Supplementary Information:

Modeling complex flow dynamics of fluvial floods exacerbated by sea level rise in the Ganges-Brahmaputra-Meghna Delta

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S1. Channel bifurcation

Bifurcation channels were delineated automatically by the same method as Yamazaki et al 2014 [1] by analyzing the digital elevation model (DEM) and satellite-derived water body data (SRTM Water Body Dataset, https://lta.cr.usgs.gov/srtm_water_body_dataset). SRTM Water Body Dataset (SWBD) was a snapshot image taken around February 2000. February is a low water season in GBM Rivers, so we expect that the water bodies in SWBD represent low water channels in the target domain that can be used to define flow routes in regular (non-flooding) conditions.

S2. Model validation against observations

A validation of the retrospective simulation was conducted against observations to confirm the performance of CaMa-Flood. CaMa-Flood ver. 3.5.2 was employed for this study. Runoff input to CaMa-Flood was calculated from an offline simulation of a land-surface model MATSIRO-GW [2, 3], which was driven by climate forcing based on the Japan Meteorological Agency’s JRA-25 reanalysis dataset [4] with altitude correction at a sub-daily time step and spatial resolution of 1° over the period 1979–2010 [5]. In CaMa-Flood, the channel depth parameter $B$ is given by an empirical power-low equation as $B = \max [2.00, 0.15 \times R_{up}^{0.4}]$ where $R_{up}$ is the 30-day moving average of annual maximum runoff upstream. This equation was determined by adjusting the equation for global simulation in Yamazaki et al [6]. For validation, we used results simulated with channel bifurcation and without SLR (that is, Bif and 0 m SLR conditions). The validated items were river discharge, water level, and flooded area. Names and locations of the gauge stations are shown in figure 1. Modeled inundation depth was
downscaled onto a 9 arc-second (approximately 250 m at the equator) high-resolution DEM by determining whether the elevation of the DEM pixels was lower than the modeled water level. This method is similar to Winsemius et al [7]. Because CaMa-Flood incorporates the same high-resolution sub-grid topography, the water volume in downscaled results is consistent with the water volume before downscaling.

2.1 River discharge

Modeled river discharge was validated against observations from the Institute of Water Modeling (IWM) at two locations: the Ganges River at Hardinge Bridge (HB) and the Brahmaputra River at Bahadurabad (BD). The target period was 2000–2010. Three different indicators were used to check the performance of the CaMa-Flood: Nash-Sutcliff (NS) efficiency [8], the Pearson linear correlation coefficient (R), and percentage bias (PBIAS).

CaMa-Flood captured both the peak flow and seasonal variation in river discharge quite well (figure S1). In the Ganges, although low flow was slightly overestimated, the simulation results were reasonably consistent with observations, with good NS and R values (table S1). Although the modeled increase in the discharge of the Brahmaputra River was slow compared to observations, the seasonal changes and the values of peak and low flow were well simulated, as shown by the high R value.

One of the main reasons for the inconsistency may be the runoff forcing calculated from MATSIRO-GW. Errors in precipitation input to MATSIRO-GW or the calculated runoff of the retrospective MATSIRO-GW simulation could be reasons for the model inconsistency. Another possible source of error could be anthropogenic activity (e.g., water intake and reservoir operation), which was not included in the model.
Table S1. Comparison of observed and simulated river discharge (m³/s) averaged over the period 2000–2010.

|                      | Ganges River at Hardinge Bridge (HB) | Brahmaputra River at Bahadurabad (BD) |
|----------------------|--------------------------------------|---------------------------------------|
| Observation          | Max (m³/s)                           | 52,409                                | 85,879                                |
|                      | Ave (m³/s)                           | 10,379                                | 21,186                                |
|                      | Max (m³/s)                           | 53,621                                | 81,546                                |
|                      | Ave (m³/s)                           | 9,811                                 | 14,307                                |
| Simulation           | NS (-)                               | 0.836                                 | 0.664                                 |
|                      | R (-)                                | 0.915                                 | 0.910                                 |
|                      | PBIAS (%)                            | 0.200                                 | 30.9                                  |

2.2 River water surface elevation

Observed data from the IWM were used to validate the modeled water surface elevation (figure S2). The target period was 2000–2010, and the gauging points were Bhairab Bazar (BB), Goalondo (GL), and Chandpur (CD). Because the reference elevation of the gauging points was unknown, we subtracted the median of the annual minimum observations within the target period from all observations for each gauging station. The model reproduced the variation in
river water surface elevation well in both upstream locations (GL, BB) and in the coastal region (CD), which is supported by the high correlation coefficient (figure S2, table S2). The peak river water surface elevation at BB and CD was also reproduced well. However, the peak river water level was underestimated at the confluence of the Ganges and Brahmaputra (GL). This may be caused by uncertainty in the river depth, which was empirically determined in the model [6]. The degree of variation in the simulations was less than that observed at GL and CD. This may be due to tidal effects, which were not taken into account in this study.

Figure S2. Time series of observed (gray lines) and modeled daily water surface elevation (red lines).
Table S2. Comparison of the observed and modeled water surface elevation (m) averaged over the period 2000–2010. Locations and names of the abbreviated gauging stations are shown in figure 1.

|           | BB    | GL    | CD    |
|-----------|-------|-------|-------|
| Observation | Max (m) | 6.47  | 7.87  | 3.15  |
|           | Ave (m) | 4.12  | 5.21  | 3.17  |
| Simulation | Max (m) | 6.80  | 6.72  | 3.19  |
|           | Ave (m) | 1.43  | 0.908 | 0.412 |
|           | NS (-)  | 0.503 | -0.210 | 0.375 |
|           | R (-)   | 0.874 | 0.840 | 0.689 |
|           | PBIAS (%) | 32.4 | 69.6 | 35.4 |

2.3 Flood area

Modeled flood area was validated against the satellite-derived (MODIS) flood area maps [9]. Figures S3, S4, and S5 show flood area in flood years (2000, 2007) and a normal year (2009), respectively. CaMa-Flood reproduced well the different characteristics of the distribution of flood area (surrounded by red rectangular boxes in figure S3 and S4) for both floods in 2000 and 2007. In the 2000 flood, the west side of Bangladesh (domain ‘B’ in figure S3) was inundated around the bifurcation point from the Ganges (25.0% and 31.8% in MODIS and the model result with the bifurcation scheme (Bif), respectively), whereas in 2007, the upstream of the Ganges was inundated (domain ‘A’ in the figure S4; 13.1% and 16.5% in MODIS and Bif, respectively). The percentages of large flood extent in both observations and simulations are significantly larger in each year (2000 and 2007) than the normal year (2009) as shown in table S2. Furthermore, the large inundation extent in the Meghna basin (the domain ‘D’ in figure S3, S4 and S5) in 2000 and 2007 is also reasonably reproduced (table S3).

However, there were some discrepancies in reproducing flood areas. First, flood inundation along the Brahmaputra (domain ‘C’ in figure S3, S4 and S5) was not represented. The reason for this underestimation is that the empirical power-low equation overestimated river channel depth, preventing water from overflowing from river banks. Second, flood inundation in small tributaries in the upstream Ganges was overestimated. This can also be attributed to the empirical power-low equation for river channel depth. The equation assumes the minimum river channel depth to be 2 m, which may be too small in such a region.

In addition, we analyzed the effect of channel bifurcation on flood inundation. The difference between Bif and NoBif is relatively small compared to the difference between
MODIS and Bif. At domain ‘B’ in 2000 flood, the inundation area in Bif is larger than that in NoBif. This is because flood water from the Ganges flows into this domain through bifurcation channels. On the other hand, at domains ‘A’, ‘C’ and ‘D’, the inundation area in Bif is smaller than that in the NoBif simulation, leading to the better representation of flood extent in Bif. The reason for the decrease in inundation extent at these domains due to channel bifurcation is that floodwater in the main channels flowed into tributaries through bifurcation channels and the resulting decrease in flood extent in the main channels was larger than the increase in tributaries. Given that flood risk estimation is based on inundation depth (section 4 in the main text), channel bifurcation that causes significant differences in simulating inundation depth cannot be neglected in flood risk estimation.
Flood area in 2000

(a) MODIS

(b) CaMa-Flood (Bif)

(c) CaMa-Flood (NoBif)
**Figure S3.** Annual maximum flood area (a) derived from MODIS, (b) modeled with channel bifurcation by CaMa-Flood and (c) modeled without channel bifurcation by CaMa-Flood in 2000. Red rectangles indicate the target domains for the quantitative analysis in table S3.
Figure S4. Same as figure S3 but for the case of 2007.
Figure S5. Same as figure S3 but for the case of 2009.
Table S3. Percentages (%) of flooded areas within each domain indicated in figure S3, S4 and S5.

|       | 2000 | 2007 | 2009 |
|-------|------|------|------|
|       | 2000 | 2007 | 2009 |
| MODIS | 7.20 | 25.0 | 9.44 |
|       |     | 21.5 | 13.1 |
|       |     |     | 10.8 |
|       |     |     | 15.0 |
|       |     |     | 25.3 |
|       |     |     | 4.96 |
|       |     |     | 3.57 |
|       |     |     | 8.82 |
|       |     |     | 15.6 |
| Bif   | 13.9 | 31.8 | 8.11 |
|       |     | 21.9 | 16.5 |
|       |     |     | 13.3 |
|       |     |     | 9.64 |
|       |     |     | 23.3 |
|       |     |     | 5.38 |
|       |     |     | 7.51 |
|       |     |     | 6.58 |
|       |     |     | 18.4 |
| NoBif | 14.6 | 28.4 | 8.20 |
|       |     | 23.9 | 17.0 |
|       |     |     | 13.3 |
|       |     |     | 9.69 |
|       |     |     | 24.4 |
|       |     |     | 5.44 |
|       |     |     | 7.51 |
|       |     |     | 6.71 |
|       |     |     | 19.3 |

S3. Results of annual maximum inundation depth for 1 m SLR

Here we present a set of figures that are the same as figure 3(b) but for 1 m SLR.

Figure S6. Same as figure 3(b) in the main text but for 1 m SLR.

S4. Calculation of flood exposure

Table S4 shows the list of atmosphere-ocean general circulation models (AOGCMs) used in this study. Table S5 shows calculated flood exposure of each AOGCM for the case of RCP 8.5. Results from experiments with and without channel bifurcation or SLR are shown.
**Table S4.** Summary of AOGCMs selected for this study, following [10].

| Model          | Institution                                                                 | No. of grids |
|----------------|------------------------------------------------------------------------------|--------------|
| BCC-CSM1.1     | Beijing Climate Center, China Meteorological Administration, China           | 128×64       |
| CCCma-CanESM2  | Canadian Centre for Climate Modelling and Analysis, Canada                    | 128×64       |
| CMCC-CM        | Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy                  | 480×240      |
| CNRM-CM5       | Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France | 256×128      |
| CSIRO-Mk3.6.0  | Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence, Australia | 192×96       |
| GFDL-ESM2G     | Geophysical Fluid Dynamics Laboratory, USA                                   | 144×90       |
| INM-CM4        | Institute for Numerical Mathematics, Russia                                  | 180×120      |
| MIROC5         | Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan | 256×128      |
| MPI-ESM-LR     | Max Planck Institute for Meteorology (MPI-M), Germany                        | 192×96       |
| MRI-CGCM3      | Meteorological Research Institute, Japan                                     | 320×160      |
| NCC-NorESM1-M  | Norwegian Climate Centre, Norway                                             | 144×96       |
Table S5. Flood exposure in Bangladesh (population in millions). Average values for 2070–2099 for the RCP8.5 scenario. Results under the 0 m and 1 m SLR experiments and simulations with and without bifurcation channels (Bif and NoBif, respectively) are shown. The population is fixed at the 2010 level.

| Model                | 0 m SLR | 1 m SLR | 0 m SLR | 1 m SLR |
|----------------------|---------|---------|---------|---------|
|                      | Bif     | NoBif   | Bif     | NoBif   |
| BCC-CSM1.1           | 50.0    | 40.8    | 51.6    | 42.0    |
| CCCma-CanESM2        | 49.0    | 41.5    | 50.6    | 42.8    |
| CMCC-CM              | 73.4    | 65.6    | 74.6    | 66.6    |
| CNRM-CM5             | 28.3    | 23.4    | 29.9    | 24.7    |
| CSIRO-Mk3.6.0        | 35.7    | 24.6    | 37.3    | 26.01   |
| GFDL-ESM2G           | 34.8    | 31.8    | 36.3    | 33.1    |
| INM-CM4              | 16.8    | 14.0    | 18.3    | 15.3    |
| MIROC5               | 30.0    | 27.2    | 31.4    | 28.5    |
| MPI-ESM-LR           | 23.1    | 20.1    | 24.7    | 21.4    |
| MRI-CGCM3            | 83.3    | 71.6    | 84.5    | 72.7    |
| NCC-NorESM1-M        | 40.5    | 35.2    | 42.0    | 36.6    |
| Multi model mean     | 42.3    | 36.0    | 43.7    | 37.2    |

S5. Limitations

There are some uncertainties that may have affected the flood calculations in this study. These include potential errors caused by the empirical equation of river channel depth in CaMa-Flood, the anthropogenic regulation of river discharge (e.g., dykes, dams, human intakes), and the uncertainty in runoff estimation by MATSRO-GW due to the potential bias in climate forcing or uncertainty in model processes. While we assumed the same increase in the sea level among different locations, SLR may differ among locations [11]. As mentioned in the Conclusions section of the main text, we focused on static SLR projected at 2100 (1 m and 2 m). However, given that coastal storm surges have caused severe damage in deltaic regions, assessments that compound the effects of SLR and coastal storm surges need to be conducted in the future.

Glacier melting due to climate warming is not addressed in this study, though its effect on flood inundation may be small in comparison to runoff increase or SLR.

In flood exposure calculations, the AOGCM runoff data were adjusted using the GSWP2 multi-model mean runoff to avoid the effects of potential biases in raw AOGCM outputs. This means that the adjusted runoff includes the biases in precipitation and hence runoff estimations in GSWP2. Despite the bias in the adjusted runoff, its effects on relative change in flood
exposure should be minimal as the runoff data for both past and future AOGCMs are adjusted by the same ratio. In all simulations, the population was fixed at the 2010 level; that is, we did not take into account changes in human population over time.

References

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