large agrarian population in the basin (Fig. 1a). Furthermore, a large dam (the Farakka Barrage) lies on the Ganges just upstream from the India–Bangladesh border (Fig. 1c). Jian et al. (2009) compared the summer flow both prior to and after the construction of the dam and found them statistically undistinguishable. The major impact of the Barrage occurs in winter, when it diverts much of the flow to the Kolkata (Calcutta) harbor to reduce silt buildup and in early spring when cross-border flow is reduced while the dam fills.

Figure 2a indicates a clustering of extreme Ganges flood events occurring in the early part of the data record and fewer floods in recent years. It is difficult to assess whether these differences are due to the erection of the Farakka Barrage or the result of climatological factors. Although Jian et al. (2009) found no statistical significance differences in annual mean discharge into Bangladesh before and after the construction of the dam or much of a change in the annual cycle of discharge, the dam may have reduced the number of extreme flooding events. Prior to 1975, Ganges flow at Hardinge Bridge exceeded flood levels in 58% of years. After 1975, they occurred at a 42% rate but with 71% of these taking place in the first 16 years of the 35-yr period. Thus, it is unlikely that the Farakka Barrage is responsible for the recent decrease in Ganges flooding. At the same time, the amplitude of Brahmaputra flood events has increased during the last 20 years. It is possible that a rapidly increasing population (doubling in India since 1975) using more irrigation water has depleted the Ganges discharge. Although the rates of population increase in the Ganges and Brahmaputra basins have been similar, the overall population of the former (nearly 500 million in the present day) dwarfs that of the latter (30 million), so the increased irrigation in the Ganges would be most noticeable. Possibly, changes in the discharge of either river may be associated with long-term natural variability or perhaps are a manifestation of global climate change. Population effects would overshadow the slow creep in discharge levels associated with a variable climate.

Analysis of the Hardinge Bridge and Bahadurabad time series (Fig. 2a) provides an estimate of the probability of flooding exceeding particular durations



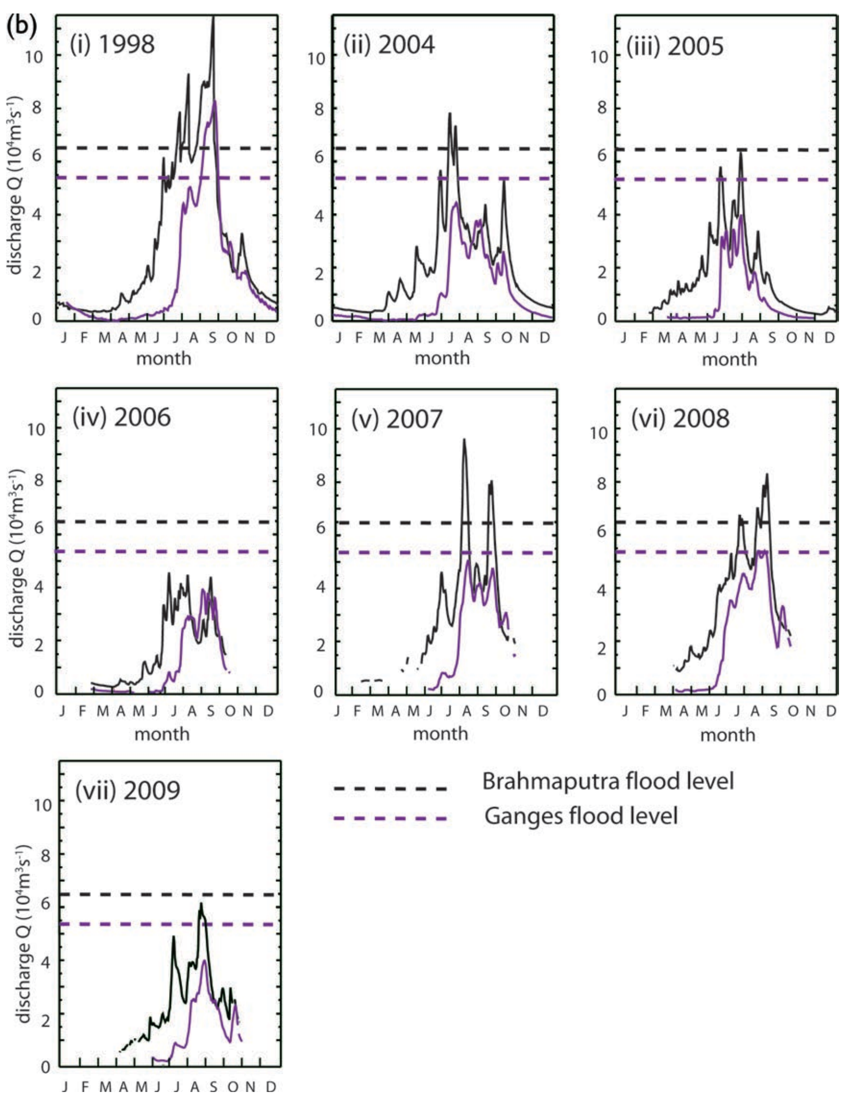




**Fig. 2. (a) Ganges (magenta) and Brahmaputra (black) river discharge ($10^4$ m$^3$ s$^{-1}$) collected at Hardinge Bridge (Fig. 1c) and Bahadurabad for the periods (i) 1950–2008 for the Ganges and (ii) 1956–2008 for the Brahmaputra. Flood levels are shown as dashed horizontal lines. During the last half-century, the flood levels have been exceeded many times. The insert shows the mean annual cycle for both rivers ±one standard deviation. In general, the rapid springtime river surge occurs more than one month earlier at Bahadurabad than at Hardinge Bridge. (b) Detailed river flow time sections of the Ganges (magenta) and the Brahmaputra (black) measured at Hardinge Bridge and Bahadurabad, respectively, for the 1998 (i) the year of the great Bangladesh flood) and 2004–09 (ii–vi). Since 2006, Bangladesh has not made winter streamflow data available.**

occurring at different times of the year (Table 2). Brahmaputra flooding can occur as early as July, the month with the highest probability of flooding. Overall there is a 35% chance of a Brahmaputra 1-day flooding event occurring during the flood season. This probability is reduced to 25%, 20%, and 8% for 3-, 5-, and 10-day flooding, respectively, with the 10-day flood period having a 13-yr return period. The statistics for the Ganges are very different. There is no record of a Ganges flood occurring in Bangladesh during June and July. Ganges flooding occurs primarily during August and September, with double the probability of the Brahmaputra flood levels during these months.

In most years, however, short-lived flooding occurs in Bangladesh throughout the summer and early autumn but with sufficient irregularity to have adverse unanticipated social and agricultural impacts (Mirza et al. 2003; Chowdhury and Ward 2004; Jian et al. 2009; Hopson and Webster 2010). During these years, about one-fifth of the country can be inundated for relatively short periods; however, the timing of the flooding becomes critical for harvesting the winter rice crop, planting of summer rice, and the viability of other crops planted throughout the year (Chowdhury and Ward 2007; Jian et al. 2009).

Three flooding episodes occurred during the 2003–08 CFAB period. A detailed view of the Ganges and Brahmaputra discharge for this period (and also 1998, for comparison) is shown in Fig. 2b. In 2004, widespread flooding of the Brahmaputra occurred, exceeding flood stage for more than three weeks. In 2005 and 2006, neither river reached flood stage in the Brahmaputra delta. However, the Brahmaputra exceeded flood stage in both 2007 and 2008 with inundation lasting longer than 10 days. Although the Ganges did not exceed flood level throughout this period, it came close to flood level in 2008.

A critical requirement for this study is a precipitation dataset for the South Asian region. These data are required to determine the nature of precipitation in the Ganges–Brahmaputra basins and also to calibrate computer-generated forecasts of precipitation. Three precipitation datasets are used and averaged with equal weight to produce a merged precipitation product on a 0.5° × 0.5° grid. These data are necessary to provide an independent statistical correction to the numerical QPFs. The satellite sets include the Climate Prediction Center (CPC) morphing technique (CMORPH) (Joyce et al. 2004) from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center and the Tropical Rainfall Measuring Mission (TRMM) from the National Aeronautics and Space Administration (NASA) (Huffman et al. 2007). The third dataset is an interpolated rain gauge product using data from the World Meteorological Organization's (WMO's) Global Telecommunications System (GTS) (Xie et al.

**Table 2. The climatological expectation of flooding of a prescribed duration occurring in a given month in (a) the Brahmaputra and (b) the Ganges. For example, there is a 15% chance of a >3-day flood occurring in July in the Brahmaputra. Return periods in years are shown in parentheses.**

(a) Brahmaputra

| | Jun | | Jul | | Aug | | Sep | | Annual | |
|---|---|---|---|---|---|---|---|---|---|---|
| | % | yr | % | yr | % | yr | % | yr | % | yr |
| >1 day | 2 | (52) | 23 | (4) | 12 | (9) | 8 | (13) | 35 | (3) |
| >3 day | 2 | (52) | 15 | (7) | 8 | (13) | 8 | (13) | 25 | (4) |
| >5 day | 0 | — | 12 | (9) | 6 | (17) | 6 | (17) | 20 | (5) |
| >10 day | 0 | — | 4 | (26) | 2 | (52) | 2 | (52) | 8 | (13) |

(b) Ganges

| | Jun | | Jul | | Aug | | Sep | | Annual | |
|---|---|---|---|---|---|---|---|---|---|---|
| | % | yr | % | yr | % | yr | % | yr | % | yr |
| >1 day | 0 | — | 0 | — | 14 | (7) | 21 | (5) | 24 | (4) |
| >3 day | 0 | — | 0 | — | 12 | (8) | 17 | (6) | 21 | (5) |
| >5 day | 0 | — | 0 | — | 10 | (10) | 12 | (8) | 16 | (6) |
| >10 day | 0 | — | 0 | — | 9 | (12) | 7 | (15) | 10 | (10) |

1996). Time series of the three precipitation datasets and the resultant merged dataset averaged over each of the basins for the summer of 2007 are shown in Figs. 3a and 3b.

During the summer monsoon season, South Asian precipitation is characterized by alternating active (rainy) and break (dry) periods with periods of 20–40 days (Lawrence and Webster 2002; Webster and Hoyos 2004; Hoyos and Webster 2007), within which reside higher-frequency precipitation events (Webster and Houze 1991; Hoyos and Webster 2007). Figure 4 shows a time series of merged precipitation data during 2004 averaged over the Ganges and Brahmaputra basins. The plots, typical of most years, provide a clear example of the low-frequency active and break monsoon periods within which higher-frequency precipitation events reside. In the lower panels of Fig. 4, the low-pass filtering and lag effects of the basins are evident in the similarity of the lagged averaged precipitation and the streamflow at the collection points of the basin. Plots of the Hardinge Bridge and Bahadurabad streamflow, together with the 10-day average basin precipitation, advanced by +15 days and +8 days, respectively. The Ganges shows a good relationship between the shifted rainfall and discharge. The Brahmaputra also shows a similar correspondence early in the season but the agreement wanes later. Thus, there is some correspondence between lagged basin outflow and average precipitation within the basin; however, it is far from linear. One reason is that the basins upstream of Bangladesh are very large. Some precipitation patterns cover the entire basin, while others are more regional.

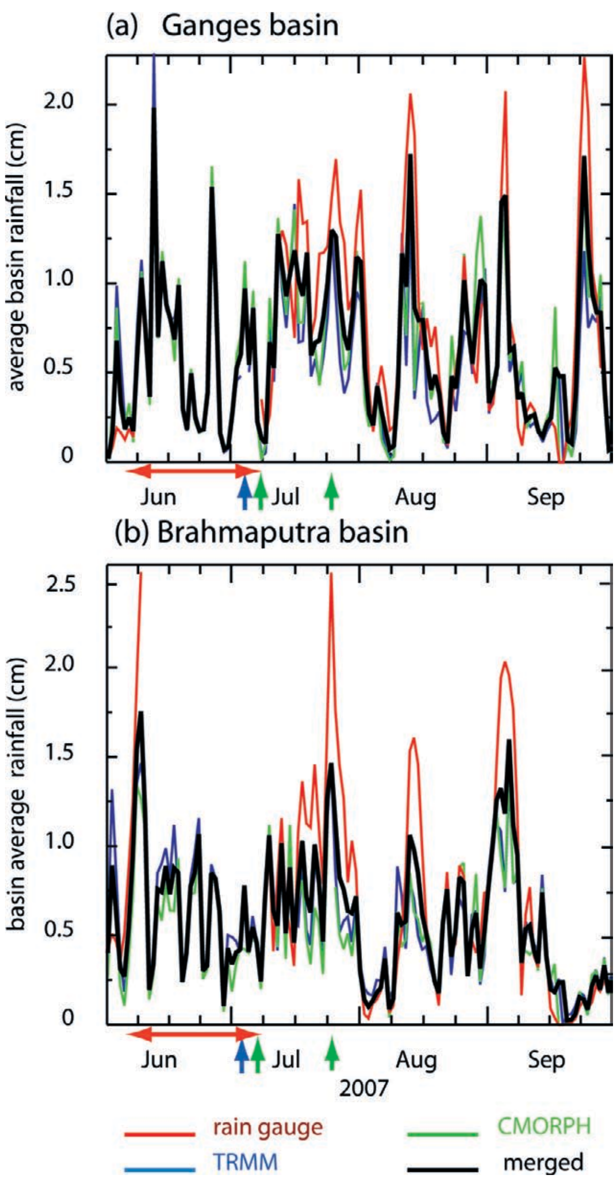



**Fig. 3. The independent "merged" precipitation product (black line) for 2007. The set is the unweighted average of CMORPH (green; Joyce et al. 2004), TRMM (blue; Hoffman et al. 2007), and a rain gauge product (red; Xie et al. 1996) for the (a) Ganges and (b) Brahmaputra for 2007. When data are not available (e.g., periods and days with colored arrows), the merged product is the average of the remaining components.**

Figure 5 shows the hydrological isochrone maps of each basin. Isochrones represent the average time it takes a parcel of surface water, located at some location within the basin, to reach the entrance point of the rivers into Bangladesh [see Jian et al. (2009) for a description of the isochrone methodology], thus defining the hydrological time scales of the basin: roughly 20–25 days in both basins. The figure also shows that the gradients of isochrones differ markedly between basins and within each basin, suggesting that differential streamflow can be expected. Coupled with the interpretations of Fig. 3, such differences emphasize the need for precipitation forecasts to determine with some accuracy the location and timing of precipitation events across the two basins.

**FORECAST METHODOLOGY.** Early in the CFAB project, it became evident that the forecasting model would have to be developed with an almost complete reliance on forecasts of precipitation over the catchment areas rather than the traditional reliance on a mix of upstream data and QPFs. Figure 6 presents a flowchart of the basic composite model. Overall, the forecast system integrates traditional hydrological models within a probabilistic meteorological framework. Hopson and Webster (2010) provide a detailed description of the 1–10-day version of the model; only a brief overview is presented here.

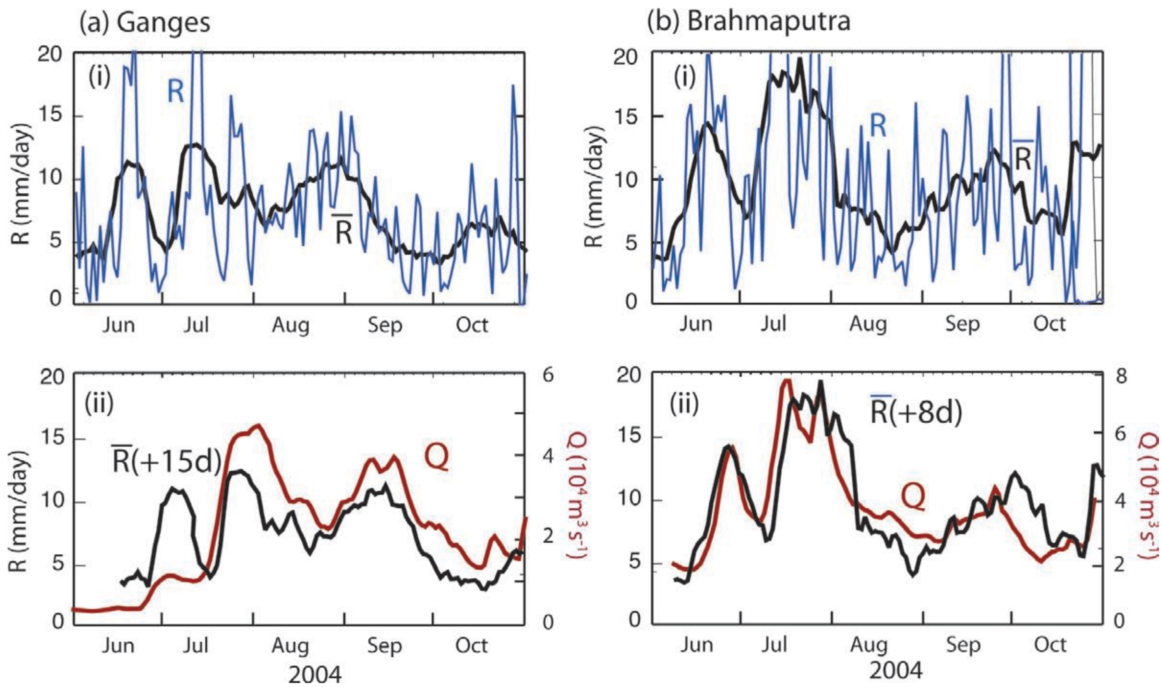



**FIG. 4. (top) Basin-averaged precipitation (thin blue lines) for 2004 for the (a) Ganges and (b) Brahmaputra together with a 10-day running average rainfall (black line). (bottom) Discharge of the Ganges and the Brahmaputra at Hardinge Bridge and Bahadurabad, respectively, plotted with the mean basin rainfall advanced by 15 days for the Ganges and 8 days for the Brahmaputra.**

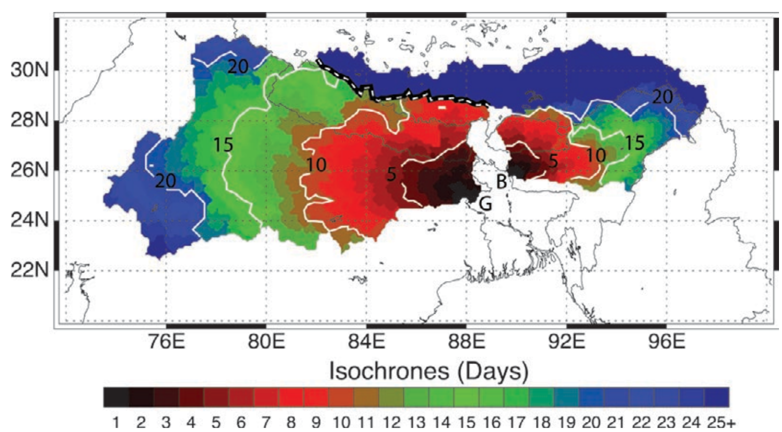



**FIG. 5. Isochrones (days) for the Brahmaputra and Ganges basins. The contours estimate the time taken for water at a particular location in the basin to pass to Bahadurabad or Hardinge Bridge, the staging stations shown in Fig. 1c. Isochrones were constructed using a flow routing algorithm and digital elevation data. The separation of the two basins is shown as a thick dashed white line. The 5-, 10-, 15-, and 20-day isochrones are shown as solid white lines.**

The forecast system is initialized using four sets of initial conditions: operational QPFs, satellite and surface precipitation data, the Ganges and Brahmaputra streamflow at Hardinge Bridge and Bahadurabad, and meteorological data for the hydrological model to provide estimates of soil moisture and evapotranspiration.

i) Quantitative precipitation forecasts. The QPFs are obtained from the ECMWF Variable Resolution Ensemble Prediction System (VarEPS) 51-member ensemble operational system for the 1–10-day (2003–09), 1–15-day (2008/09) and 30-day (2008/09) forecasts (Molteni et al. 1996; Vitart 2004). Seasonal forecasts use the 1–6-month predictions of the 41-member ECMWF System 3 coupled ocean–atmosphere climate model (Anderson et al. 2007). Details of the ECMWF model data, including resolution and time of availability of the forecasts, are shown in Table 3.

ii) The merged precipitation data. The dataset, an example of which is shown in Fig. 3, is computed daily on a 0.5° × 0.5° grid across the Ganges and Brahmaputra. Since the merged dataset is used and calculated in real time, it is necessary to check continually for missing or erroneous data. The red, blue, and green arrows in Fig. 3 highlight

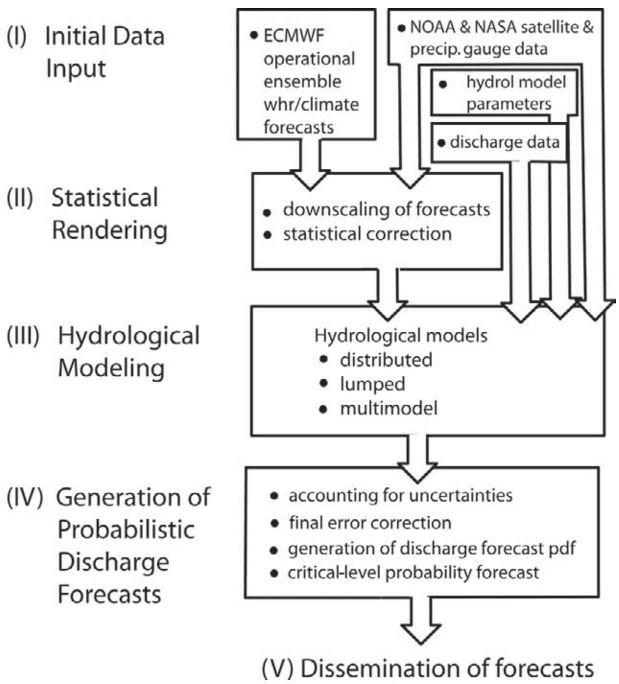



**Fig. 6. Five major steps of the CFAB probabilistic forecast scheme. The basis of the model is the environmental prediction scheme (EPS) quantitative weather (whr) and climate precipitation forecasts (step I), which are statistically corrected using merged precipitation data (step II). The adjusted precipitation forecasts, together with meteorological and initial discharge data, initialize a suite of hydrological models (step III). Step IV provides a final statistical rendering. The models are then disseminated (step V) to user communities. In 2007 and 2008, river flow forecasts were used at the district and village levels to prepare for flooding, resulting in a lower economic loss and timely evacuations ahead of the Brahmaputra floods.**

examples of missing data. During these periods, the merged dataset is calculated as the unweighted mean of the data available.

iii) Streamflow data. Daily river discharge data, similar to those shown in Fig. 2a, are measured at Hardinge Bridge and Bahadurabad (Fig. 1c). These data are provided daily by FFWC.

iv) Meteorological conditions. Near-surface wind, humidity, and temperature are obtained from the ECMWF ensemble forecasts in addition to the QPFs (Hopson and Webster 2010). These data are used in the hydrological models to estimate evapotranspiration (Hopson and Webster 2010).

How well do the ECMWF VarEPS precipitation forecasts compare with observed fields? Figure 7 provides a comparison of the ensemble mean of the forecasts of accumulated rainfall at different lead times compared to observations from the merged precipitation dataset. Results for the summer of 2007 are shown for the Ganges and Brahmaputra basins. The 5-, 10-, and 15-day forecasts correlate well with observations, showing similar low- and high-frequency behavior. At 30 days, the correlations for the Ganges are still high; however, much of this agreement comes from the model duplicating the seasonal cycle correctly. We conclude that there is little skill at 30 days. The 30-day estimates for the Brahmaputra seem better, but there is a substantial phase lag between the forecasts and the observed values. At all lead times, there is considerable bias, with the forecasts overestimating the area average precipitation by about

**Table 3. ECMWF model data used in CFAB forecasts showing period for each model, the forecast horizon, model, grid resolution, ensemble number, and frequency with which forecasts were made. The first two rows describe the global operational system (Molteni et al. 1996). The second two rows describe the evolution of the ECMWF monthly forecasting system (Vitart 2004). The last two rows describe the seasonal forecasting system (Anderson et al. 2007).**

| Period | Horizon | Model | Resolution | # | Frequency |
|---|---|---|---|---|---|
| 2003–07 | 1–10 days | Atmospheric EPS | 100 km | 51 | Twice daily |
| 2008– | 1–15 days | Atmospheric EPS | 50 km | 51 | Twice daily |
| 2004–06 | 1–30 days | Atmospheric EPS 1–30 days | 100 km | 51 | Weekly |
| | | | 150 km > day 10 | | |
| | | Ocean coupled 10–30 days | | | |
| 2007– | 1–30 days | Atmospheric EPS 1–30 days | 50 km to day 10 | 51 | Weekly |
| | | | 80 km > day 10 | | |
| | | Ocean coupled 10–30 days | | | |
| 1981–2007 | 0–6 months | System 3 coupled climate model | 150 km | 11 | Monthly |
| 2007– | 0–6 months | System 3 coupled climate model | 150 km | 41 | Monthly |

30%. If this bias can be corrected, then there is useful predictability at least out to 15 days.

The bias correction to the ECMWF QPFs is accomplished in step II using the merged precipitation product (Fig. 8) and a quantile-to-quantile (q-to-q) bias correction at each grid point in each basin (Hopson and Webster 2010). An example of the q-to-q statistical adjustment is shown in Fig. 8, where modeled rainfall is adjusted to the distribution of monthly rainfall rates obtained from satellite and in situ rain gauges. A similar approach has been applied to adjust nonsimultaneous radar data to rain gauge observations (Calheiros and Zawadski 1987). Here, the q-to-q technique forces each ECMWF ensemble

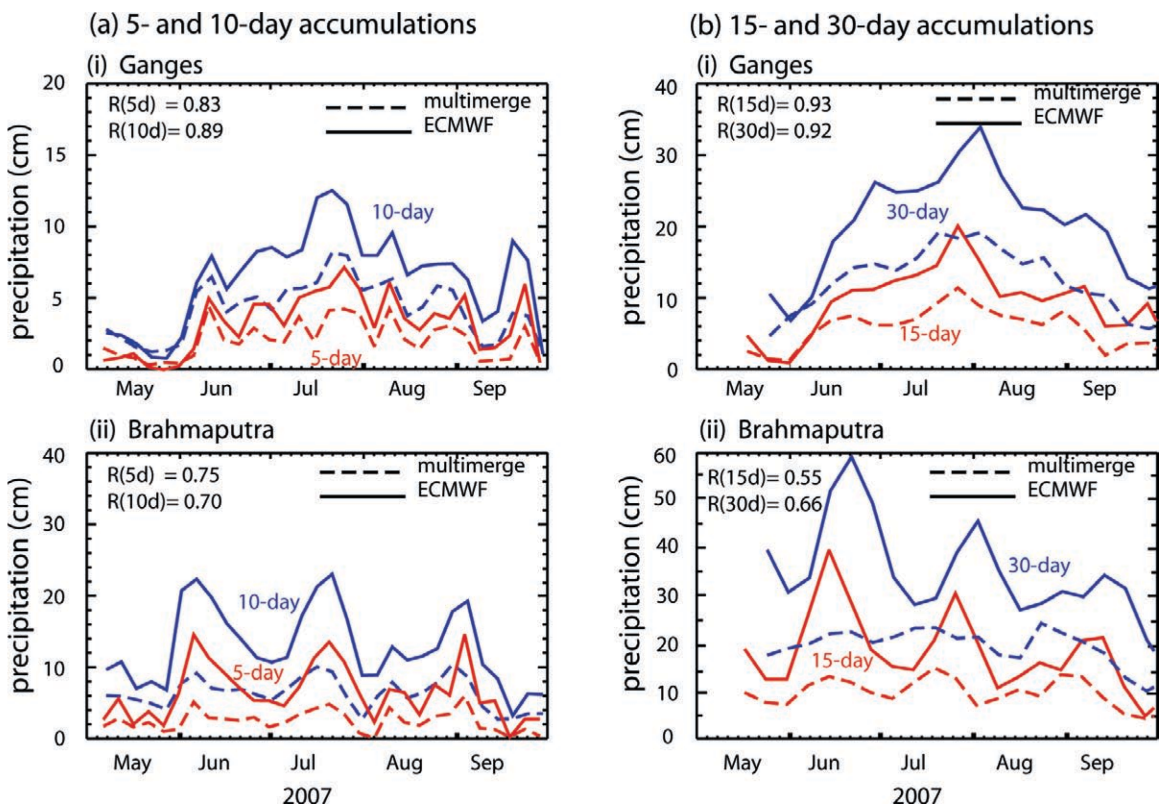



**FIG. 7. (a) Time series of the 2007 area-averaged 5- and 10-day accumulated rainfall over the (i) Ganges and (ii) Brahmaputra using the merged satellite product (dashed) and the ECMWF EPS (solid). A high degree of correlation is evident between the estimates, but the model shows a significant positive bias. (b) As in (a), but for the 15- and 30-day accumulations. The 30-day modeled rainfall is from recently accessible ECMWF monthly products (Vitart 2004).**

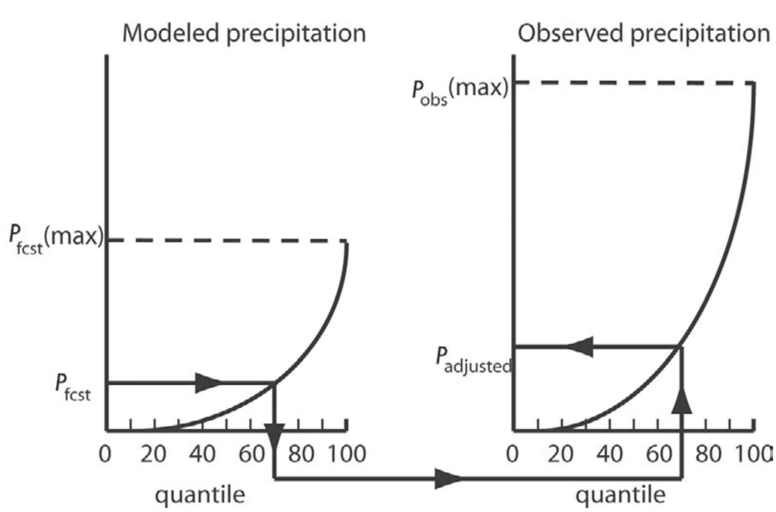



**FIG. 8. Statistical correction of the model rainfall using the q-to-q technique. Model precipitation is mapped against observed merged precipitation and scaled accordingly after binning into quantiles. Here, the forecast precipitation ($p_{fcst}$) of the 70th percentile is set to the 70th percentile of the observed precipitation ($p_{adjusted}$). The technique ensures that the forecasts produce the same climatological rainfall distribution as the observations, including the number of "no rain" events and "heavy" rain events. The q-to-q technique reduces the bias shown in the basin precipitation estimates shown in Fig. 7.**

precipitation forecast at each 0.5° × 0.5° grid point to be sampled statistically from the cumulative distribution function of the associated observational record for the same grid point. The q-to-q statistical corrections minimize systematic error in the forecasts of model precipitation; random error in the precipitation forecast is less important because of the large ensemble size used and the integrating effect of the large-catchment basin on the streamflow. Finally, it is important to note that the q-to-q technique ensures that the forecasts produce the same climatological rainfall distribution as the observations, including the number of "no rain" events as well as heavy rainfall events.

Step III executes the hydrological forecasts using one of two hydrological models (the "lump" and the "semidistributed" models), or a combination of both, with the choice depending on the meteorological conditions and the state of the river (Hopson and Webster 2010). The lump model (Beven 2000) has a statistical basis and uses derived relationships between previous basin-averaged precipitation forecasts and the climatological discharge shown in Fig. 2. The precipitation used in the lump model is a q-to-q adjusted product averaged across the basin computed as shown in Fig. 8. The semidistributed model employed here [described in detail in Hopson and Webster (2010)] utilizes a simple nine-parameter two-layer representative area soil model that parameterizes most of the physical processes of water storage and transport with both a slow and a fast time-scale response. Water balance calculations are carried out independently on each subcatchment, with each subcatchment outflow routed to the forecast location. This model is designed to be of intermediate complexity but with a limited number of parameters because of both the large spatial scale and the lack of available data in the Ganges and Brahmaputra catchments. The lack of direct discharge, irrigation, soil, and vegetation data limits the benefits of employing more complex models.

Step IV provides final corrections to account for the many sources of uncertainty in hydrologic discharge modeling, which include uncertainty in the initial state of the watershed state (soil moisture, etc.), sufficiency of the hydrologic model structure, and physical parameterizations to capture water transport at the scale required, among many other factors. To generate statistically accurate discharge forecasts, these uncertainties are accounted for using statistical procedures

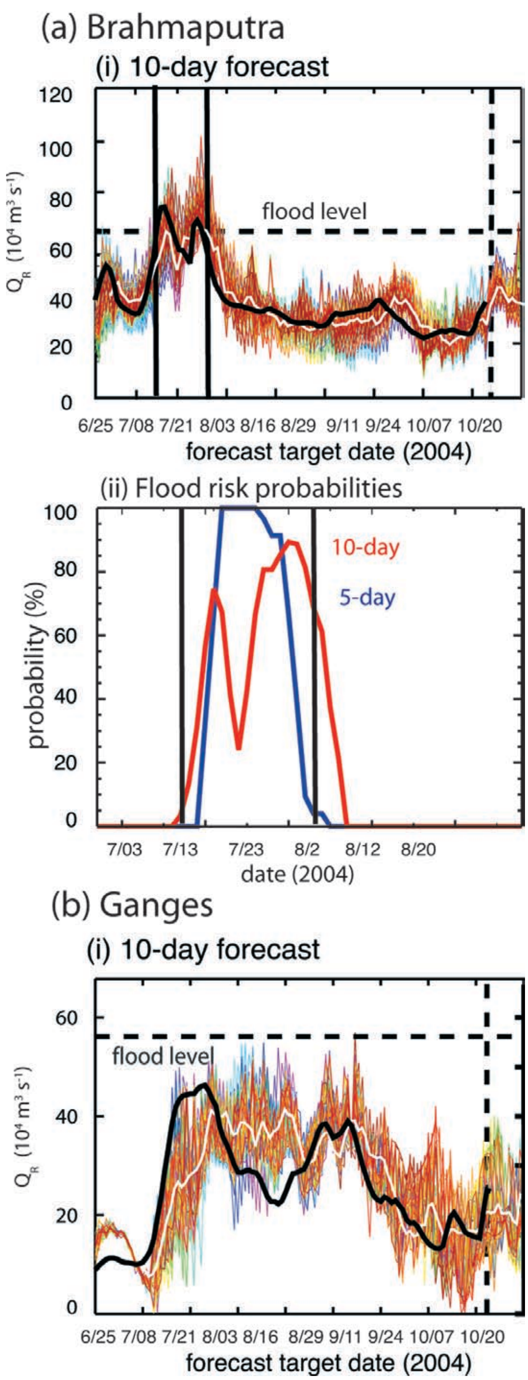



**Fig. 9. (a) 2004 10-day Brahmaputra real-time discharge forecasts. (i) Summary of 10-day forecasts for the entire summer plotted against the forecast target date. The colored swath represents the 10-day forecasts of the collective 51 ensemble members with the white line showing the ensemble average. The bold black line indicates the observed values of the discharge at Bahadurabad. The two vertical solid lines indicate the flood period. (ii) The spread of the ensembles in (i) is used to compute the probabilities of discharge exceeding flood level 5 (blue) and 10 (red) days in advance. (b) As in (a), but for the Ganges at Hardinge Bridge. As flood conditions were not forecast, a probability figure is not shown.**

described in detail by Hopson and Webster (2010). After these statistical corrections have been applied, probabilistic discharge forecasts are produced. The final step (step V), the dissemination and utilization of the forecasts, is discussed in section 5.

**QUANTITATIVE FORECASTS.** Starting in 2003, CFAB provided the Bangladeshi FFWC with daily forecasts of streamflow out to 10 days for the Ganges and Brahmaputra entry points into Bangladesh. Bias-corrected precipitation data over the Bangladesh region were also provided daily to FFWC. These forecasts were used as evolving initial conditions for the FFWC MIKE II river routing model to provide detailed streamflow forecasts at points throughout Bangladesh, shown as the green circles in Figure 1c. Figures 9–12 show 10-day forecasts made in real time for the Brahmaputra and Ganges for the years 2004 and 2007–09.

Figure 9a(i) shows the ensembles of the 2004 10-day forecasts of Brahmaputra river discharge at Bahadurabad plotted against the forecast target date. The observed discharge (the verification of the forecast and matching the time of the forecasts) is shown as a solid black line. The ensemble mean of the 10-day forecast appears as a white line. The forecast scheme captured both the onset and the end of the flood period, including the double maximum discharge. Estimates of flood risk at 5- and 10-day horizons, calculated from the spread of the plumes, are shown in Fig. 9a(ii). Both the 5- and 10-day forecasts provided a very high probability of flooding at the correct time and an accurate estimate of the duration of the flood. Figure 9b shows the corresponding 10-day forecast for the Ganges: no flooding occurred and none was forecast.

The 2007 ensemble hydrological forecasts are shown in Fig. 10. There were two Brahmaputra flood events (labeled I and II) during July and September but no Ganges flooding. Each Brahmaputra flood event was forecast at 10 days quite accurately in terms of both the timing of the flood onsets and their duration. Figure 10a(ii) shows that forecasts initiated on 13 July provide an increasing probability of a growing discharge. Furthermore, the rapid decrease

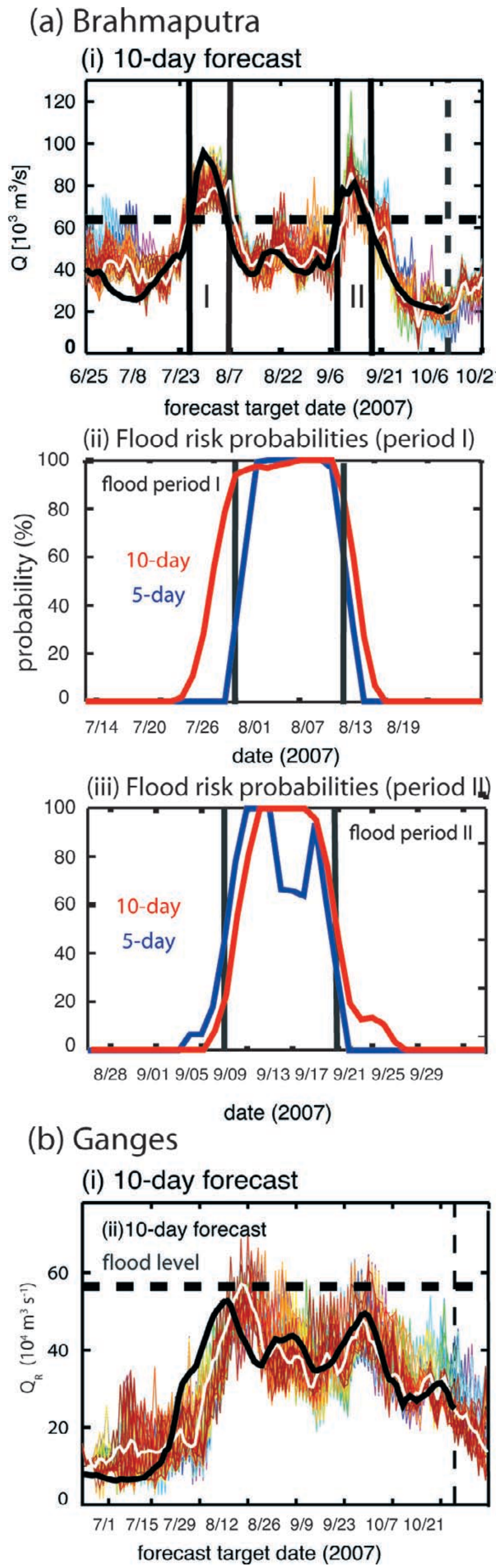



**FIG. 10. (a) 2007 10-day Brahmaputra discharge real-time forecasts. (i) Summary of forecasts. Two extended flooding events occurred: 27 Jul–6 Aug (I) and 7–17 Sep (II). (ii),(iii) Flood exceedance probabilities (%) at 5- (blue) and 10-day (red) horizons for the two Brahmaputra floods. (b) 10-day Ganges flood forecasts for 2007.**

in discharge in early August was also forecast quite well. Similar warning was given for flood II [Fig. 10a, (i) and (iii)]. The 2007 Ganges forecast is shown in Fig 10b. Although the ensemble mean never exceeded the flood level, the model forecast a higher probability of stronger subflood discharge than was observed.

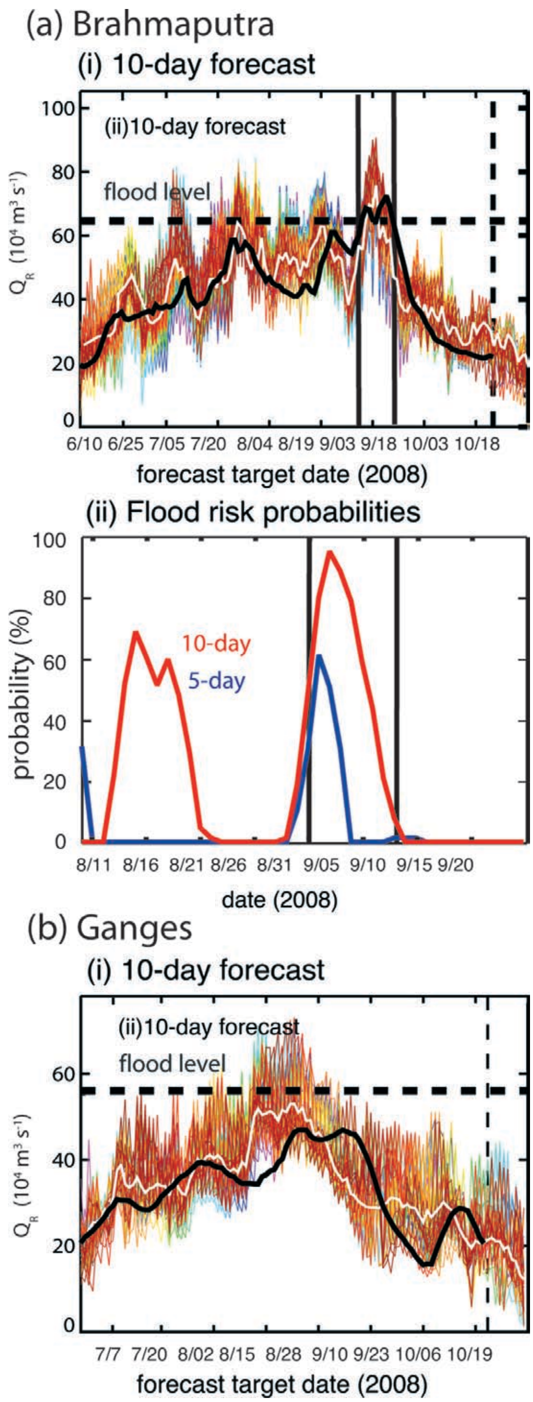



**Fig. 11. As in Fig. 9, but for (a) (i) 2008 10-day Brahmaputra forecast indicating one flooding event in September, and (ii) Probabilities of flood level exceedance at 5 and 10 days. (b) Ganges 10-day forecasts.**

The 10-day forecasts for the single Brahmaputra flood event in 2008 are shown in Fig. 11a. The observed flow throughout the season is contained within the spread of the ensembles, and the onset of the flooding was well forecast at 10 days.[2] Figure 12 shows the Brahmaputra and Ganges river discharge forecasts for 2009. Flooding in Bangladesh did not occur in either basin and none was forecast, although moderate Brahmaputra probabilities were forecast in late September/early August. It is interesting to note

[2] A spurious maximum was forecast in early September. This maximum resulted from an erroneously high TRMM estimate of precipitation across the Brahmaputra. As the operational system is conducted in real time, these spurious data were included in the calculation of the merged precipitation product and the EPS QPF was anomalously increased. An automatic check on outliers has now been included in the system.

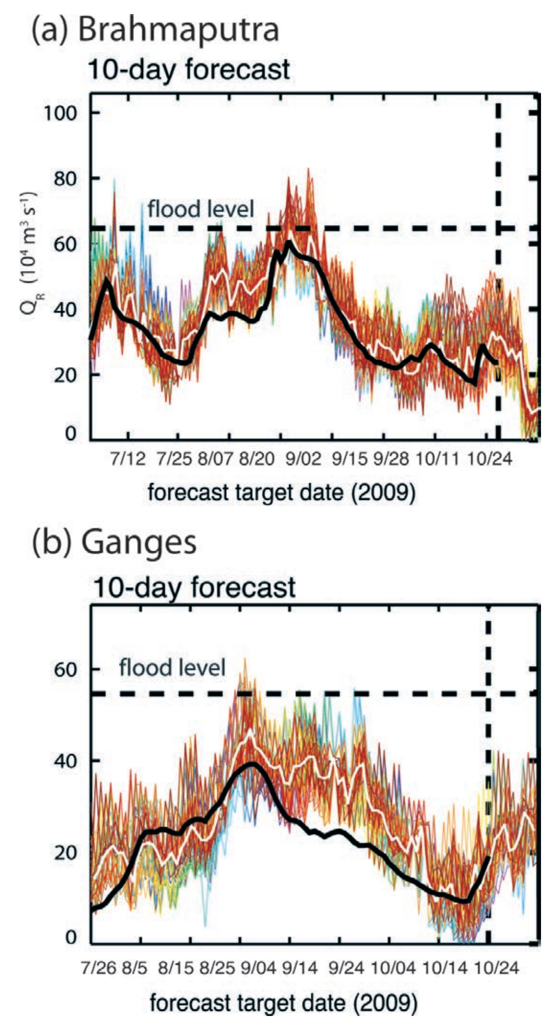



**Fig. 12. As in Fig. 9, but for 2009 for the (a) Brahmaputra and (b) Ganges forecasts for 2009.**

that the Ganges discharge forecast was far higher than observed in what transpired to be one of the driest years over India in a century. This point will be discussed later.

Figure 13 shows an evaluation of the real-time forecasts for both the Ganges and the Brahmaputra for the period 2003–08 in the form of observed/predicted scatterplots. High correlations exist between the ensemble mean of the forecasts and observations. For both rivers, correlations are in excess of 0.95 for 1-day forecasts to 0.87 for 5 days and 0.8 for 10 days. We also calculated the Brier scores for extreme flooding of the Brahmaputra (Brier 1950). The Brier score is a commonly used verification measure for assessing the accuracy of probability forecasts for a specified threshold, where the smaller the Brier score, the better the forecast. Values of 0.01, 0.03, and 0.04 were found for the 1-, 5- and 10-day forecasts respectively. Brier scores for the Ganges are not shown because the river did not appreciably exceed the extreme flood level at Hardinge Bridge throughout the period. In addition, the Brier skill score (Wilks 2001), a metric that gauges a forecast relative to a "persistence" forecast, was calculated. The larger the Brier skill score (up to a limiting value of one), the better the forecast, with zero representing no improvement over the reference forecast (e.g., persistence). Brier skill scores for the Brahmaputra are >0.65 at all forecast lead times and show that the forecasts are substantially superior over persistence.

How much of the skill displayed in Fig. 13 can be attributed to the use of the ECMWF QPFs as initial data? To determine the contribution of QPFs, a number of experiments were conducted and compared with the operational 10-day forecasts. The results of the experiments for the 2007 and 2008 10-day forecasts for the Brahmaputra are shown in Fig. 14 compared with the operational forecasts and the observed discharge shown in red and black, respectively. In the first experiment ("random," green curves), the QPFs were replaced by 1–10-day QPFs chosen randomly from the January–October period. In the second experiment ("climatology," blue), the QPFs were replaced by the climatological rainfall distribution. In the third experiment ("zero," dashed), the QPFs are set to zero. All the experiments use initial discharge data at the start of the forecast and only the ensemble means are shown. The results are summarized in Table 4 for both the Brahmaputra and the Ganges. At the 1-day forecast horizon, there

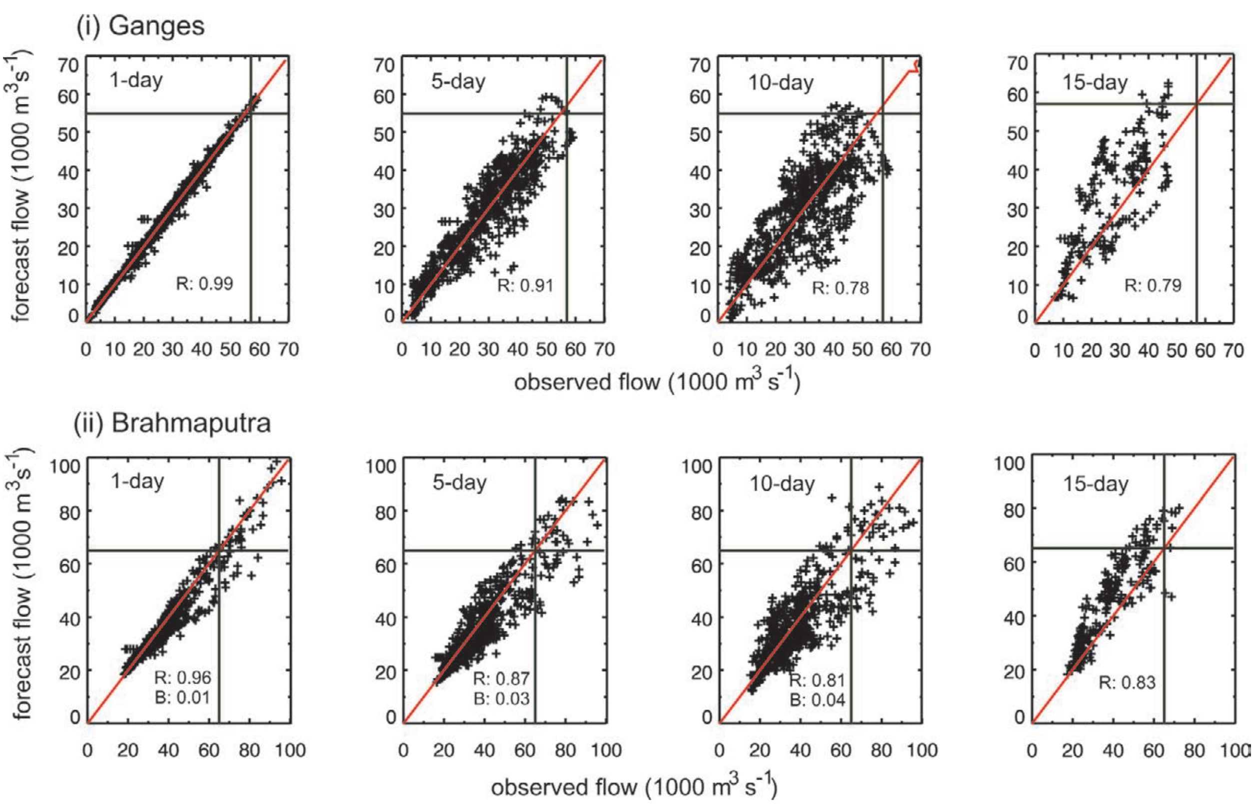



**Fig. 13. Verification statistics for the (i) Ganges and (ii) Brahmaputra. Figures compare the ensemble mean of the discharge forecasts with the 5-, 10-, and 15-days observed discharge. Correlations (R) and the Brier score (B) are also plotted. Statistics for the 15-day forecasts refer only to 2008 and 2009.**

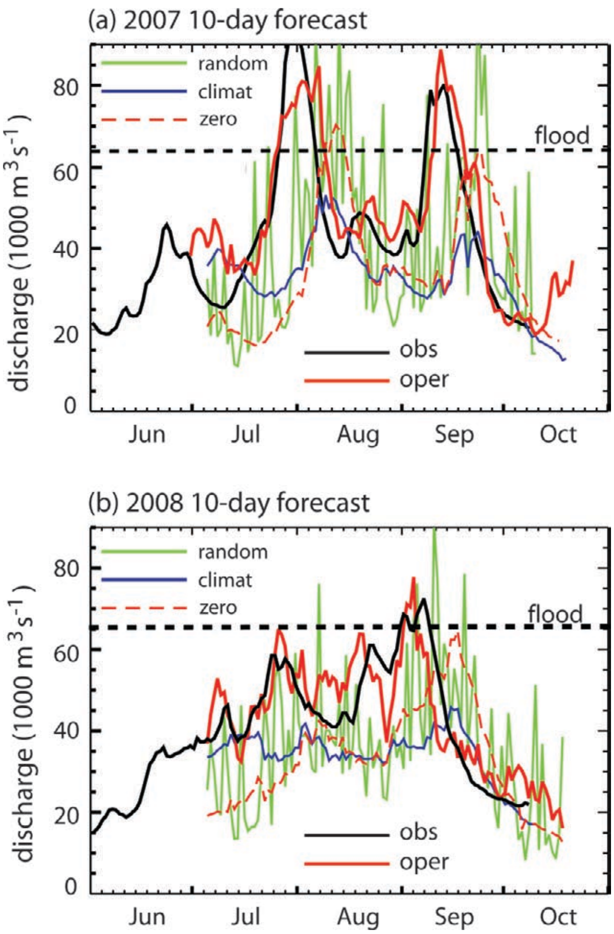



**FIG. 14. Estimates of the value of using ECMWF EPS quantitative precipitation forecasts in 10-day Brahmaputra discharge forecasts for (a) 2007 and (b) 2008. Bold red line shows the ensemble mean of the 10-day forecasts, and the bold black line shows the observed discharge. Other curves represent ensemble means of forecasts when randomly chosen precipitation forecasts (green), climatological precipitation (blue), and no data (dashed red) replaced the QPFs from ECMWF. Correlations for the various forecasts are given in Table 4.**

is little impact of the QPFs, indicating that most of the variance is explained by the initial discharge data upon which each of the forecasts is based. At 5 days, the operational forecast using QPFs explains 76% and 82% of the variance in the Brahmaputra and Ganges, respectively, compared to a reduction of 30%–40% of the variance when random values of precipitation are used. At 10 days the value of using QPFs is even more evident, with the operational forecasts explaining 60%–65% of the variance compared to far lower values for the other experiments. The similarity of the random, climatology and zero experiments to observations reduces rapidly with increasing forecast horizon as the influence of the initial discharge condition diminishes. In summary, the majority of the skill in the discharge forecasts comes from the use of the QPFs.

In 2008, the ECMWF EPS system was extended to 15 days and to 30 days as described in Table 3. Figure 15 shows the 15-day forecasts for the Brahmaputra (Fig. 15a) and the Ganges (Fig. 15b) for 2008 and 2009. A strong correlation appears between the verification curves (black lines) and the ensemble averages (dashed black lines). However, in all cases there is a bias with the forecast producing false positives in both rivers. Whereas it is encouraging that the correlations suggest that useful predictability may eventuate, it is clear that further work is necessary. Part of the issue is lack of a sufficiently long database of forecasts to allow construction of meaningful statistical corrections to the QPFs. The 30-day experimental forecasts (Vitart 2007) showed little clustering of the ensemble members at 30 days and hence, in the present manifestation of the forecast system, little skill. These results of these experimental forecasts are not reported here.

A perspective for the reduced skill of the 30-day forecasts can be found by a comparison with the

**TABLE 4. Estimates of the value of extended ensemble forecast information in terms of correlations between observed river discharge at the Ganges at Hardinge Bridge (G) and the Brahmaputra at Bahadurabad (B) and the numerical forecasts. Comparisons are made between the operational product and the random, climatology, and zero rainfall cases. Forecasts using the extended precipitation forecasts are far superior, especially at 10 days.**

| Experiment | 1-day forecast | | 5-day forecast | | 10-day forecasts | |
|---|---|---|---|---|---|---|
| | G | B | G | B | G | B |
| Operational* | 0.99 | 0.96 | 0.91 | 0.87 | 0.78 | 0.81 |
| Random** | 0.99 | 0.98 | 0.84 | 0.71 | 0.48 | 0.25 |
| Climatology** | 0.99 | 0.99 | 0.89 | 0.76 | 0.48 | 0.38 |
| Zero** | 0.98 | 0.98 | 0.83 | 0.68 | 0.35 | 0.14 |

*Based on 2003–09 forecasts. ** Based on 2007 and 2008 only.

20–25-day Bayesian statistical river flow forecasts of Webster and Hoyos (2004). The empirical forecasts predicted the Brahmaputra and Ganges flow at skill levels higher than the experimental forecasts shown here. Their Fig. 9b shows 20-day forecasts for both rivers for the years 1996 and 1998, depicting well below average discharge in the former year and flooding in both rivers in the latter year. The Webster–Hoyos model was based on the observed physical structure of the intraseasonal or Madden–Julian modes (e.g., Madden and Julian 1972; Hoyos and Webster 2007) and was thus directly related to intraseasonal variability. However, numerical weather prediction models have shown limited propensity for extended prediction of the Madden–Julian oscillation (e.g., Kim et al. 2008). The success with empirical techniques suggests that as numerical models improve their portrayal of intraseasonal variability, 30-day forecasts of flooding using QPFs will show improved skill. In the meantime, it may be useful to develop a hybrid scheme for these extended on a combination of the Webster–Hoyos technique and the ECMWF forecasts used here.

We also produced experimental monthly predictions out to 6 months of Brahmaputra and Ganges river discharge for 2007–09 using the ECMWF 1–6-month System 3 projections (Anderson et al. 2007), downscaled to provide the probability of shorter-term flooding based on the probabilities shown in Table 1. The results are encouraging and show similar skill to that found diagnostically by Jian et al. (2009). A high probability of flooding was suggested late in the season for 2007 and 2008 and lower probability for the entire 2009 season. The seasonal forecasts will be the subject of a subsequent report.

## APPLICATIONS AND EFFECTS OF THE 2007 AND 2008 FLOOD FORECASTS.

Solving the technical aspects of flood forecasting constitutes a solution to only half of the problem: communicating and building confidence in the forecasts to those potentially affected by floods are equally challenging and important tasks.

In 2007, in conjunction with the Asian Disaster Preparedness Centre and CEGIS, a number of flood-prone unions (equivalent to counties) along the Brahmaputra and the Brahmaputra–Ganges were chosen as test bed locations for applications of the flood forecasts (yellow areas in Fig. 1c). The forecasts were based on the CFAB 10-day probabilistic forecasts that provided Ganges and Brahmaputra inflow conditions into Bangladesh for the FFWC MIKE II model. During 2007 and 2008, advanced notice of each of the impending three floods was communicated by the FFWC to the unions by a planned cell phone network and communicated further to the villages by a series of flag alerts. In each union, government agriculture extension personnel and village leaders were trained by CFAB partners (CEGIS and ADPC) to understand and interpret the forecasts in terms of local references and landmarks so that the expected degree of inundation could be readily expressed unambiguously to the villagers. Assessments of the responses at the village level are discussed in the ADPC reports (ADPC 2008, 2009).

Early in the process, local officials had acknowledged that 10-day forecasts were optimal in horizon. Such forecasts would provide a reasonable lead time for people to make agricultural adjustments and decisions. In addition, such advanced warning would also allow regional professionals time to coordinate regional efforts, to suggest to agricultural dealers to hold off on the sale of seeds and pesticide, and to offer advice to famers and fishermen and agricultural dealers (ADPC 2008). Communities were vitally interested in when the flooding would occur, what height the flood level would be, and how long the flood level would be exceeded. This last metric is of considerable concern, since inundation greater than about 10 days means that there would be little chance of a return on a crop planted before the flood.

A National Disaster Emergency Response Group planned the overall emergency response and logistics for preflood preparedness and postflood relief. Agencies with local representation (e.g., the Department of Agricultural Extension) prepared rehabilitation plans in advance for regions of high vulnerability. With the forecast of an impending flood, communities were advised to "wait-watch-worry and work" (ADPC 2009). Evacuation assembly points were identified with adequate communication and sanitation facilities. In the vulnerable regions defined by the forecasts, fisheries were protected by the placement of nets. Suggestions were made about harvesting crops early ahead of the impending flood or delaying of planting. Families were advised to store about 10 days' worth of dry food and safe drinking water, as relief would not be forthcoming until at least 7 days after the advent of a flood. In addition, cattle and poultry, crop seed, and portable belongings were to be secured in safe locations, such as on road embankments. Of particular concern were the people of the river islands (or chars) farmed by the poorest of the poor that are rapidly engulfed by rising water and may disappear from year to year. Plans

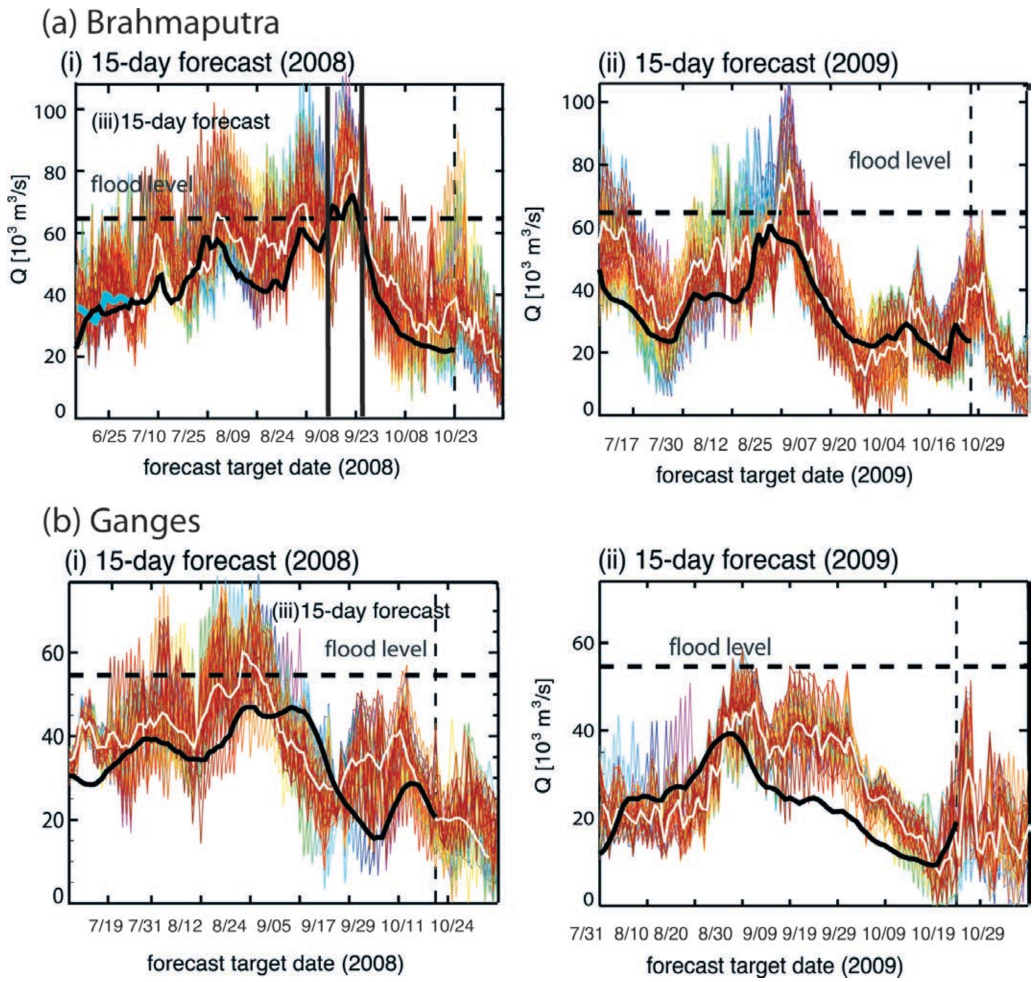



**Fig. 15. As in Fig. 9, but for 15-day forecasts of the (a) Brahmaputra and (b) Ganges for (i) 2008 and (ii) 2009.**

were made for the rapid deployment of manual and mechanized boats for evacuation. With the normal 2–3-day FFWC forecast, these extensive plans would have been impossible to implement; the 7–10-day forecasts produced by CFAB enabled adequate time to prepare properly for the floods.

ADPC (2009) assessed the utility of the 1–10-day forecasts together with a cost–benefit analysis by interviewing more than 100 households following the floods. Although limited in scope, the survey indicated that there were substantial financial benefits resulting from the use of the flood forecasts. It was estimated that the average savings for each household involved in fisheries was equivalent to $130 and in agriculture $190. The greatest savings per household were from the protection of livestock ($500 per animal) and household assets ($270 per household). Given that the average income in Bangladesh is approximately $470 per year and that 50% of the population exists on less than $1.25 per day (www.unicef.org/infobycountry/bangladesh_bangladesh_statistics.html), the savings were very substantial in the flooded regions in terms of man-years of labor. For example, the loss of a bull would require the equivalent of two man-years of labor for recuperation. The report concludes that the forecasts were accurate, timely, and well utilized in the pilot unions. The interviews by the ADPC team that took place in the villages following the 2008 floods provided us with a final justification for producing and communicating probabilistic forecasts. As stated by the Imam from the Mosquein Koijuri Union of Sirajgong District in Bangladesh: "We disseminate the forecast information and how to read the flag and flood pillar to understand the risk during the prayer time. In my field, T. Aman (a rice variety) was at seedling and transplanting stage, I used the flood forecast information for harvesting crops and making decision for seedling and transplantation of T. Aman. Also we saved household assets." Not only were the flood warnings heeded but the concept of risk, being the product of probability of the occurrence of an event and its cost, was understood and discussed. Initially, we had hypothesized correctly as it turned out that societies that are faced with environmental catastrophe a number of times each generation are ready to accept and use probabilistic forecasts.

CFAB's models and data procedures were transferred to FFWC at the beginning of the 2008 season so that they could make their own predictions. This technology transfer required the training of Bangladeshi personnel in the use of the models, increasing Bangladesh's Internet bandwidth, and upgrading of computer facilities at FFWC. The capacity building was accomplished by many visits of CFAB personnel to FFWC and two workshops held prior to the flood season in Bangkok in 2007 and Bangladesh in 2008 that included lectures on the background meteorology and climate and the practical use of the models. These technical steps were accomplished by the beginning of the 2008 flood season, but because of technical and personnel problems in Bangladesh, Georgia Institute of Technology continued to produce the forecasts during the 2008 and 2009 flood seasons.

**CONCLUDING COMMENTS.** During the initial planning of CFAB, we decided to work toward an overlapping forecast system described in Table 1. We have achieved some success in the shorter-period forecasts and there is some suggestion that the intermediate forecast horizon is feasible. We are not yet satisfied with the current skill in the seasonal forecast. We have described the development of a unique forecasting system of river discharge into Bangladesh from India on 1–10-day horizons. Furthermore, we suggested that predictability extends out to 15 days, although this conclusion was based on only two years of predictions. The forecasts were highly successful, accounting for the three Brahmaputra floods that occurred in the CFAB period with a minimum of false positives. No floods occurred along the Ganges and none was forecast with the exception of 2009, when errors in TRMM data provided a high probability of floods that did not occur. Postprocessing lowered this probability considerably.

The Ganges forecasts in 2009 were interesting for another reason: they provided a substantial overestimate of the observed Ganges discharge into Bangladesh (Fig. 15). Rainfall amounts (Fig. 5) show that the precipitation forecasts were quite accurate, suggesting well below average precipitation. In fact, rainfall in the Ganges basin was one of the lowest in the last century. The disparity between forecast and observations can probably be attributed to the large use of river water for irrigation during the drought. As our principal goal is in the forecasting of floods, the error is not too important. But to provide an accurate estimate of water discharge into Bangladesh from India during drought periods, substantial upstream data from India will be required.

Even though there have been suggestions that springtime snowmelt in the Himalaya and Tibetan Plateau is important for seasonal river discharge of the Ganges and Brahmaputra, snowmelt has not been included in the CFAB forecasting schemes. Albeit with limited data, both Shaman et al. (2005) and Kamel-Heikman (2007) find strong correlations between seasonal flooding and springtime snow. The 10- and 15-day forecasts used observed discharge of the Ganges and Brahmaputra at the India–Bangladesh border as initial conditions. Thus, in effect, snowmelt is taken care of in the initial conditions, as the two staging stations are well removed from the highlands. In fact, the isochrones of Fig. 4 show that there is at least a 20-day separation from regions of snowmelt to Hardinge Bridge and Bahadurabad. However, these stations do lie within a 30-day time scale, and one of the reasons that the 30-day forecasts were without skill may have been that snowmelt was not taken into account sufficiently. If the 15-day limit is to be extended and if numerical seasonal forecasts are to be attempted, snow accumulation/melt needs to be incorporated into the forecast system.

Further exploration is required on the role of sea level in restricting the outflow of the Ganges–Brahmaputra into the Brahmaputra. Sea level at the head of the bay varies considerably on intraseasonal and interannual time scales, the latter being associated with the phase of the Indian Ocean dipole (Webster et al. 1999; Saji et al. 1999). Between 1997 and 1998, there was a 30-cm rise in the sea level in the northern Bay of Bengal. The importance of this rise in producing floods in 1998 requires further study.

How transferable is the CFAB flood forecasting system to other river basins? The system has been shown to work well in two large river basins and is perhaps best suited for river systems that are large monsoonal river basins. Thus, of the river basins located around the Tibetan Plateau (Fig. 1a), the Irrawaddy, Mekong, Red, Yangtze, Yellow, and Indus are amenable to the deployment of the Ganges–Brahmaputra system. Probably systems such as the Congo and major rivers in South America could also profit from the CFAB system. Furthermore, discharge forecasts in the Ganges and Brahmaputra basins could be improved immediately if streamflow data were freely distributed even within India itself. Given the flooding that occurs annually across India, it is difficult to understand why a nationwide quantitative hydrological prediction scheme based on extended QPFs has not been implemented. Such a system would not only provide advance warning of flooding but also allow quantitative water resource management and agricultural optimization in both "rainfed" and irrigated regions.

The particular application of CFAB forecast system in Bangladesh represents a "world is flat" approach (Friedman 2007), with the collaboration of scientists in Europe (producing the ensemble meteorological and climate forecasts), the United States (developing and producing the integrated flood forecasts), and the developing world (integrating the flood forecasts into their disaster management decision-making protocol), all enabled by high-speed Internet connections. In essence, the project was truly "end to end," with strong connections between scientists and villagers and farmers located on different parts of the planet. To ensure the end-to-end nature of the system, substantial iteration of the producers of the forecasts and the users was necessary. Toward this end, CFAB teams from the United States visited Bangladesh 17 times over the project lifetime. We consider this a worthwhile commitment, laying a basis for the alleviation of poverty in the developing world (Webster and Jian 2011).

While the project was fully successful in its aims of producing and using the forecasts and transferring the technology, our experiences with this project highlight some concerns regarding the manner in which developed nations engage with developing nations in technology transfer and capacity building. These concerns relate to how projects are funded and to the objectives and strategies of in-country capacity building and, in particular, how the capacity is sustained.

USAID and the World Bank are reluctant to provide funds to university groups, as they worry that such groups are more concerned with research rather than with the "deliverables" required for successful applications. To supplement the sporadic funding received for this project from USAID (whose priorities changed from the Clinton to the Bush administration) and CARE, we were able to use funds from the National Science Foundation and Georgia Tech Foundation to support the research and development of the forecasting scheme and use USAID and CARE funding for "incountry" application of the modules and training. A better funding base and collaboration between federal and international agencies to support such projects is desperately needed. There are few opportunities within the federal system to fund university-based projects to support applications projects in the developing world, such as CFAB, even though these projects can have significant humanitarian and national security benefits.

Once technology transfer has occurred, funding for involvement of the developed world group typically ceases and the capacity building often does not succeed. Each time we visited government agencies in Bangladesh and conducted training sessions, we found that the eager young scientists and technicians who attended the previous session were no longer present, many of whom had left Bangladesh to attend graduate school overseas. Although the CFAB technology was successfully transferred in spring 2008 and the required local infrastructure was established, the FFWC has been unable to produce operational forecasts for 2008 and 2009 because of the departure of trained personnel and technical problems. For the 2008 and 2009 seasons, CFAB has continued to produce forecasts without external funding (subsidized by funds from Georgia Institute of Technology).

Our experiences in Bangladesh raise the issue of the relative importance of in-country capacity building in countries with a relatively low human development index versus direct provision of information to the country. Sagasti (2004) discusses the problems encountered by CFAB in more general terms. He refers to technological interactions between developed and less developed nations as a "Sisyphus effect" that requires continually rebuilding of capacity in the developing world. When the capacity building is related to information (e.g., the CFAB forecasts), we argue for a "world is flat" approach that links collaboratively the information providers from the developed world with the information users in the developing world to use the information for development effectively. Once the developing country reaches a certain level of capacity for the project at hand (e.g., reliable internet band width), then in-country capacity building can proceed. Better developmental and funding models are needed to provide aid to developing economies for the provision of relevant decision-oriented information. The envisioned system needs to engage the academic research and applications community to provide technologies to support the developing world.

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