October 22, 2014

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Dear Editor,

Please find enclosed our detailed point-to-point responses to Editor's and Reviewers' comments on our manuscript entitled "Model study of the impacts of future climate change on the hydrology of Ganges-Brahmaputra-Meghna (GBM) basin". This manuscript has been submitted previously to HESSD as hess-2014-156 with the encouragement for resubmission. We thank Editor and two anonymous Reviewers for their thoughtful and constructive comments. We have revised our manuscript thoroughly, including re-running hydrologic model simulations by using additional 4 GCMs forcing data in order to address the concerns from the Editor. We have also validated our model at three more streamflow gauging stations located at the upstream of the GBM basins. Also, we have followed one Reviewer's instructions to correct the bias of GCM data based on the monthly scaling factor instead of the previously used annual scaling factor.

A summary of the major revisions that have been made by us is provided in the following:

1. We have improved our model simulations with the calibration of additional model parameters (i.e., the meandering ration and effective flow velocity) following the comments of both Reviewer #1 and #2.
2. We have validated our model at three more upstream stations according to suggestion of Reviewer #2.
3. We have added 4 more GCMs, all participating in the Coupled Model Inter-comparison Project Phase 5 (CMIP5) in our analysis according to suggestion of Editor.
4. We have corrected the bias of GCM data based on the monthly scaling factor (multiplier) instead of the previous annual scaling factor following the suggestion of Reviewer #1.
5. We have included a new Table 1 describing the major characteristics of three basins of GBM

according to suggestion of Reviewer #2.

6. We have included a new Table 3 providing the basic information of streamflow gauging stations used for calibration and validation.
7. We have revised Table 2 (former Table 1), Table 4 (former Table 2), Table 5 (former Table 3) and Table 6 (former Table 4) to be higher quality.
8. We have revised Fig. 1, Fig. 2, Fig. 4 (former Fig. 6), Fig. 5 (former Fig. 7), Fig. 6 (former Fig. 8), Fig. 7 (former Fig. 9), Fig. 8 (former Fig. 10) and Fig. 9 (former Fig. 11).
9. We have removed a figure (former Fig. 4) as it was less important to this study.
10. We have revised Fig. 4 (former Fig. 6) by combining former Fig. 5 and Fig. 6 according to suggestion of Editor.
11. We have corrected all technical and grammatical mistakes as suggested by both Reviewer #1 and #2.

Please let us know if there are any questions or issues that we need to provide additional information. Thank you for your consideration on our manuscript.

Sincerely,

Muhammad Masood
Pat J.-F. Yeh
Naota Hanasaki
Kuniyoshi Takeuchi

Reference Number: hess-2014-156

RESPONSE TO THE EDITOR'S COMMENTS

We are grateful to the Editor for his helpful and insightful comments. The provided comments have contributed substantially to improving the manuscript. Accordingly, we have made significant efforts to revise the manuscript, with the details being explained as follows.

Point #1

COMMENT: *Pay attention to the logistic of the sentences in the first paragraph. Revise it to focus on the topic. For example, you need some words to emphasise the importance of climate change impact study. Also, please pay attention to the language as pointed out by the Referees.*

RESPONSE: Thanks for the comments. We are grateful to the Editor for his concerns. Accordingly, we have revised the manuscript thoroughly to improve writing quality. We have revised the first paragraph as follows:

> Bangladesh is situated in the active delta of the world's three major rivers, the Ganges, Brahmaputra and Meghna. Due to its unique geographical location, the occurrence of water-induced disasters is a regular phenomenon. In addition, the anticipated change in climate is likely to lead to an intensification of the hydrological cycle and to have a major impact on overall hydrology of these basins and ultimately lead to increase the frequency of water-induced disasters in Bangladesh. However, the intensity, duration, and geographic extent of floods in Bangladesh mostly depend on the combined influences of these three river systems. Previous studies revealed that flood damages have become more severe and devastating when more than one flood peaks in these three river basins coincide (Mirza, 2003;Chowdhury, 2000).

Point #2

COMMENT: *As authors realised, just one GCM is subject to a lot of uncertainties for projecting future hydrological regime. I would suggest to bring several more GCM results for comparison, at least for climatic variables. It should not be a difficult task..*

RESPONSE: Thanks for the comments. Accordingly, we have added 5 GCMs (MIROC5, MIROC-ESM, MRI-CGCM3, HadGEM2-ES and MRI-AGCM3.2S), all participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) in our analysis. We have revised all concerning text accordingly and revised Fig. 7 (former Fig. 9), Fig. 8 (former Fig. 10) and Fig. 9

(former Fig. 11). We have also revised Table 2 (former Table 1), Table 5 (former Table 3), Table 6 (former Table 4) and also included a new Table (Table B1) presenting basic information of all the GCMs in Appendix B.

Point #3

COMMENT: *Please remove country boundaries in Figure 1 to avoid political conflict.*

RESPONSE: Thanks for the comments. Accordingly, we have removed all country boundaries in Figure 1 as follows:

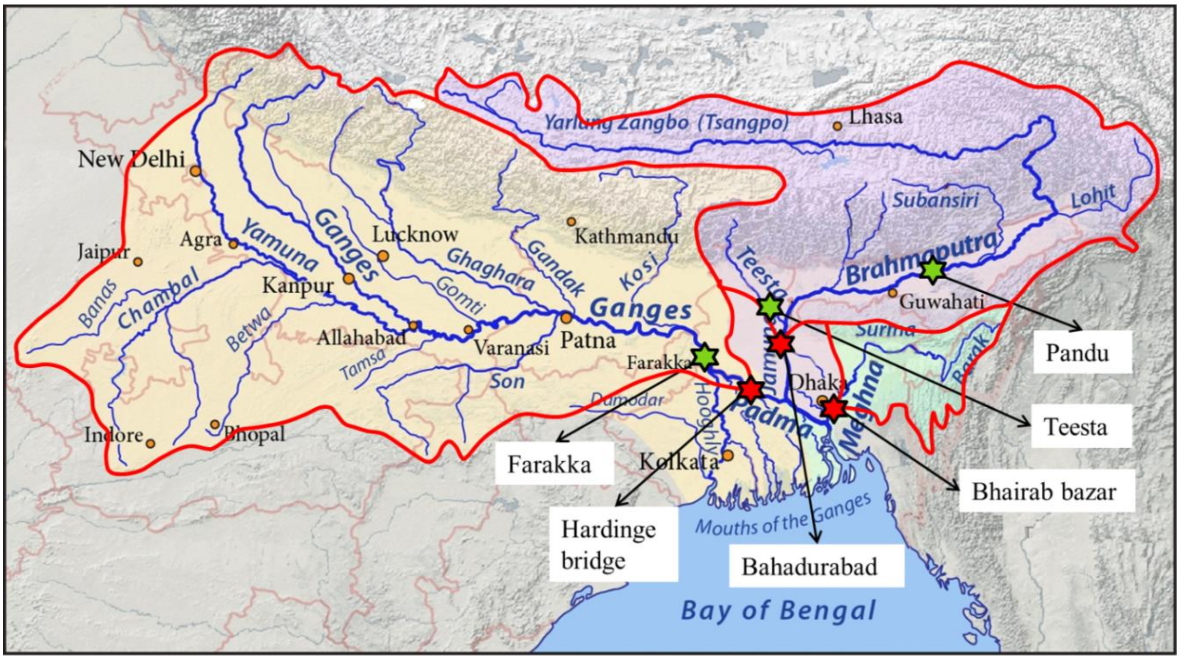


Figure 1. The boundary of the Ganges-Brahmaputra-Meghna (GBM) River basin (thick red line), the three outlets (red star): Hardinge bridge, Bahadurabad and Bhairab bazar for the Ganges, Brahmaputra and Meghna River basin, respectively. Green stars indicate the locations of three additional upstream stations; Farakka, Pandu and Teesta. (modified from Pfly, 2011).

Point #4

COMMENT: *Can you combine Fig5 and 6 together? It would be better to understand the modelling uncertainty.*

RESPONSE: Thanks for the comments. Accordingly, we have revised Fig. 4 (former Fig. 6) by combining former Fig. 5 and Fig. 6. However, we have shown the uncertainty band of simulated discharge in a typical year (1985) as plotted in Fig. 4e. Because, it is difficult to identify the uncertainty band in time series plots (in Fig. 4a, b, c). The revised figure is as follows:

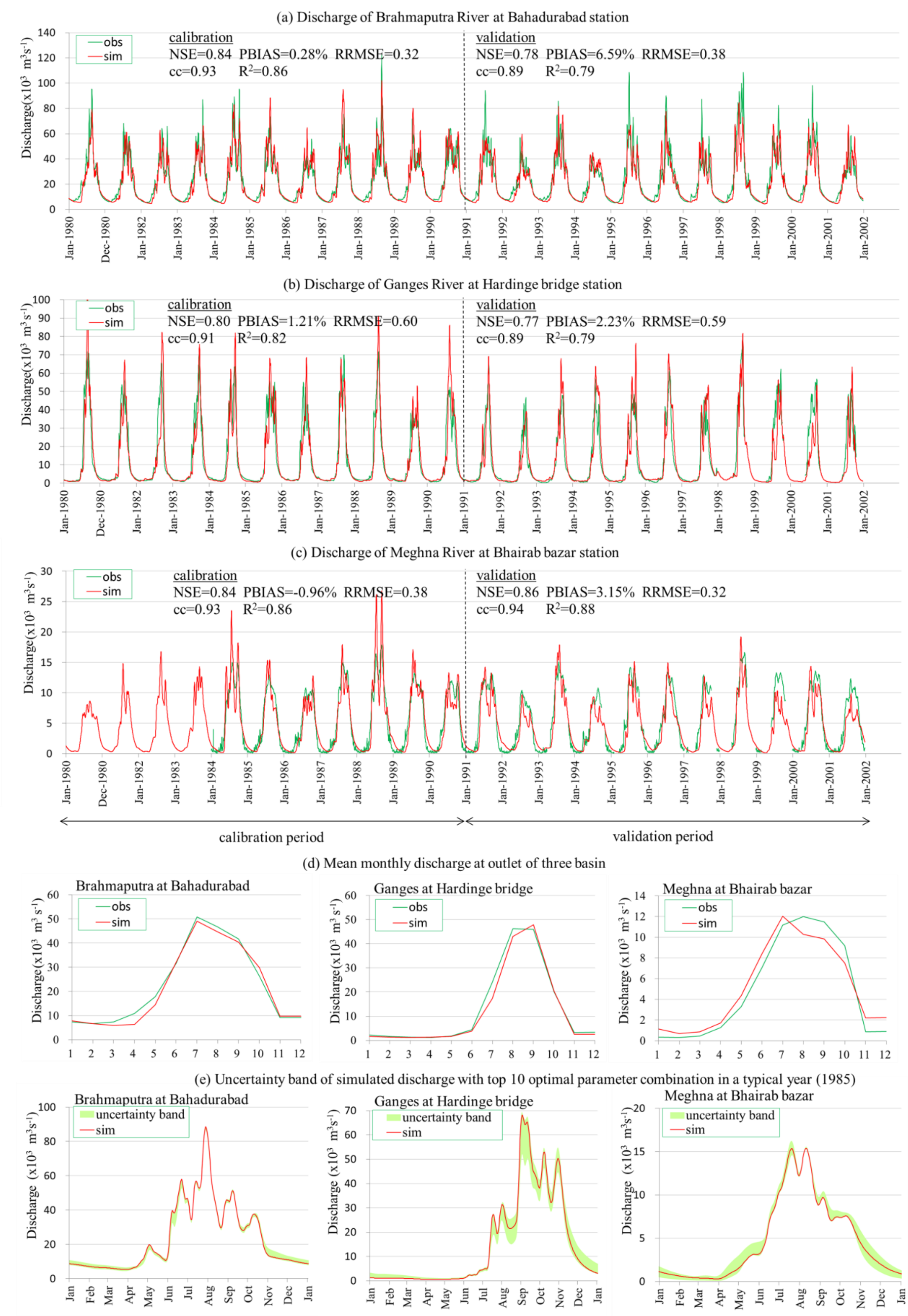


Figure 4. The simulated discharges (red line) using the WFD forcing data (both calibration and validation period) compared with observations (green line) at outlets of the (a) Brahmaputra, (b) Ganges, (c)

Meghna River, (d) mean monthly (1980-2001) simulated discharges compared with that of observations at outlets, (e) simulated discharges by using the 10 optimal parameter sets (red line) and the associated uncertainty bands (green shading) in a typical year (1985). Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), relative Root-Mean Square Error (RRMSE), correlation coefficient (cc) and coefficient of determination (R^2) for both calibration and validation period are noted at sub-plot (a), (b) and (c).

RESPONSE TO THE FIRST REVIEWER'S COMMENTS

We are grateful to Reviewer #1 for his/her helpful and insightful comments. The provided comments have contributed substantially to improving the manuscript. Accordingly, we have made significant efforts to revise the manuscript, with the details being explained as follows.

Point #1

COMMENT: *The paper is well organised but the writing need to be improved substantially (English editing) for publication in HESS.*

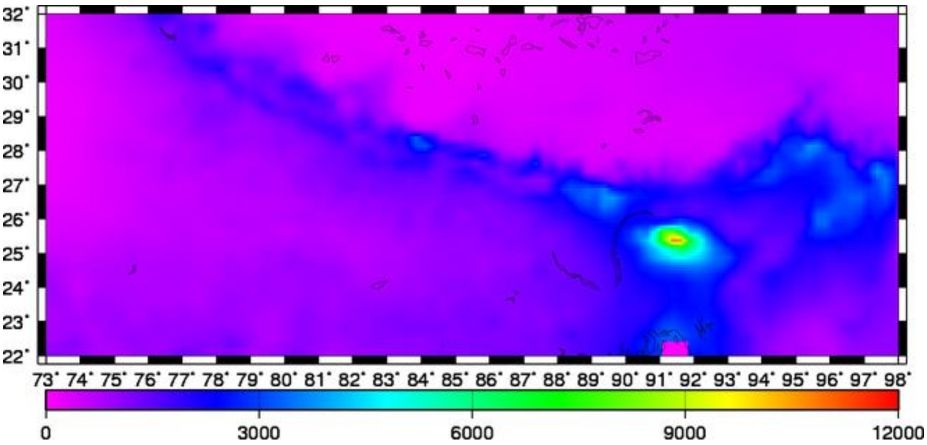
RESPONSE: Thanks for the comments. We are grateful to the Reviewer for his/her concerns. Accordingly, we have revised text to improve writing quality.

Point #2

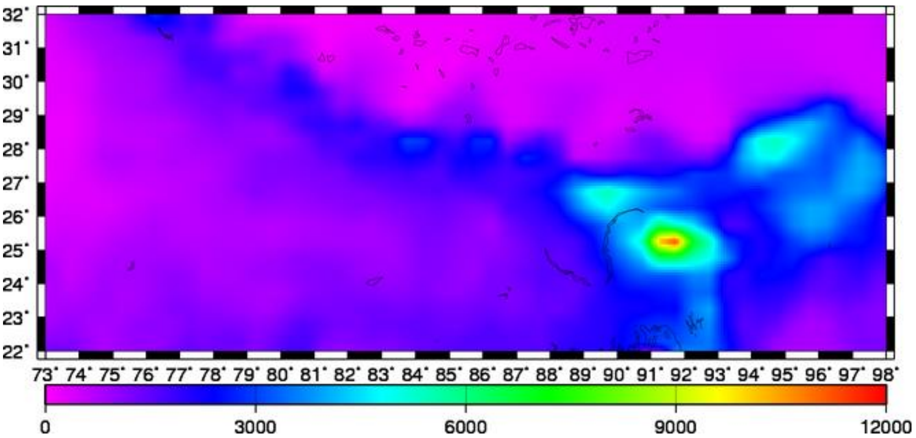
COMMENT: *The authors have used WFD forcing data when there are a number of publications which show that the APHRODITE reanalysis data is the best available climate data for this region.*

RESPONSE: Thanks for the comments. We do agree with the Reviewer that the APHRODITE precipitation dataset is the best available dataset. However, the required climate forcing data for running H08 include seven metrological variables: precipitation, specific humidity, air temperature, surface pressure, wind speed, downward shortwave radiation and downward long-wave radiation. The WFD dataset provides all of these seven forcing variables, but the APHRODITE only provides precipitation and temperature. Following the Reviewer's comments, we have re-simulated H08 by using the APHRODITE precipitation and temperature data. We found the simulation using APHRODITE precipitation and temperature data does not give better simulation results than the simulation using WFD.

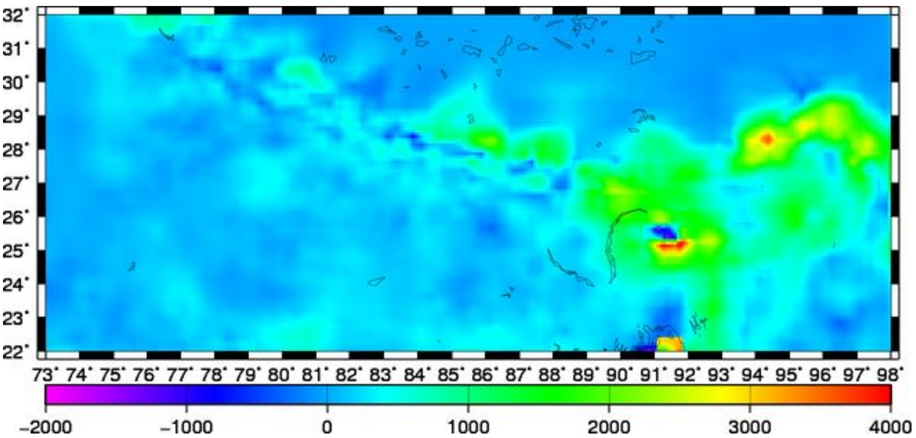
Spatial distribution of annual (1988) precipitation of the WFD and the APHRODITE over entire GBM basin and difference between two data are shown below:



APHRODITE (mm year^{-1})



WFD (mm year^{-1})

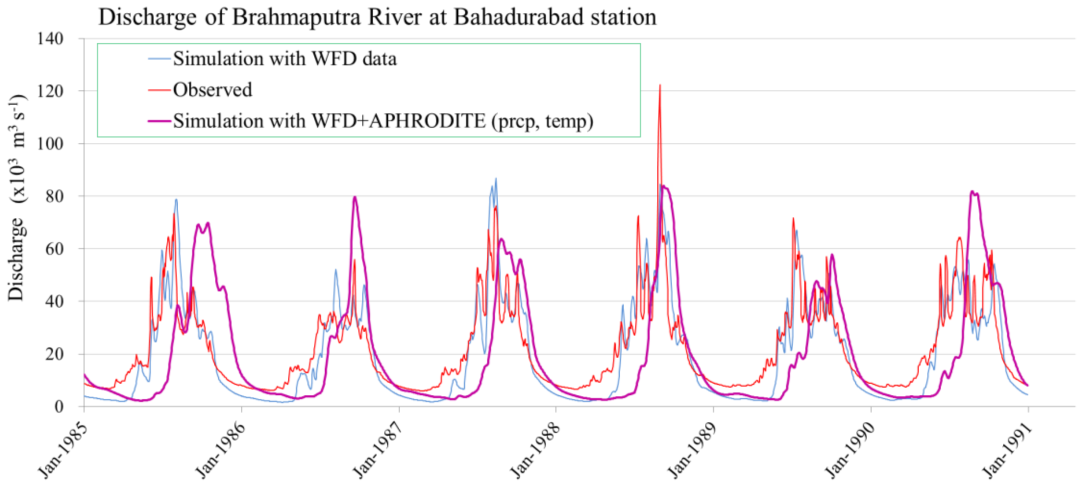


WFD - APHRODITE (mm year^{-1})

Result obtained from two different simulations (1988) using the APHRODITE and the WFD precipitation data (unit: mm year^{-1})

		Rainfall	Snowfall	Total runoff	ET
APHRODITE	Entire GBM	1 171	27	664	524
	Brahmaputra	1 252	9	852	424
	Ganges	959	27	442	537
WFD	Entire GBM	1 555	27	1 034	538
	Brahmaputra	1 819	16	1 430	426
	Ganges	1 178	18	627	565

Time series plot of simulated discharge using both (i) complete dataset from the WFD and (ii) combination of precipitation and temperature data from the APHRODITE dataset and other metrological variables from the WFD is shown below:



Point #3

COMMENT: *I have a major issue with the way the authors have used bias correction for the GCM rainfall. The authors state that the GCM does okay for pre and post monsoon as well as for the drier winter months but it underestimates the monsoon high rainfall. The bias (underestimation) when compared to WFD rainfall is due to this underestimation by MRI for monsoon high rainfall events. But the authors apply an annual scaling factor (multiplier) which will push up all the rainfall throughout the year by a small amount instead of only the monsoon high events. This will lead to underestimation of monsoon high rainfall and eventually high runoff events as evident from Figure 6 a and b. The authors should be adjusting (bias correcting) different rainfall amounts based on seasons differently to overcome this issue.*

RESPONSE: We fully agree with the Reviewer's comment. We much appreciate the Reviewer's suggestion. Accordingly, we have corrected the bias of GCM data based on the monthly scaling factor (multiplier) instead of using the previous annual scaling factor. We have revised all our modelling results accordingly. Also, we have revised the text in the Introduction as follows:

> In order to be consistent with the historical data, the monthly correction factor (i.e. the ratio between the basin-scale long-term monthly mean precipitation of the WFD data and that of the GCM data for each month) for each basin is applied to each GCM's precipitation forcing data.

And we have revised in the Section 2.4 as follows:

> In order to be consistent with the historical data, the bias of precipitation forcing data of each GCM has been corrected by multiplying the monthly correction factor equal to the ratio between the basin-averaged long-term mean precipitation from a GCM and that from WFD for each of the twelve months in each GBM basins.

Figure 4 (former Figure 6) presents the hydrograph comparisons for both the calibration and validation period using the WFD forcing dataset. We have revised the caption of Figure 4 (former Figure 6) as follows:

> Figure 4. The simulated discharges (red line) using the WFD forcing data (both calibration and validation period) compared with observations (green line) at outlets of the (a) Brahmaputra, (b) Ganges, (c) Meghna River, (d) mean monthly (1980-2001) simulated discharges compared with that of observations at outlets, (e) simulated discharges by using the 10 optimal parameter sets (red line) and the associated uncertainty bands (green shading) in a typical year (1985). Nash–Sutcliffe efficiency (NSE), percent bias

(PBIAS), relative Root-Mean Square Error (RRMSE), correlation coefficient (cc) and coefficient of determination (R2) for both calibration and validation period are noted at each sub-plot.

Point #4

COMMENT: *Page 5756 top paragraph: Having worked in this region for a long time, I do not agree that the authors should be ignoring crop growth (as most of the area is under agriculture) and reservoir operations components of the HO8 model. This is a major shortcoming of this analysis. And later on in the paper when the model simulations are poor, the authors speculate that this is due to ignoring these components. They should be switching on the components and show whether they can explain the processes.*

RESPONSE: Thanks for the comments. We have improved our model simulation. Now we have found that our results agreed satisfactorily with observed data. However, we are not ignoring the crop growth process. The rationale here is to run the crop growth model (CGM) and reservoir model (ReM), we need to complete the land surface model (LSM) and river models (RiM) beforehand because the output of LSM and RiM becomes the input of CGM and ReM. In this paper, we are not neglecting the human activities, but we are now just first focusing on the natural part of the basin. Moreover, we have compared our simulation result with the results of Biemans et al. (2013) who explicitly considered crop production and water use in this basin. The following table shows comparison of mean discharge at Bahadurabad station, the outlet of Brahmaputra basin:

Mean discharge at Bahadurabad (outlet of Brahmaputra) (1986-1991) ($m^3 s^{-1}$)			
Our simulation result	Global Runoff Data Centre (GRDC)	Observed (rating equation)	Biemas et al. (2013)
23 299	23 719	22 767	20 947

Biemans, H., Speelman, L. H., Ludwig, F., Moors, E. J., Wiltshire, A. J., Kumar, P., Gerten, D., and Kabat, P. (2013). Future water resources for food production in five South Asian river basins and potential for adaptation — A modeling study, Science of The Total Environment, 468–469, Supplement, S117-S131, http://dx.doi.org/10.1016/j.scitotenv.2013.05.092.

Point #5

COMMENT: *'Soil moisture is expressed as a single-layer bucket which is 15 cm deep for all soils and vegetation types'. This is surely not valid for this region.*

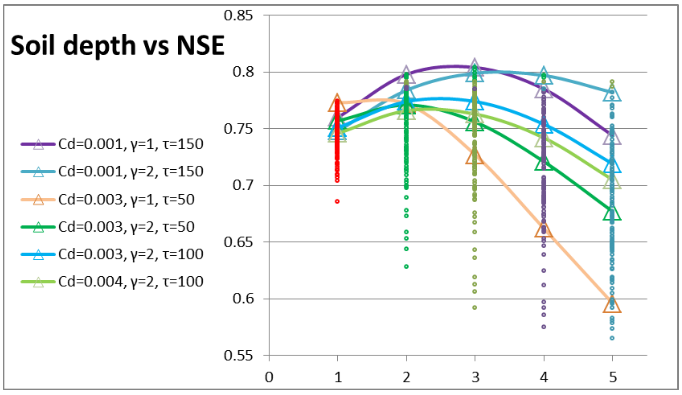
RESPONSE: Thanks for the comments. What we meant that our model assumes "a 15-cm deep single-layer bucket" is that the water holding capacity of soil is set to be 150 mm, which is the commonly specified value in the global land surface model simulations since the original pioneering work of the bucket model developed by Professor Manabe in 1969.

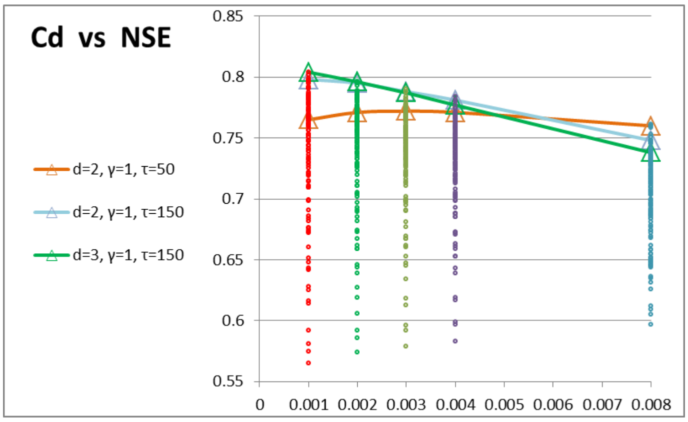
Point #6

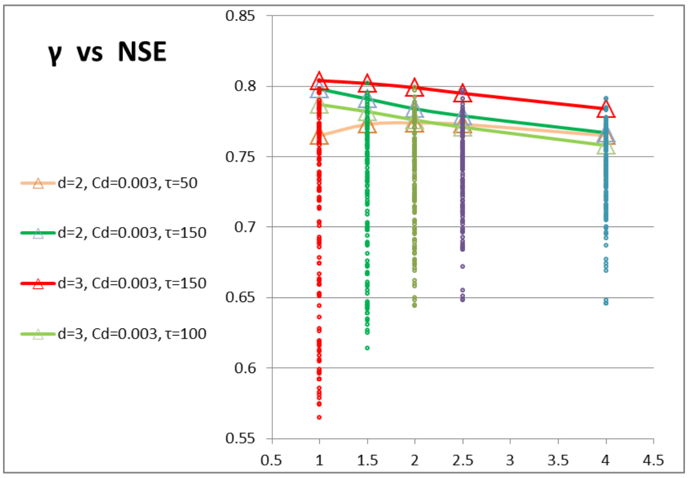
COMMENT: *Section 3.1 Parameter sensitivity: The analysis the authors have undertaken is not really Monte Carlo as they are just sampling 5 random seeds for the entire parameter distribution. The five points picked can be all away from the optimum.*

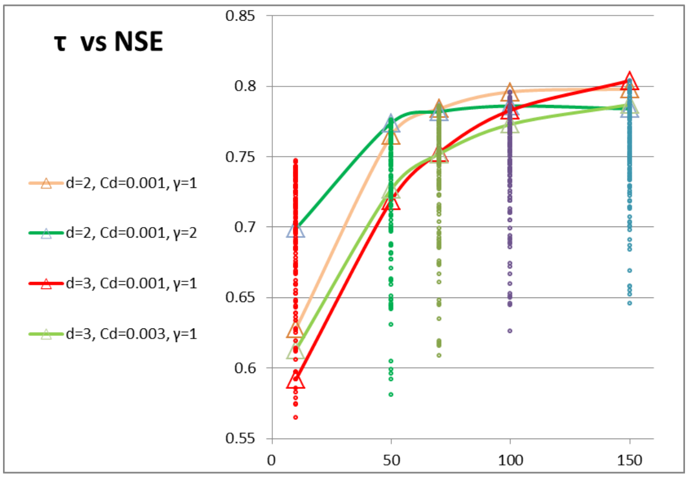
RESPONSE: Thanks for the comments. Five parameter values were chosen for each calibration parameter within their respective feasible physical ranges, then in total 625 simulations were conducted considering the extensive combinations from these parameter spaces and based on that the optimal parameters were determined. We agree with the Reviewer that the method we used in this study is not the same as the Monte Carlo simulation since we did not consider/analyse the statistical distributions of either parameter values or the simulation results. Therefore, we revise the wording "the Monte Carlo simulation" into "the parameter-sampling simulation" throughout the entire manuscript.

As regarding the identification of optimal parameter values, the following plots of the evaluation of model simulations in terms of Nash–Sutcliffe efficiency (NSE) to each calibration parameter suggest that there is little possibility of escaping from the optimum, given the fact that all parameters must lie within their respective feasible ranges.









<u>**Point #7**</u>

COMMENT: *Discussion on page 5759'Figure 4 shows that: : :: : :unchanged'. I do not agree that we need to do any model simulations to find out what the authors are reporting here. Having used the model before, the model equations/formulation already tells you this and you don't need to do any model simulations.*

RESPONSE: Thanks for your comments. We agree with the Reviewer's instructions, and accordingly the former Figure 4 as well as the related discussion in the text, have been totally removed in the revised manuscript.

Point #8

COMMENT: *Page 5761 - 3.2 Calibration and validation (bottom of this page 'This is likely : : :: : :..present model simulation'. This statement is factually incorrect as it is a well accepted fact that backwater effect is larger under low flow conditions than high flow conditions'.*

RESPONSE: Thanks for the comments. We do agree with the Reviewer's comments, so we have removed these sentences in the revised manuscript.

Point #9

COMMENT: *Page 5762 – 4.1 Seasonal cycle: 'Lower ET of Brahmaputra : : :..compared to other two basins'. Brahmaputra NDVI is 0.38, Ganges is 0.41 and Meghna is 0.65. The physical/hydrological explanation for the results provided by the authors is incorrect as Brahmaputra and Ganges have very close NDVI (0.38 and 0.41).*

RESPONSE: Thanks for the comments. However, the magnitude of ET depends on several other factors than NDVI. Lower ET values in the Brahmaputra basin is likely due to its cooler air temperature (Ganges: 21.7°C vs. Brahmaputra: 9.1°C) and higher elevation than that in the Ganges though these two basins have very similar NDVI. We have revised the sentences in Section 4.1 as follows:

> Lower ET in the Brahmaputra basin is likely due to its cooler air temperature, higher elevation and less vegetated area. The basin-averaged Normalized Difference Vegetation Index (NDVI) of the Brahmaputra is 0.38, whereas for the Ganges and Meghna, NDVI are 0.41 and 0.65, respectively (NEO, 2014).

Point #10

COMMENT: *Page 5768 – 4.5 Uncertanity in projection due to model parameter (towards the bottom of this page 'Therefore, uncertainty of future: : :: : :..). the authors are missing some key references here which sheds light on parameter usability under climate change or variable* *climate conditions. Coron, L., Andréassian, V., Perrin, C., Lerat, J., Vaze, J., Bourqui, M., Hendrickx, F. 2012. Crash testing hydrological models in contrasted climate conditions: an experiment on 216 Australian catchments, Water Resour. Res., 48, 5, doi:10.1029/2011WR011721. Vaze, J., Post, D. A., Chiew, F. H. S., Perraud, J.-M., Viney, N., Teng, J., 2010. Climate nonstationarity - Validity of calibrated rainfall-runoff models for use in climate change studies. Journal of Hydrology, Volume 394, pp. 447–457, doi:10.1016/j.jhydrol.2010.09.018.*

RESPONSE: We are grateful to the Reviewer for his/her concerns. Thanks to the Reviewer for referring these two important articles. We have referred these studies and revised text in Sec. 4.5 as follows:

> Therefore, uncertainty of future projection due to model parameter cannot be neglected (Vaze et al., 2010; Merz et al., 2011; Coron et al., 2012), which is mostly ignored in the climate change impact studies (Lespinas et al., 2014). Result obtained by Vaze et al. (2010) indicates that the model parameter can generally be used for climate impact studies when model is calibrated using more than 20 years of data and where the future mean annual rainfall is not more than 15% drier or 20% wetter than the mean annual rainfall in the model calibration period. However, Coron et al. (2012) found significant level of errors in simulations due to this uncertainty and suggested further research to improve methods to diagnose parameter transferability under a changing climate.

Point #11 (i)

COMMENT: *Page 5769 i) toward the top– 'uncertanity band for runoff is low' this is partly because you are showing total runoff and not the components (surface and subsurface);*

RESPONSE: Thanks for your comments. We do agree with the Reviewer that the uncertainty band of the two (surface and sub-surface) runoff components is not necessarily narrow although the uncertainty of the total runoff is low. The two model parameters (τ and γ) have very sensitive impacts on the flow partitioning (as shown in the Fig. 3). However, in this study we focused on estimating the future change and the associated uncertainty of the total runoff ONLY, not attempted to address the uncertainty of the simulations of two runoff components since we do not have any baseflow data available to validate this runoff partitioning.

Point #11 (ii)

COMMENT: *ii) just below the above statement' from Fig 5 it is observed that: : :..' This statement is misleading as you are looking at the 10 simulations and all of them being similar to* *each other does not imply that uncertainty is low.*

RESPONSE: Thanks for the comments. We fully agree with the Reviewer. The uncertainty of runoff is low since we calibrated our model against the observed stream discharge and we chose the optimal 10 parameter sets to estimate the uncertainty, as mentioned in Section 4.5 (line 15, page 5769).

Point #11 (iii)

COMMENT: *The discussion on this whole page is speculative and misleading. You are comparing results from multiple realisations of the model and all of them giving similar answer only tell that the predicted/simulated variable is insensitive to the parameter value. The real value is when you compare the simulations to observations, either on-ground or secondary such as satellite ET and soil moisture data. Page 5786 Figure 6 – a). The figure shows that the model cannot reproduce peak flows well (this is due to the fact that the bias correction method you have used underestimates peak rainfall – see comment 3 above). The model cannot reproduce the peaks in the validation period as well. Page 5769 – 7th line from top 'Lower uncertainty: : :: : :: : :could be ignored'. Your calibrated model is not able to reproduce the peak flows in calibration and validation. What confidence do you have in the model simulations for the future climate conditions.*

RESPONSE: Thanks for the comments. According to the suggestion of Reviewer we have improved our model simulations as described in Section 3.2 and also shown in Figure 4 (the former Figure 6). In this study, we have attempted to estimate the uncertainty in projection due to non-stationary model parameter. It is very common in hydrologic modelling study that calibrated model parameters are assumed as stationary over the whole span of study period. Therefore, our hypothesis was "calibrated model parameter might not be stationary over time". In other words, best model parameter set obtained from calibration in current climate might not be represented as best set in future climate. Therefore, in our study we tried to compare uncertainty in projecting different hydrologic variables through model simulation with considering 10 optimal parameter set (assuming any one set among 10 set might be represented as best set in future) while most of previous studies considered a single best parameter set.

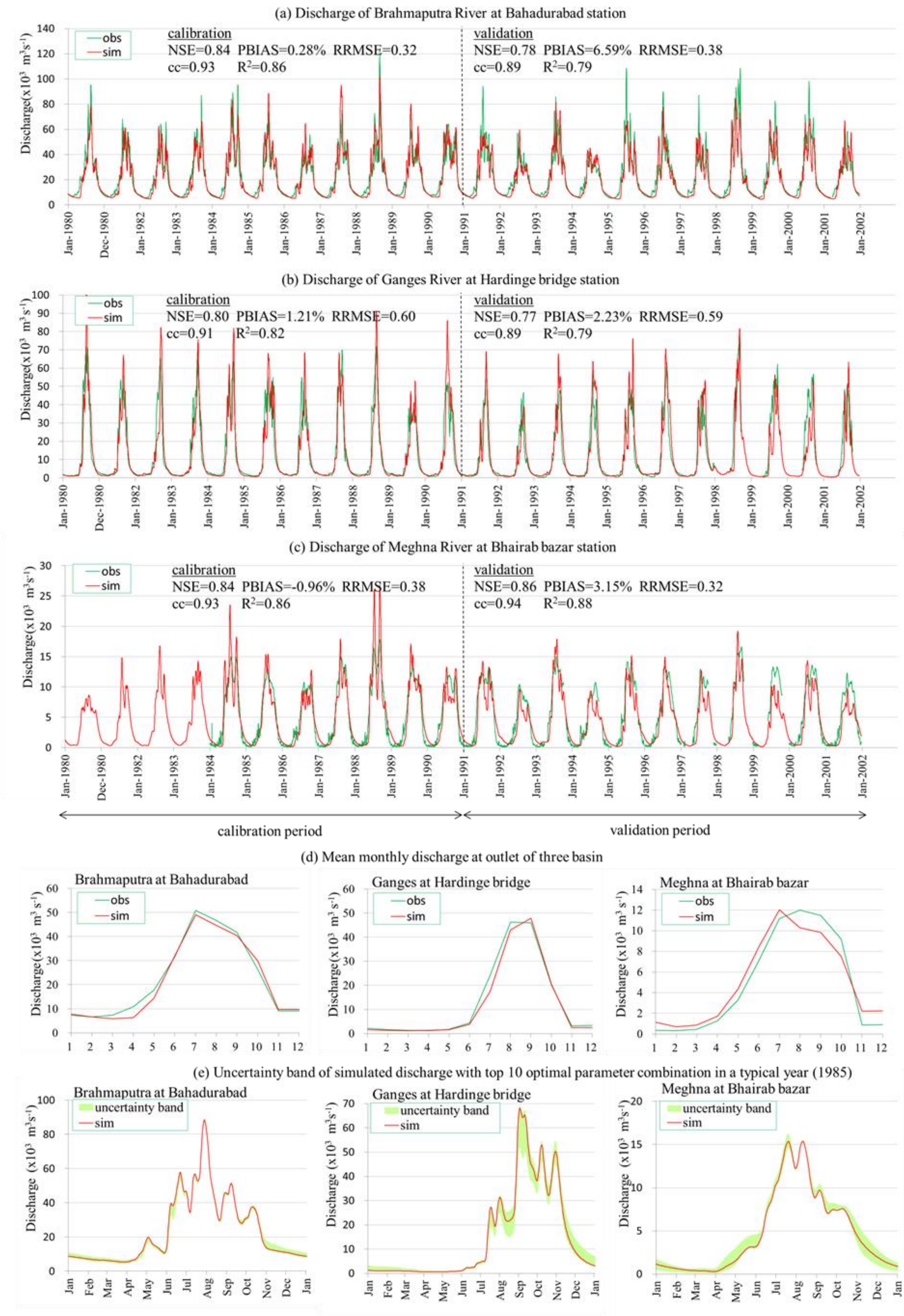


Figure 4. The simulated discharges (red line) using the WFD forcing data (both calibration and validation

period) compared with observations (green line) at outlets of the (a) Brahmaputra, (b) Ganges, (c) Meghna River, (d) mean monthly (1980-2001) simulated discharges compared with that of observations at outlets, (e) simulated discharges by using the 10 optimal parameter sets (red line) and the associated uncertainty bands (green shading) in a typical year (1985). Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), relative Root-Mean Square Error (RRMSE), correlation coefficient (cc) and coefficient of determination (R^2) for both calibration and validation period are noted at sub-plot (a), (b) and (c).

RESPONSE TO THE SECOND REVIEWER'S COMMENTS

We are grateful to Reviewer #2 for his/her helpful and insightful comments. The provided comments have contributed substantially to improving the manuscript. Accordingly, we have made significant efforts to revise the manuscript, with the details being explained as follows.

Specific comments

Point #1

COMMENT: *The length of time periods should correspond to the standard of 30 years applied in climate impact assessment.*

RESPONSE: Thanks for the comments. The MRI-AGCM3.2S data which we obtained from MRI to use in this study only contain three 25-year time-slice experiments: the present-day (1979–2003), near-future (2015-2039) and far-future (2075–2099) periods. After hearing Reviewer's comments back, we have asked for getting longer MRI-AGCM data, but unfortunately without success. Therefore, we have to stick to the analysis of three 25-year periods, and we do not think this will cause large differences comparing to the 30-year simulation analysis.

Point #2

COMMENT: *From the abstract should be clear, which climate scenarios were applied, before describing the final results.*

RESPONSE: We much appreciate the Reviewer's suggestion. Accordingly, we have updated the Abstract as follows:

> The impacts of climate change (considering high emissions path) not only on the runoff, but also on the basin-scale hydrology including evapotranspiration, soil moisture and net radiation have been assessed in this study by using 5 GCMs of CMIP5 through three time-slice experiments; present-day (1979–2003), near-future (2015-2039) and far-future (2075–2099) periods.

Point #3

COMMENT: *Abstract: "due to increased net radiation" and Section 4.4.6: why is the net radiation increasing? Please discuss.*

RESPONSE: Thanks for the comment. Accordingly, we have revised the Section 4.4.6 as follows:

> Net radiation is projected to be increased by >4% for all the seasons except summer in the entire GBM basin by the end of the century (Figure 9g-i). Due to the increase in the future air temperature, the downward long-wave radiation will increase accordingly and lead to the increase in net radiation. However, the change of net radiation in the far-future period is larger in dry season (Brahmaputra: 10.3%, Ganges: 5.3%, Meghna: 6.5%) than wet season (Brahmaputra: 3.1%, Ganges: 3.4%, Meghna: 3%). For the near-future period, net radiation is projected to decrease by <1% through about all seasons due to the smaller increase in air temperature (~1°C) as well as decreased incoming solar radiation (not shown) in this basin.

Point #4

COMMENT: *Please include a Table with main characteristics of 3 basins, like: average elevation and elevation range, average T, P, Q, major land use classes, soils, extent of water use (irrigation etc.). It would be helpful for analysis the results, e.g. in Section 4.1.*

RESPONSE: We much appreciate the Reviewer's suggestion. Accordingly, we have included the following new table (as the Table 1 in the revised manuscript) describing the major characteristics of the three GBM basins. As regarding the average temperature (T) and precipitation (P), they were already included in the Table 4 (former Table 2).

Table 1: Major characteristics of Ganges, Brahmaputra and Meghna river basin

Item	Brahmaputra	Ganges	Meghna
Origin and major properties [a]	The Brahmaputra River begins in the glaciers of the Himalayas and travels through China, Bhutan, and India before emptying into the Bay of Bengal in Bangladesh. It is snow-fed braided river and it remains a natural stream with no major hydraulic structures built along its reach.	The Ganges River originates at the Gangotri glaciers in the Himalayas and it passes through Nepal, China, and India and empties into the Bay of Bengal at Bangladesh. It is snowmelt-fed river regulated by upstream India.	The Meghna River is a comparatively smaller, rain-fed, and relatively flashier river that runs through a mountainous region in India before entering Bangladesh.

Basin area (km^2)		583 000[b]	907 000[b]	65 000[b]
		530 000[f,g]	1 087 300[h]	82 000[h]
		543 400[h]	1 000 000[c]	
River length (km)		1 800[b]	2 000[b]	946[b]
		2 900[f]	2 510[c]	
		2 896[a]	2 500[a]	
Elevation	Range	8 ~ 7057	3 ~ 8454	-1 ~ 2579
(m a.s.l.) [e]	Average	3141	864	307
	Area below 500 m:	20%	72%	75%
	Area above 3000 m:	60%	11%	0%
Discharge	Station	Bahadurabad	Hardinge bridge	Bhairab bazar
($m^3 s^{-1}$)	Lowest	3 430[d]	530[d]	2[d]
	Highest	102 535[d]	70 868[d]	19 900[d]
	Average	20 000[g]	11 300[d]	4 600[d]
Land use	Agriculture	19%	68%	27%
(% area) [i]	Forest	31%	11%	54%
Basin-averaged Normalized Difference Vegetation Index (NDVI)[j]		0.38	0.41	0.65
Total number of dams (both for hydropower and irrigation purpose)[k]		6	75	-

[a] Moffitt et al. (2011)

[b] Nishat and Faisal (2000)

[c] Abrams (2003)

[d] BWDB (2012)

[e] Estimated from SRTM DEM data by Lehner et al. (2006)

[f] Gain et al. (2011)

[g] Immerzeel (2008)

[h] FAO-AQUASTAT (2014)

[i] Estimated from Tateishi et al. (2014)

[j] Estimated from NEO (2014)

[k] Lehner et al. (2008)

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Point #5

COMMENT: *Using only Nash and Sutcliffe efficiency and correlation coefficient for evaluation of model performance is not sufficient. In addition, at least one else criterion, e.g. PBIAS, should be applied. It is also recommended to compare the simulated and observed long- term average daily (or monthly) discharges for the calibration and validation periods in addition to graphs presented in Fig. 6.*

RESPONSE: We much appreciate the Reviewer's suggestion. Accordingly, we have evaluated our simulated hydrographs by the Nash–Sutcliffe efficiency (NSE), the percent bias (PBIAS), the relative Root-Mean Square Error (RRMSE), the correlation coefficient (cc) and the coefficient of determination (R^2). We have revised the manuscript (in Section 3.2) as follows:

> The obtained NSE for the calibration (validation) period is 0.84 (0.78), 0.80 (0.77), and 0.84 (0.86), while the percent bias (PBIAS) is 0.28% (6.59%), 1.21% (2.23%) and -0.96% (3.15%) for the Brahmaputra, Ganges, and Meghna basins, respectively. For all basins, the relative Root-Mean Square Error (RRMSE), the correlation coefficient (cc), and the coefficient of determination (R2) for the calibration (validation) period ranges from 0.32 to 0.60 (0.32 to 0.59), 0.91 to 0.93 (0.89 to 0.94) and 0.82 to 0.86 (0.79 to 0.88), respectively. These statistical indices suggest the model performance is overall satisfactory.

We have revised the following Figure 4 (former Figure 6) with the above important statistical indices; also, we have plotted the long-term mean monthly discharges of the three basins in this Figure.

Point #6

COMMENT: *The calibration/validation results are not fully convincing, especially for the Ganges. It is doubtful that water use upstream can explain the time lag in the simulated hydrograph. Besides, is water used in the Ganges to a larger extent than in the other two basins? Please clarify this point, and add some numbers to make it evident.*

RESPONSE: We are grateful to the Reviewer's comment. Accordingly, we have improved our simulation by including two more calibration parameters; that is, the meandering ratio and the effective flow velocity. The statistical indices of our new simulations, as summarized in each sub-plots of Figure 4 (former Figure 6), suggest that the model performance is overall quite satisfactory.

Point #7

COMMENT: *The calibration and validation only for one gauge per basin for such large river basins is still doubtful. In section 2.2 is said: "data were mainly for the outlets". It means, there were additional data for other intermediate gauges? This would be very beneficial to include them into the calibration procedure (multi-site calibration).*

RESPONSE: Thanks for the comment. Accordingly, we have validated model simulations by comparing the simulated and observed daily streamflow at three outlets of the GBM basins. These long-term observed daily streamflow data were collected regularly by the Bangladesh Water Development Board (BWDB). Although there are other gauging stations located in

Bangladesh, they are not available to us at this moment. The remaining large parts (~93%) of the basin areas located in the neighbour countries are nearly un-gauged; even the gauges exit, the data are not publicly sheared due to their geo-political constraints. However, for further validation of model simulations we have collected monthly discharge data at three upstream gauging station (Farakka, Pandu and Teesta) from the Global Runoff Data Centre (GRDC) dataset. Although the available data periods are not overlapping with our study period, we have compared the mean seasonal cycle and the mean, maximum, minimum streamflow and the corresponding standard deviation as the further model validation. As shown in the following newly added Table A1 and Figure A1 (in the Appendix A of the revised manuscript), the comparisons are reasonably well at all of these three upstream statiopns:

Appendix A: Model validation at upstream station

Table A1. Comparison between observed (data source: GRDC) and simulated discharge ($m^3\ s^{-1}$) for Farakka of Ganges basin, Pandu and Teesta of Brahmaputra basin.

Basin	Ganges		Brahmaputra		Brahmaputra	
Station	Farakka		Pandu		Teesta	
Data type	observed	simulated	observed	simulated	observed	simulated
Data period (with missing)	1949-1973	1980-2001	1975-1979	1980-2001	1969-1992	1980-2001
Mean	12 037	11 399	18 818	15 868	915	920
Maximum	65 072	69 715	49 210	46 381	3 622	4 219
Minimum	1 181	414	4 367	3 693	10	122
Standard deviation	14 762	15 518	12 073	11 709	902	948

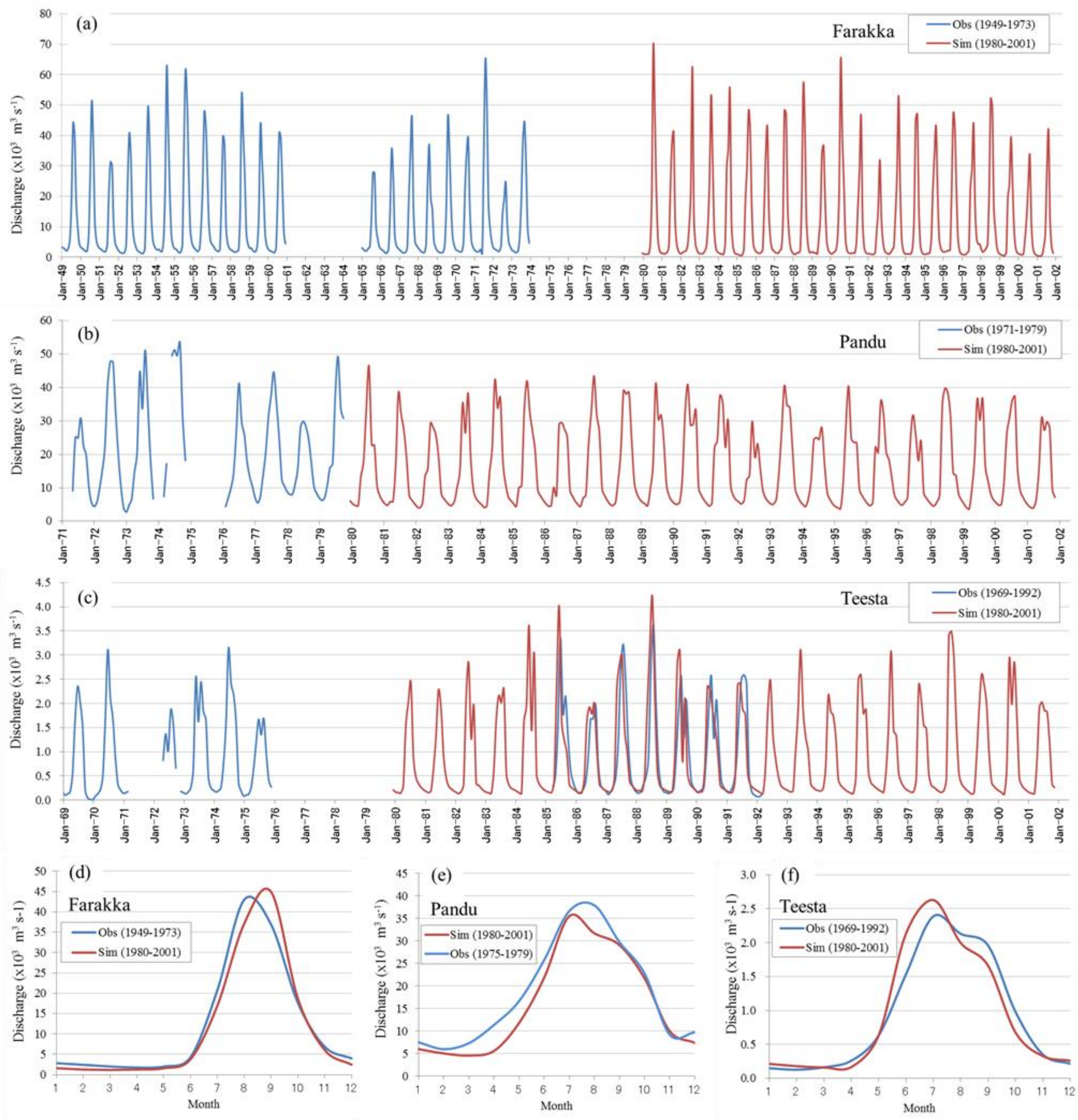

Figure A1. (a-c) Hydrographs and (d-f) mean seasonal cycles at Farakka of Ganges basin, Pundu and Teesta of Brahmaputra basin respectively both for simulated (magenta line) and observed (data source: GRDC) (blue line) data.

Also, we have revised the Figure 1 by adding the locations of the three additional up-stream validation stations. We have also added a new table (Table 3) in the manuscript which presents the basic information of the in total six validation stations.

Point #8

COMMENT: *5760: 2 sentences on lines 21-24 seems to have opposite senses: how the reduced discharge can be explained by backwater effect, and how the reduced discharge is connected with the overestimation of peaks? Besides, usually gauge stations are placed so that there is no backwater effect. Is it different in this case? If so, please clarify and add a reference.*

RESPONSE: Thanks for the comments. We do agree with the Reviewer's comment. We have removed the statement from the manuscript.

Point #9

COMMENT: *5761, l. 20-25: much lower ET in the Brahmaputra is probably mainly due to higher elevation and lower T, as vegetation in the Ganges is only slightly higher. Please check and correct.*

RESPONSE: Thanks for the comments. We fully agree with the Reviewer's comment. Accordingly, we have revised our manuscript in Section 4.1 as follows:

> Lower ET in the Brahmaputra basin is likely due to its cooler air temperature, higher elevation and less vegetated area. The basin-averaged Normalized Difference Vegetation Index (NDVI) of the Brahmaputra is 0.38, whereas for the Ganges and Meghna, NDVI are 0.41 and 0.65, respectively (NEO, 2014).

Point #10

COMMENT: *Section 4.2: statistical significance of correlation coefficients has to be evaluated as well. This would help to better analyse the results. Besides, the usual Pearson correlation may be not eligible, as some of variables are not normally distributed, and other methods could be used.*

RESPONSE: Thanks for the comments. We fully agree with the Reviewer. Accordingly, we have evaluated the statistical significance of the correlation coefficients and have revised our manuscript in the 1st and 2nd paragraph of Section 4.2 as follows:

> Total runoff and surface runoff of Brahmaputra have stronger correlation (cc= 0.95 and 0.97, both are statistically significant at $p<0.05$) with precipitation than in other two basins. However, subsurface runoff in Brahmaputra has weaker correlation (cc=0.62, $p<0.05$) with precipitation than that in Ganges (cc=0.75, $p<0.05$) and Meghna (cc=0.77, $p<0.05$). These relationships imply that the deeper soil depths enhance the

correlation between subsurface runoff and precipitation. The deeper root-zone soil depth (calibrated d = 5m) in Meghna generates more subsurface runoff (69% of total runoff) than other two basins. Soil moisture in Meghna also shows stronger correlation (cc=0.87, $p<0.05$) with precipitation than that in Brahmaputra (cc=0.77, $p<0.05$) and Ganges (cc=0.82, $p<0.05$).

The relationships of evapotranspiration with various atmospheric variables (radiation, air temperature) and soil water availability are rather complex (Shaaban et al., 2011). Different methods for estimating potential evapotranspiration (PET) in different hydrological models may also be a source of uncertainty (Thompson et al., 2014). However, the ET scheme in the H08 model uses the bulk formula where the bulk transfer coefficient is used to calculate turbulent heat fluxes (Haddeland et al., 2011). In estimating PET (and hence ET), H08 uses humidity, air temperature, wind speed and net radiation. Figure 6 presents the correlation of ET with different meteorological variables in three basins. The ET in the Brahmaputra has a significant correlation with precipitation, air temperature, specific humidity and net radiation with the correlation coefficients (cc) range from 0.70 to 0.89 (all of which are statistically significant at $p<0.05$). The correlation of ET in Meghna with the meteorological variables are also relatively strong (cc range from 0.61 to 0.80, $p<0.05$) except for the net radiation (cc=0.44, $p<0.05$). However, ET in Ganges has a weak correlation with the meteorological variables (cc from 0.29 to 0.59, $p<0.05$). A weaker correlation of ET with the meteorological variables is likely attributed to the over-estimation of actual ET in the Ganges, because the up-stream water use (which is larger in Ganges) may be incorrectly estimated as ET by the H08 model to ensure water balance.

Point #11

COMMENT: *Fig. 8: were correlation coefficients calculated for all 3 periods together? ET: is it actual evapotranspiration? Please clarify this in the figure title*

RESPONSE: Yes, the correlation coefficients noted in the Fig. 6 (former Figure 8) are calculated for all the three periods together. ET is the actual evapotranspiration. We have revised the caption of Figure 6 (former Figure 8) as follows:

Figure 6. The correlation between the monthly means of meteorological variables (WFD) and that of hydrological variables for the Brahmaputra, Ganges and Meghna basins. Three different colors represent the data in three different seasons: Black: dry/winter (November-March); Green: pre-monsoon (April-June); Red: monsoon (July-October). The correlation coefficient (cc) for each pair (all 3 seasons together) is noted at each sub-plot. The units are mm day^{-1} for Prec, ET, runoff , mm for SoilMoist, °C for Tair, and W m^{-2} for net radiation. All abbreviated terms here are referred to Table 4.

Point #12

COMMENT: *Section 4.4: To add a sentence in the beginning on how the changes were estimated: by comparing simulations from the scenario and reference periods driven by climate model inputs in both periods. This is important!.*

RESPONSE: We are grateful to the Reviewer's comment. Accordingly, we have added a sentence in the beginning of Section 4.4 as follows:

> The changes in the seasonal cycles of hydro-meteorological variables in the two projected periods (2015-2039 and 2075–2099) are comparing with that in the reference period (1979-2003). All the results presented here are from the multi-model mean of all simulations driven by the climate forcing data from 5 GCMs for both reference and future periods.

Point #13

COMMENT: *Section 4.4. After the first introductory sentence Table 3, Figs. 10 and 11 should be introduced by explaining what they show. The titles of Figures 10 and 11 should state how the comparison was done: by comparing simulations from the scenario and reference periods driven by the climate model inputs in both periods. Besides, the lines for the reference period in Fig. 10 should be better distinguishable (another colour?).*

RESPONSE: Following Reviewer's suggestion, we have added a few sentences in introducing Fig. 8 (former Figure 10), Fig. 9 (former Figure 11) and Table 3 after the first introductory sentence in Section 4.4 as follows:

> The solid lines in Fig. 8 represent the monthly averages and the dashed lines represent the upper and lower bounds of the uncertainty bands as determined from the 10 simulations using the 10 optimal parameter sets (identified by ranking the Nash–Sutcliffe efficiency (NSE)). Figure 9 plots the corresponding percentage changes and Table 5 summarizes these relative changes in the hydro-meteorological variables over three basins on the annual and 6-month (dry season and wet season) basis.

According to Reviewer's suggestion, we have revised the caption of Fig. 8 (former Figure 10) and Fig. 9 (former Figure 11) as follows:

> Figure 8 (a1)-(f3). The mean (solid line), upper and lower bounds (dashed line) of the uncertainty band of the hydrological quantities and net radiation components for the present-day (black), near-future (green)

and far-future (red) simulations as determined found from 10 simulation result with considering 10 optimal parameter set according to Nash–Sutcliffe efficiency (NSE) (cu: present-day, nf: near-future, ff: far-future). Coefficient of variations (CV) for all periods (Table 6) are noted on each sub-plot.

Figure 9 (a)-(r). Percentage changes in the monthly means of the climatic and hydrologic quantities from the present-day period to the near-future and far-future periods. The dashed lines represent the annual mean changes.

To distinguish better in Fig. 8 (former Figure 10), we have revised this figure by replacing the color shading with the dashed color lines.

Point #14

COMMENT: *Conclusion: not necessary to repeat all numbers again in the Conclusion section, as they were already presented in Tables and repeated in the text above. Please formulate the results in a more general form.*

RESPONSE: We much appreciate the Reviewer's suggestion. Accordingly, we have revised the conclusion.

Technical corrections
Point #1

COMMENT: *Please check grammar. Some observed mistakes:*
5747: "results shows" (abstract);
5750: "as one of the best available global forcing dataset" -> "as one of the best available global forcing datasets";
Section 2.1: "The WATCH Forcing Data set (WFD) (Weedon et al., 2011) are used" -> The WATCH Forcing Data set (WFD) (Weedon et al., 2011) is used".
5755: the energy and water budget -> the energy and water budgets
5755: high temporal-resolution -> high temporal resolution
5759: "No surface runoff generated" -> "No surface runoff is generated"
5758, l. 6: less -> lower.
5758, l. 17: were fixed -> was fixed.
5759, l. 13: less -> lower.

5759, l. 15: ranges -> range
5761, l. 14: magnitude -> magnitudes
5761, l. 18: less -> lower
Section 4.1: numerous small mistakes, to be checked.
Section 4.2: numerous small mistakes, to be checked (monthly mean -> monthly means, representing -> represent, relationship -> relationships, generate -> generates, which result -> which results in, etc.)
Section 4.3: varies -> dynamics
4.4.1: century; -> century (to remove ;), 2 different scenario□2 different scenarios, which are -> which were
4.4.2 much warm -> much warmer
4.4.4. less change -> lower change
4.4.5 less -> lower
4.5, title: parameter -> parameters
4.5 "increasing complex" -> "increasing complexity of", mistakes of singular/plural cases (e.g. 5767, l. 27), less -> lower, peak -> peak, etc.
5: 5769, l. 23: very less changes

RESPONSE: We are grateful to Reviewer for his/her enormous effort to identify these grammatical mistakes. We have corrected all these mistakes as well as similar mistakes in other places of the manuscript.

Point #2

COMMENT: *The language of the whole manuscript has to be checked by a native speaker. There are many poor and/or unclear formulations, like:*
5748: "the impact of climate change on not only the runoff",
5748: relatively less -> relatively low
5750: "this study, a hydrologic model simulation will be calibrated"
5751: "which has been demonstrated suitable" -> "which has been demonstrated as suitable"
5751: "which benefit the analysis of their combined influences"
5751: "in most previous work" -> "in most previous works"
5754: "MRI-AGCM3.2S is based on an atmospheric climate model with a 20km grid model" – too many "models".
5754: "Climate change impacts on the south Asian climate" ???
5754: "by multiplying a correction coefficient" -> "by multiplying using a correction coefficient"
5756: "The module accumulates runoff generated by the land surface model and rout them"

-> "The module accumulates runoff generated by the land surface model and routes it"
5756: "to become streamflow" -> "where it becomes streamflow" 5760: "This is likely due to that the Meghna as a tidal river .."
Section 4.3: variability of runoff and precipitation are closely similar -> inter-annual dynamics of runoff and precipitation are similar
Section 4.3: To reformulate: "Though there is no clear trend is noticed ..." Title of 4.4: Projected changes in the mean -> Projected mean changes
4.4.3: is predicted -> is projected
4.4.3: directed -> could be directed, flood -> floods
4.4.4: "It is observed in Fig. 11m–o, changes of ET in near-future are very less" please formulate in proper English
4.4.6: "Due to projected air temperature increase in dry period is large", and the rest of this sentence – please formulate in proper English
4.5: the sentence about "many parameter sets can reproduce the observations" is poor, please reformulate
4.5: "uncertainty of future projection due to model parameter should consider carefully" – please formulate in proper English
4.5, 5768, l. 23-25: "Larger uncertainty in predicting soil moisture is significant in land use management, agriculture in particular ..." – poor formulation (what does it mean: "larger uncertainty in land use management"?), please reformulate.

RESPONSE: We are grateful to Reviewer for his/her enormous effort to identify these mistakes. We have corrected all these mistakes as well as similar mistakes in other places of the manuscript.

Point #3

COMMENT: *Abstract: "evapotranspiration is predicted" is wrong, it is only projected. The word "prediction" should never be used in this context. Please check in the whole manuscript (e.g. p. 5749, 5765).*

RESPONSE: We much appreciate the Reviewer's careful review. We have replaced the word "prediction" with "projection" in the whole manuscript. The sentence in the abstract has been revised as follows:

> (c) evapotranspiration is projected to increase significantly for the entire GBM basins (Brahmaputra: +16.4%, Ganges: +13.6%, Meghna: +12.9%) due to increased net radiation (Brahmaputra: +5.6%, Ganges: +4.1%, Meghna: +4.4%) as well as warmer air temperature.

Point #4

COMMENT: *Abstract: the sentence about the "largest hydrological response" should be reformulated, as the largest hydrological response may not necessarily lead to the higher risk of flooding. Better: "the highest increase in discharge".*

RESPONSE: We have revised the sentence as follows:

> Amongst three basins, Meghna shows the highest increase in runoff which indicates higher possibility of flood occurrence in this basin.

Point #5

COMMENT: *A reference to Fig. 1 is needed in Introduction, 2nd. Paragraph.*

RESPONSE: We have referred the figure in 1st line of 2nd paragraph of Introduction as follows:

> The Ganges-Brahmaputra-Meghna (hereafter referred to as GBM) river basin with a total area of about 1.7 million km^2 (FAO-AQUASTAT, 2014; Islam et al., 2010) encompasses a number of countries including parts of China, India, Nepal, Bhutan and Bangladesh (Fig. 1).

Point #6

COMMENT: *Please correct: in Introduction: "encompasses a number of countries including China, India, ..." -> "encompasses a number of countries including parts of China and India, ...".*

RESPONSE: We have revised the sentence as follows:

> The Ganges-Brahmaputra-Meghna (hereafter referred to as GBM) river basin with a total area of about 1.7 million km^2 (FAO-AQUASTAT, 2014; Islam et al., 2010) encompasses a number of countries including parts of China, India, Nepal, Bhutan and Bangladesh (Fig. 1)

Point #7

COMMENT: *5749: why "due to the lack of calibration data"? Probably, -> "due to the lack of calibration"?*

RESPONSE: We have revised the sentence as follows:

> Although their modelling domains include the GBM basin, these global-scale simulations are not well constrained due to the lack of calibration at the basin scale.

Point #8

COMMENT: *5750: what means "well-constrained hydrologic modelling"? Please reformulate.*

RESPONSE: Thanks for the comments. Accordingly, we have replaced the term "well-constrained" with the term "well-calibrated".

.

Point #9

COMMENT: *Introduction: please subdivide the long paragraph starting "Few studies ...", and the next paragraphs in Introduction, as well as in the following Sections.*

RESPONSE: Thanks for the comments. Accordingly, we have subdivided the paragraph mentioned by the Reviewer as follows:

> Few studies have been conducted to investigate the impact of climate change on the hydrology and water resources of the GBM basins (Immerzeel, 2008;Kamal et al., 2013;Biemans et al., 2013;Gain et al., 2011;Ghosh and Dutta, 2012;Mirza and Ahmad, 2005a). In most of these studies, future streamflow is projected on the basis of linear regression between rainfall and streamflow derived from historical data (Immerzeel, 2008;Chowdhury and Ward, 2004;Mirza et al., 2003). Immerzeel (2008) used the multiple regression technique to predict streamflow at the Bahadurabad station (the outlet of Brahmaputra basin) under future temperature and precipitation conditions based on the statistically downscaled GCM output. However, since most of the hydrologic processes are nonlinear, they cannot be predicted accurately by using empirical regression equations derived from historical data and then extrapolating to the future conditions with the non-stationary changes. The alternative for the assessment of climate change impacts on basin-scale hydrology is by using well-calibrated hydrologic modelling, but this has rarely been conducted for the GBM basin due to the lack of data for model calibration and validation. Ghosh and Dutta (2012) applied a physically-based, macro-scale distributed hydrologic model to study the change of future flood characteristics at the Brahmaputra basin, but their study domain only focused on the regions inside India rather than the entire basin. Gain et al. (2011) estimated the future trends of the low and high flows in the lower Brahmaputra basin using outputs from a global hydrologic model forced by multiple

> GCM outputs (grid resolution: 0.5º). Instead of calibrating the model, the simulated future streamflow was weighted against the observations to assess the impacts due to climate change.
>
> In contrast to the above studies, in this study a hydrologic model simulation will be conducted. The calibration and validation will be based on a rarely obtained long-term (1980-2001) observed daily streamflow dataset in the GBM basin provided by the Bangladesh Water Development Board (BWDB). Relative to previous studies over the GBM basin, it is believed that the availability of this unique long-term streamflow data can lead to more precise estimation of model parameters and hence more accurate simulation of hydrological processes as well as more reliable future projection of the hydrology over the GBM basin.

However, all of the literatures introduced in the following two paragraphs are relevant; hence it is difficult to further subdivide.

Point #10

COMMENT: *Fig. 3: why is it called "climatology"??? It is a long-term average seasonal dynamics.*

RESPONSE: Thanks for the comments. Accordingly, we have revised text in manuscript (2nd paragraph of Section 3.1) as follows:

> Figure 3 plots the 11-year long-term average seasonal cycles of simulated total runoff, surface runoff and sub-surface runoff of Brahmaputra basin.

We have revised the caption of Figure 3 as follows:

> The 11-year (1980–1990) long-term average seasonal cycles of the simulated total runoff, surface runoff and sub-surface runoff (unit: mm day^{-1}) of Brahmaputra basin. Each of the five lines in each panel represents the average of 5^3 (=125) runs with one of the four calibration parameters fixed at the given value.

Point #11

COMMENT: *5759: Why "envelopes"??? What is the meaning? Maybe to reformulate?*

RESPONSE: Thanks for the comments. We have replaced the term as "uncertainty band" in the whole manuscript. For example, 1st line of 7th paragraph in Section 3.1 has been revised as follows:

> Figure 4e plots the uncertainty bands of the simulated discharges by using 10 optimal parameter combinations according to Nash-Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe, 1970).

Point #12

COMMENT: *5759: "for the Brahmaputra and Ganges basin": Not, for all three basins..*

RESPONSE: Yes, Figure 4e (former Figure 5) plots the uncertainty bands of the simulated discharges for all three basins. Accordingly, we have revised the sentence as follows:

> Figure 4e plots the uncertainty bands of the simulated discharges by using 10 optimal parameter combinations according to Nash-Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe, 1970)..

Point #13

COMMENT: *Title of section 4: Result and discussion -> Results and discussion*

RESPONSE: Thanks for the comments. Accordingly, we have revised the title as "4 Results and discussion:

Point #14

COMMENT: *5761, first sentence in 4.1: please correct, as Table 2 does not present seasonal cycles, only mean values*

RESPONSE: Thanks to Reviewer for his/her comment. We have revised the sentence as follows:

> Figure 5 plots the 22-year (1980-2001) mean seasonal cycles of the climatic (from WFD forcing) and hydrological (from calibrated hydrologic model simulation) quantities averaged over these three basins (yearly mean values are presented in Table 4).

Point #15

COMMENT: *5761: second sentence in 4.1 about interannual variation precipitation: "was mainly from May to September " -> "was higher from May to September".*

RESPONSE: Thanks to Reviewer for his/her comment. We have revised the sentence as follows:

> The interannual variation of precipitation in Brahmaputra and Meghna was higher from May to September (Fig. 5a,c) whereas for Ganges was from June to October.

Point #16

COMMENT: *The last sentence in 4.2 is poorly formulated ("upstream water use ... is estimated as ET"), please reformulate.*

RESPONSE: Thanks for the comments. We have revised the sentence as follows:

> A weaker correlation of ET with the meteorological variables is likely attributed to the over-estimation of actual ET in the Ganges, because the up-stream water use (which is larger in Ganges) may be incorrectly estimated as ET by the H08 model to ensure water balance.

Point #17

COMMENT: *Section 4.3, second sentence is poor (there could be a long–term trend despite of a high inter- annual variability). Please correct.*

RESPONSE: Thanks for the comments. Accordingly, we have revised the sentence as follows:

> Figure 7a1-a3 show the long-term trend in precipitation is not pronounced for all three basins, but its interannual variability is rather large for each GCM.

Generally, we are deeply grateful to Editor and two Reviewers for their insight and careful review. Their comments have greatly helped to improve the paper.

LIST OF ALL RELEVANT CHANGES MADE IN THE MANUSCRIPT

1. We have improved our model simulations with the calibration of additional model parameters (i.e., the meandering ration and effective flow velocity) following the comments of both Reviewer #1 and #2.
2. We have validated our model at three more upstream stations according to suggestion of Reviewer #2.
3. We have added 4 more GCMs, all participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) in our analysis according to suggestion of Editor.
4. We have corrected the bias of GCM data based on the monthly scaling factor (multiplier) instead of the previous annual scaling factor following the suggestion of Reviewer #1.
5. We have included a new Table 1 describing the major characteristics of three basins of GBM according to suggestion of Reviewer #2.
6. We have included a new Table 3 providing the basic information of streamflow gauging stations used for calibration and validation.
7. We have revised Table 2 (former Table 1), Table 4 (former Table 2), Table 5 (former Table 3) and Table 6 (former Table 4) to be higher quality.
8. We have revised Fig. 1, Fig. 2, Fig. 4 (former Fig. 6), Fig. 5 (former Fig. 7), Fig. 6 (former Fig. 8), Fig. 7 (former Fig. 9), Fig. 8 (former Fig. 10) and Fig. 9 (former Fig. 11).
9. We have removed a figure (former Fig. 4) as it was less important to this study.
10. We have revised Fig. 4 (former Fig. 6) by combining former Fig. 5 and Fig. 6 according to suggestion of Editor.
11. We have corrected all technical and grammatical mistakes as suggested by both Reviewer #1 and #2.

MARKED-UP MANUSCRIPT

Model study of the impacts of future climate change on the hydrology of Ganges-Brahmaputra-Meghna (GBM) basin

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Abstract

The intensity, duration, and geographic extent of floods in Bangladesh mostly depend on the combined influences of three river systems, Ganges, Brahmaputra and Meghna (GBM). In addition, climate change is likely to have significant effects on the hydrology and water resources of the GBM basins and might ultimately lead to more serious floods in Bangladesh. However, the assessment of climate change impacts on basin-scale hydrology by using well-calibrated hydrologic modelling has seldom been conducted for GBM basins due to the lack of data for model calibration and validation. In this study, a macro-scale hydrologic model H08 has been applied regionally over the basin at a relatively fine grid resolution (10 km) by integrating the fine-resolution (~0.5 km) DEM data for accurate river networks delineation. The model has been calibrated via analysing model parameter sensitivity and validated based on a long-term observed daily streamflow data. The impacts of climate change (considering high emissions path) not only on the runoff, but also on the basin-scale hydrology including evapotranspiration, soil moisture and net radiation have been assessed in this study by using 5 GCMs of CMIP5 through three time-slice experiments; present-day (1979–2003), near-future (2015-2039) and far-future (2075–2099) periods. Results show that, by the end of 21st century (a) the entire GBM basin is projected to be warmed by ~4.3°C (b) the changes of mean precipitation are projected to be +16.3%, +19.8% and +29.6%, and the changes of mean runoff to be +16.2%, +33.1% and +39.7% in the Brahmaputra, Ganges and Meghna basins, respectively (c) evapotranspiration is projected to increase significantly for the entire GBM basins (Brahmaputra: +16.4%, Ganges: +13.6%, Meghna: +12.9%) due to increased net radiation (Brahmaputra: +5.6%, Ganges: +4.1%, Meghna: +4.4%) as well as warmer air temperature. Changes of hydrologic variables will be larger in dry season (November-April) than that in wet season (May-October). Amongst three basins, Meghna shows the highest increase in runoff which indicates higher possibility of flood occurrence in this basin. The uncertainty due to the specification of key model parameters in predicting hydrologic quantities, has also been analysed explicitly in this study, and it is found that the uncertainty in estimated runoff, evapotranspiration and net radiation is relatively low. However, the uncertainty in estimated soil moisture is rather large (coefficient of variation ranges from 14.4 to 31% among three basins).

1 Introduction

Bangladesh is situated in the active delta of the world's three major rivers, the Ganges, Brahmaputra and Meghna. Due to its unique geographical location, the occurrence of water-induced disasters is a regular phenomenon. In addition, the anticipated change in climate is likely to lead to an intensification of the hydrological cycle and to have a major impact on overall hydrology of these basins and ultimately lead to increase the frequency of water-induced disasters in Bangladesh. However, the intensity, duration, and geographic extent of floods in Bangladesh mostly depend on the combined influences of these three river systems. Previous studies revealed that flood damages have become more severe and devastating when more than one flood peaks in these three river basins coincide (Mirza, 2003;Chowdhury, 2000).

The Ganges-Brahmaputra-Meghna (hereafter referred to as GBM) river basin with a total area of about 1.7 million km^2 (FAO-AQUASTAT, 2014;Islam et al., 2010) encompasses a number of countries including parts of China, India, Nepal, Bhutan and Bangladesh (Fig. 1). Major characteristics of the GBM rivers have been presented in Table 1. This river system is the third largest freshwater outlet in the world to the oceans (Chowdhury and Ward, 2004). During the extreme floods, over 138 700 $m^3 s^{-1}$ of water flows into the Bay of Bengal through a single outlet, which is the largest intensity in the world even exceeding that of the Amazon discharge into the sea by about 1.5 times (FAO-AQUASTAT, 2014). The GBM river basin is unique in the world in terms of diversified climate. For example, the Ganges river basin is characterized by low precipitation (760–1020 mm $year^{-1}$) in the northwest upper region and high precipitation (1520–2540 mm $year^{-1}$) along the coastal areas. High precipitation zones and dry rain shadow areas are located in the Brahmaputra river basin, whereas the world's highest precipitation (~5690 mm $year^{-1}$) area is situated in the Meghna River basin (FAO-AQUASTAT, 2014).

Several studies have focused on the rainfall and discharge relationships in the GBM basin by (1) identifying and linking the correlation between basin-scale discharge and the El Nino-southern oscillation (ENSO) and sea surface temperature (SST) (Chowdhury and Ward, 2004;Mirza et al., 1998;Nishat and Faisal, 2000), (2) analysing available observed or reanalysis data (Chowdhury and Ward, 2004, 2007;Mirza et al., 1998;Kamal-Heikman et al., 2007), and (3) evaluating historical data of flood events (Mirza, 2003;Islam et al., 2010). Various statistical approaches were used in most of these studies instead of conducting hydrologic model simulations. In recent years, a number of global-scale hydrologic modelling studies (Haddeland et al., 2011;Haddeland et al., 2012;Pokhrel et al., 2012) have been reported. Although their modelling domains include the GBM basin, these global-scale simulations are not well constrained due to the lack of calibration at the basin scale.

Few studies have been conducted to investigate the impact of climate change on the hydrology and water resources of the GBM basins (Immerzeel, 2008;Kamal et al., 2013;Biemans et al., 2013;Gain et al., 2011;Ghosh and Dutta, 2012;Mirza and Ahmad, 2005a). In most of these studies, future streamflow is projected on the basis of linear regression between rainfall and streamflow derived from historical data (Immerzeel, 2008;Chowdhury and Ward, 2004;Mirza et al., 2003). Immerzeel (2008) used the multiple regression technique to predict streamflow at the Bahadurabad station (the outlet of Brahmaputra basin) under future temperature and precipitation conditions based on the statistically downscaled GCM output. However, since most of the hydrologic processes are nonlinear, they cannot be predicted accurately by using empirical regression equations derived from historical data and then extrapolating to the future conditions with the non-stationary changes. The alternative for the assessment of climate change impacts on basin-scale hydrology is by using well-calibrated hydrologic modelling, but this has rarely been conducted for the GBM basin due to the lack of data for model calibration and validation. Ghosh and Dutta (2012) applied a physically-based, macro-scale distributed hydrologic model to study the change of future flood characteristics at the Brahmaputra basin, but their study domain only focused on the regions inside India rather than the entire basin. Gain et al. (2011) estimated the future trends of the low and high flows in the lower Brahmaputra basin using outputs from a global hydrologic model forced by multiple GCM outputs (grid resolution: 0.5°). Instead of calibrating the model, the simulated future streamflow was weighted against the observations to assess the impacts due to climate change.

In contrast to the above studies, in this study a hydrologic model simulation will be conducted. The calibration and validation will be based on a rarely obtained long-term (1980-2001) observed daily streamflow dataset in the GBM basin provided by the Bangladesh Water Development Board (BWDB). Relative to previous studies over the GBM basin, it is believed that the availability of this unique long-term streamflow data can lead to more precise estimation of model parameters and hence more accurate simulation of hydrological processes as well as more reliable future projection of the hydrology over the GBM basin.

The objective of this study is to (1) setup a hydrologic model by calibration and validation with long-term observed daily discharge data that can reproduce the long-term hydrographs of this basin reliably, and to (2) study the impact of future climate changes on the basin-scale hydrology of this basin. A global-scale hydrologic model H08 (Hanasaki et al., 2008;Hanasaki et al., 2014) is applied regionally over the GBM basin at a relatively fine grid resolution (10 km) by integrating the fine-resolution (~0.5 km) DEM data for the accurate river networks delineation. The hourly atmospheric forcing dataset from the Water and Global Change (WATCH) model-inter-comparison project (Weedon et al., 2011) (hereafter referred to as WFD (WATCH Forcing Dataset)) is used for the historical simulations in this study. WFD is considered as one of the best available global climate forcing datasets to provide accurate representation of meteorological events, synoptic activity, seasonal cycles and climate trends (Weedon et al., 2011). The studies by Lucas-Picher et al. (2011) and Siderius et al. (2013) found that for the South Asia and the Ganges, respectively, the WFD rainfall is consistent with the observed APHRODITE data (Yatagai et al., 2012) -a gridded (0.25°) rainfall product for the South Asia region developed based on a large number of rain gauge data. For the future simulations, the hydrologic model is forced by climate output from simulations of high emissions scenario (RCP

8.5 of all model except MRI-AGCM3.2S which includes SRES A1B scenario) from 5 different coupled atmosphere–ocean general circulation models and earth system models (hereafter referred to as GCMs), all participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). In order to be consistent with the historical data, the monthly correction factor (i.e. the ratio between the basin-scale long-term monthly mean precipitation of the WFD data and that of the GCM data for each month) for each basin is applied to each GCM's precipitation forcing data. Several time-slice experiments are performed for the present-day (1979–2003), near-future (2015-2039) and far-future (2075–2099) periods.

The modelling study in the present study makes advances from previous studies in three aspects. First, a hydrologic model H08 (Hanasaki et al., 2008) is used which has been demonstrated as suitable for large-scale analyses. The model is well calibrated for the GBM basin via analysing model parameter sensitivity from the parameter-sampling simulations. The model has been validated against daily observed streamflow satisfactorily. Moreover, the uncertainty due to the determination of key model parameters in predicting hydrologic quantities, which has seldom been performed in previous studies, is analysed explicitly in this study. Second, three large basins of GBM and their spatial variability are studied in this study which benefit the analysis of their combined influences on the large-scale hydrologic floods and droughts occurred in Bangladesh as extensively reported in literature (Chowdhury, 2000;Mirza, 2003). Finally, the impacts of climate change not only on the discharge but also on the basin-scale hydrology including evapotranspiration, soil moisture and net radiation, are assessed in this study, whereas in most previous studies the climate change impact on streamflow was often the only focus.

The paper is organized into five sections as follows. A brief description of the data and the hydrologic model used is presented in Sect. 2. Section 3 presents the methodology of model setup as well as the results from the model parameter sensitivity analysis. Results and discussion are presented in Sect. 4. Finally, important conclusions of this study are summarized in Section 5.

2 Data and Tools

2.1. Meteorological Forcing datasets

The WATCH Forcing Data set (WFD) (Weedon et al., 2011) is used to drive the H08 model for the historical simulation. The WFD variables, including rainfall, snowfall, surface pressure, air temperature, specific humidity, wind speed, long-wave downward radiation, and shortwave downward radiation were taken from the ERA-40 reanalysis product of the European Centre for Medium Range Weather Forecasting (ECMWF). The one-degree resolution ERA40 reanalysis data were interpolated into the half-degree resolution on the Climate Research Unit of the University of East Anglia (CRU) land mask, adjusted for elevation changes where needed and bias-corrected using monthly observations. For detailed information on the WFD, see Weedon et al. (2011) and Weedon et al. (2010). The albedo values are based on the monthly albedo data form the Second Global Soil Wetness Project (GSWP2).

2.2. Hydrologic data

Observed river water level (daily) and discharge (weekly) data from 1980 to 2012 for the hydrological stations located inside the Bangladesh (the outlets of three basins shown in Fig. 1, i.e. the Ganges basin at Hardinge Bridge, the Brahmaputra basin at Bahadurabad, and the Meghna basin at Bhairab Bazar) were provided by the Hydrology Division, Bangladesh Water Development Board (BWDB). River water levels were regularly measured 5 times a day (at 6 am, 9 am, 12 pm, 3 pm and 6 pm) and discharges were measured weekly by the velocity-area method. Since the Brahmaputra River is highly braided, the discharge measurement at

Bahadurabad was carried out on multiple channels. In contrast, the Meghna River at Bhairab Bazar is seasonally tidal - after withdrawal of the monsoon the river at this station becomes tidal, and from December to May the river shows both a horizontal and a vertical tide (Chowdhury and Ward, 2004). Under this condition, during the dry season, tidal discharge measurements were made at this station once per month. Daily discharges of Ganges and Brahmaputra River were calculated from the daily water level data by using the rating equations developed by the Institute of Water Modelling (IWM) (IWM, 2006). Rating equation for the Meghna River was not reported in literature. In this study an attempt was made to develop the rating equation for the Meghna basin. Discharge (monthly) data of three more stations (Farakka, Pandu, Teesta) located at upstream of these basins (Fig. 1) were collected from the Global Runoff Data Centre (GRDC), which were used for validation.

2.3. Topographic Data

DEM data were collected from the HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) (HydroSHEDS, 2014). It offers a suite of geo-referenced data sets (vector and raster), including stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances and river topology information (Lehner et al., 2006). The HydroSHEDS data were derived from the elevation data of the Shuttle Radar Topography Mission (SRTM) at a ~0.5 km resolution. Preliminary quality assessments indicate that the accuracy of HydroSHEDS significantly exceeds that of existing global watershed and river maps (Lehner et al., 2006).

2.4. GCM data

Climate data from 5 CMIP5 climate models; MIROC5, MIROC-ESM, MRI-CGCM3, HadGEM2-ES under the RCP 8.5 representative concentration pathway and MRI-AGCM3.2S under the SRES A1B (Appendix B, Table B1) have been used for future simulation. The climate data has been interpolated from native climate model resolution (ranging from 0.25×0.25° to 2.8×2.8°) to 5×5′ (~10 km-mesh) using linear interpolation (nearest four point). In order to be consistent with the historical data, the bias of precipitation forcing data of each GCM has been corrected by multiplying the monthly correction factor equal to the ratio between the basin-averaged long-term mean precipitation from a GCM and that from WFD for each of the twelve months in each GBM basins. Among these GCMs, MRI-AGCM3.2S (where the 'S' refers to the "super-high resolution") provides higher resolution (20 km) atmospheric forcing data which shows improvements in simulating heavy precipitation, global distribution of tropical cyclones, and the seasonal march of East Asian summer monsoon (Mizuta et al., 2012). Therefore, climate change impacts on the south Asia were assessed in several recent studies by using the MRI-AGCM3.2S dataset (Rahman et al., 2012;Endo et al., 2012;Kwak et al., 2012).

2.5. Hydrologic Model: H08

H08 is a macro-scale hydrological model developed by Hanasaki et al (2008) which consists of six main modules: land surface hydrology, river routing, crop growth, reservoir operation, environmental flow requirement estimation, and anthropogenic water withdrawal. For this study, only two modules, the land surface hydrology and the river routing are used. The land surface hydrology module calculates the energy and water budgets above and beneath the land surface as forced by the high temporal-resolution meteorological data.

The runoff scheme in H08 is based on the bucket model concept (Manabe, 1969), but differs from the original formulation in certain important aspects. Although runoff is generated only when the bucket is overfilled as in the original bucket model, H08 uses a "leaky bucket" formulation in which subsurface runoff occurs continually as a function of soil moisture. Soil moisture is expressed as a single-layer reservoir with the holding capacity of 15 cm for all the soil and vegetation types. When the reservoir is empty (full), soil moisture is at the wilting point (the field capacity). Evapotranspiration is expressed as a function of potential evapotranspiration and soil moisture (Eq. 2). Potential evapotranspiration and snowmelt are calculated from the surface energy balance (Hanasaki et al., 2008).

Potential evaporation E_P is expressed in this model as

$$E_{\mathrm{P}}(T_{\mathrm{S}}) = \rho C_{\mathrm{D}} U (q_{\mathrm{SAT}}(T_{\mathrm{S}}) - q_{\mathrm{a}}) \quad (1)$$

.

Where ρ is the density of air, C_D is the bulk transfer coefficient U is the wind speed, q_{SAT} (T_S) is the saturated specific humidity at surface temperature, and q_a is the specific humidity. Evaporation from a surface (E) is expressed as

$$E = \beta E_{\mathrm{P}}(T_{\mathrm{S}}) \quad (2)$$

where

$$\beta = \begin{cases} 1 & 0.75 W_{\mathrm{f}} \leq W \\ W / W_{\mathrm{f}} & W < 0.75 W_{\mathrm{f}} \end{cases} \quad (3)$$

where W is the soil water content and W_f is the soil water content at field capacity (fixed at 150 kg m^{-2}).

Surface runoff (Q_s) is generated whenever the soil water content exceeds the field capacity:

$$Q_{\mathrm{s}} = \begin{cases} W - W_{\mathrm{f}} & W_{\mathrm{f}} < W \\ 0 & W \leq W_{\mathrm{f}} \end{cases} \quad (4)$$

Subsurface runoff (Q_{sb}) is incorporated to the model as

$$Q_{\mathrm{sb}} = \frac{W_{\mathrm{f}}}{\tau} \left(\frac{W}{W_{\mathrm{f}}} \right)^{\gamma} \quad (5)$$

Where τ is a time constant and γ is a parameter characterizing the degree of nonlinearity of Q_{sb}. These two parameters are calibrated in this study as described later in Sect. 3.1.

The river module is identical to the Total Runoff Integrating Pathways (TRIP) model (Oki and Sud, 1998). The module has a digital river map covering the whole globe at a spatial resolution of 1° (~111 km). The land–sea mask is identical to the GSWP2 meteorological forcing input. Effective flow velocity and meandering ratio are set as the default values at 0.5 m s^{-1} and 1.5, respectively. The module accumulates runoff generated by the land surface model and routes it downstream as streamflow. However, for this study a new digital river map of the GBM basin with the spatial resolution of ~10 km is prepared. Effective flow velocity and meandering ratio have been calibrated respectively for the three basins.

3 Methodology: model setup and simulation

Figure 2 presents the methodology used in this study from model setup to the historical and future simulations. A H08 simulation with the 10-km (5 min) resolution is calibrated to find the optimal parameter sets by using the parameter-sampling simulation technique, and validated with observed daily streamflow data. The default river module of H08 uses the digital river map from TRIP (Oki and Sud, 1998) with the global resolution of 1° (~111 km), which is too course for the regional simulation in this study with the 10-km resolution. Therefore, a new digital river map of the 10-km resolution is prepared by integrating the finer-resolution (~0.5 km) DEM data.

3.1. Parameter sensitivity

The parameter-sampling simulation is conducted to investigate the sensitivity of the H08 model parameters to model simulation results. The most sensitive parameters in H08 include the root-zone depth d [m], the bulk transfer coefficient C_D [-] controlling the potential evaporation (Eq. 1), and the parameters sensitive to subsurface flow, that is, τ [day] and γ [-] (Eq. 5)

(Hanasaki et al., 2014), hence they are treated as calibration parameters in this study. The parameter τ is a time constant determining the daily maximum subsurface runoff. The parameter γ is a shape parameter controlling the relationship between subsurface flow and soil moisture (Hanasaki et al., 2008). Their default parameter values in H08 are 1 m for d, 0.003 for C_D, 100 days for τ, and 2 for γ. For each of these four parameters, five different values are selected from their feasible physical ranges. The parameter-sampling simulations of the H08 model were run by using all the combinations of four parameters, which consist of a total of 5^4 (=625) simulations all conducted by using the same 11-year (1980–1990) atmospheric forcing data of WFD.

Figure 3 plots the 11-year long-term average seasonal cycles of simulated total runoff, surface runoff and sub-surface runoff of the Brahmaputra basin. Each of the five lines in each panel represents the average of 5^3 (=125) runs with one of the 4 calibration parameters fixed at a given value. As shown, the overall sensitivity of selected model parameters to the flow partitioning is high. When d is low, surface runoff is high (due to higher saturated fractional area) (Fig. 3 b). As d increases, sub-surface runoff increases and surface runoff decreases (Fig. 3 c and b). Due to these compensating effects, the effect of d on the total runoff becomes more complex: from March to August, higher d causes lower total runoff, but the trend is reversed from August on for the Brahmaputra basin. Similar behaviours can be observed for the other two basins (figure not shown).

The parameter C_D is the bulk transfer coefficient in the calculation of potential evaporation (Eq. 1), thus its effect on runoff is relatively small (Fig. 3d-f). However, higher C_D causes more evaporation and hence lower (both surface and sub-surface) runoff (Eq. 1 and Eq. 2). The sensitivity of parameter γ to runoff is also smaller than d and τ. As γ increases, surface runoff increases and sub-surface runoff decreases (Fig. 3h, i). The overall sensitivity of γ to the total runoff becomes negligible due to the compensating effects (Fig. 3g).

As shown in Eq. (5) and Fig. 3k-l, the parameter τ has a critical impact on the surface and sub-surface flow partitioning. A larger τ corresponds to larger surface runoff and hence smaller sub-surface runoff (Fig. 3k-l), but it has relatively a small impact on total runoff (Fig. 3j).

These four calibration parameters have the combined influences on total runoff partitioning as well as simulations of other hydrologic variables. To summarize, (1) the sensitivity of d on the total runoff is complex: the trend is reversed between the two halves of a year; (2) parameters d and τ have a significant impact on flow partitioning whereas C_D and γ have less sensitivity to runoff simulation; (3) The influence of d and τ is reversed between surface and sub-surface runoff: surface runoff increases as d decreases and τ increases.

Figure 4e plots the uncertainty bands of the simulated discharges by using 10 optimal parameter combinations according to the Nash-Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe, 1970). It is observed that the spread of uncertainty band is located mainly around the low flow period (dry season from November to March) over the Brahmaputra basin (Fig. 4e). No surface runoff is generated in dry season when the soil moisture is lower than the field capacity (Eq. 4 and Fig. 3b). It is noted from the 10 optimal parameter combinations that the optimal τ is 150, C_D is 0.001, d and γ range from 3 to 5 and 1.0 to 2.5, respectively. The spread of the uncertainty bands is mainly due to the variations of the d and γ. As d increases, the sub-surface runoff increases (Fig. 3c and Fig. 4e). On the other hand, in the case of the Ganges and Meghna basin the spread of uncertainty bands are observed through the entire period of a year (in low flow as well as in peak flow regimes). Among the 10 optimal parameter combinations for Ganges (Meghna) it is found that parameter C_D is 0.008 (0.008), τ is 150 (50), d and γ range from 4 to 5 (4 to 5) and 2.5 to 4 (1.5 to 2), respectively. In the dry period when surface runoff is nearly zero, sub-surface runoff increases as d increases. A higher C_D causes higher evaporation which influences runoff as well (Eq. 1). As discussed earlier, the influence of d on the total runoff is complex which results in the variation of simulated runoff throughout the year. The spread of the uncertainty bands is large in the peak flow period as the sensitivity of both surface and sub-surface runoff is also large with respect to the value of *d* (not shown).

3.2. Calibration and Validation

The historical simulation from 1980 to 2001 is divided into two periods with the first half (1980-1990) as the calibration period and the second half (1991-2001) as validation. Basic information and characteristics (location, drainage area, and periods of available observed data) of the 6 validation stations in the GBM are summarized in Table 3. Model performance is evaluated by comparing observed and simulated daily streamflow by the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), the optimal objective function for assessing the overall fit of a hydrograph (Sevat and Dezetter, 1991). A series of sensitivity analysis of H08 parameters was conducted from which the 10 sets of the optimal parameter are determined by using the parameter-sampling simulation as discussed earlier, and these parameter sets will be used to quantify the uncertainty in both historical and future simulations in the following. Figure 4 plots the daily hydrograph comparisons at the outlets of three river basins with the corresponding daily observations for both calibration and validation periods. The obtained NSE for the calibration (validation) period is 0.84 (0.78), 0.80 (0.77), and 0.84 (0.86), while the percent bias (PBIAS) is 0.28% (6.59%), 1.21% (2.23%) and -0.96% (3.15%) for the Brahmaputra, Ganges, and Meghna basins, respectively. For all basins, the relative Root-Mean Square Error (RRMSE), the correlation coefficient (cc), and the coefficient of determination (R^2) for the calibration (validation) period ranges from 0.32 to 0.60 (0.32 to 0.59), 0.91 to 0.93 (0.89 to 0.94) and 0.82 to 0.86 (0.79 to 0.88), respectively. These statistical indices suggest the model performance is overall satisfactory. To further evaluate the model performance at upstream stations, the observed monthly discharge data at three upstream stations (Farakka, Pandu, Teesta) are collected from the Global Runoff Data Centre (GRDC) to compare with model simulations. The results are summarized presented in Appendix A.

4 Results and Discussion

The calibrated H08 model is applied to simulate for the following three time-slices periods, present (1979–2003), near-future (2015-2039) and the far-future (2075–2099). For the present simulations, both the WFD and GCMs climate forcing data were used. For the future simulation, only the GCMs forcing data are used. Simulation results for the future periods are then compared with the present period (1979–2003) simulation forced by GCM to assess the effect of climate change on the hydrology and water resources of GBM in terms of precipitation, air temperature, evapotranspiration, soil moisture and net radiation. The results are presented in the following.

4.1. Seasonal cycle

Figure 5 plots the 22-year (1980-2001) mean seasonal cycles of the climatic (from WFD forcing) and hydrologic (from the model simulation) quantities averaged over the three basins (The corresponding mean annual amounts of these variables are presented in Table 4). Also shown in Figure 5 is the Box-and-Whisker plot showing the range of variability within each of the twelve months. The interannual variation of precipitation in Brahmaputra and Meghna is high from May to September (Fig. 5a,c) whereas in Ganges it is from June to October. However, the magnitudes of precipitation differed substantially among three basins. The Meghna has significantly higher precipitation than other two basins (Table 4), also the maximum (monthly) precipitation during 1980-2001 occurs in May with the magnitude of 32 mm day^{-1}, while those in Brahmaputra and Ganges occurs in July with the magnitudes of 15 mm day^{-1} and 13 mm day^{-1}, respectively. Moreover, the seasonality of runoff in all three basins corresponded very well with that of precipitation. Runoff (Fig. 5j-l) in Ganges was much lower (the maximum of 4.3 mm day^{-1} in August) than the other two basins (the maximum of 9.3 mm day^{-1} in Brahmaputra and 15.9 mm day^{-1} in Maghna, both in July). In addition, ET in the Brahmaputra is significantly lower (annual total 251 mm) than in the other two basins (annual total 748 mm in Ganges and 1000 mm in Meghna). Lower ET in the Brahmaputra basin is likely due to its cooler air temperature, higher elevation and less vegetated area. The basin-averaged Normalized Difference Vegetation Index (NDVI) of the Brahmaputra is 0.38, whereas for the Ganges and Meghna, NDVI are 0.41 and 0.65, respectively (NEO, 2014). However, the patterns of seasonal variability of ET in Brahmaputra and Meghna are quite similar, except there is a drop in July in Brahmaputra (Fig. 5m-o). ET is relatively stable from May to October in Brahmaputra and Meghna (which suggests ET is at the potential rate) in contrast to that in Ganges where the ET does not reach the peak until September. Finally, both the pattern and magnitude of seasonal soil moisture variations are rather different among three basins (Fig. 5p-r). However, the peak of soil moisture occurs in August in all three basins.

Figure 5d-f present the 22-year mean seasonal cycle of basin average air temperature (Tair). Brahmaputra is much cooler (mean temperature 9.1°C) than Ganges (21.7°C) and Meghna (23.0°C). Figure 5g-i plot the mean seasonal cycle of net radiation averaged over these three basins. The seasonal pattern of net radiation is similar, but the magnitude differs significantly among three basins: The average net radiation is approximately 31, 74 and 84 W m^{-2} in Brahmaputra, Ganges and Meghna, respectively, while the maximum net radiation is about 47, 100 and 117 W m^{-2}, respectively (Table 4).

4.2. Correlation between meteorological and hydrological variables

Figure 6 presents the scatter plots and the correlation coefficients (cc) between the monthly meteorological and hydrological variables in three river basins. Three different colours represent three different seasons: dry/winter (November-March), pre-monsoon (April-June), and monsoon (July-October). From this plot, the following summary can be drawn. Total runoff and surface runoff of Brahmaputra have stronger correlation (cc= 0.95 and 0.97, both are statistically significant at $p<0.05$) with precipitation than in other two basins. However, subsurface runoff in Brahmaputra has weaker correlation (cc=0.62, $p<0.05$) with precipitation than that in Ganges (cc=0.75, $p<0.05$) and Meghna (cc=0.77, $p<0.05$). These relationships imply that the deeper soil depths enhance the correlation between subsurface runoff and precipitation. The deeper root-zone soil depth (calibrated d = 5m) in Meghna generates more subsurface runoff (69% of total runoff) than other two basins. Soil moisture in Meghna also shows stronger correlation (cc=0.87, $p<0.05$) with precipitation than that in Brahmaputra (cc=0.77, $p<0.05$) and Ganges (cc=0.82, $p<0.05$).

The relationships of evapotranspiration with various atmospheric variables (radiation, air temperature) and soil water availability are rather complex (Shaaban et al., 2011). Different methods for estimating potential evapotranspiration (PET) in different hydrological models may also be a source of uncertainty (Thompson et al., 2014). However, the ET scheme in the H08 model uses the bulk formula where the bulk transfer coefficient is used to calculate turbulent heat fluxes (Haddeland et al., 2011). In estimating PET (and hence ET), H08 uses humidity, air temperature, wind speed and net radiation. Figure 6 presents the correlation of ET with different meteorological variables in three basins. The ET in the Brahmaputra has a significant correlation with precipitation, air temperature, specific humidity and net radiation with the correlation coefficients (cc) range from 0.70 to 0.89 (all of which are statistically significant at $p<0.05$). The correlation of ET in Meghna with the meteorological variables are also relatively strong (cc range from 0.61 to 0.80, $p<0.05$) except for the net radiation (cc=0.44, $p<0.05$). However, ET in Ganges has a weak correlation with the meteorological variables (cc from 0.29 to 0.59, $p<0.05$). A weaker correlation of ET with the meteorological variables is likely attributed to the over-estimation of actual ET in the Ganges, because the up-stream water use (which is larger in Ganges) may be incorrectly estimated as ET by the H08 model to ensure water balance.

4.3. Interannual variability

Figure 7 presents the interannual variability of meteorological and hydrologic variables from using 5 different GCMs and that of the multi-model mean (shown by the thick blue line) for three basins. It can be seen from the figure that the magnitude of interannual variations of each individual GCM are noticeably larger than that of the multi-model mean. However, the long-term trends in the meteorological and hydrologic variables of the multi-model mean are generally similar to that of each GCMs. Figure 7a1-a3 show the long-term trend in precipitation is not pronounced for all three basins, but its interannual variability is rather large for each GCM. Among 5 GCMs used, the precipitation of MRI-AGCM3 has the largest interannual variability (particularly in the Ganges and Meghna basin). A clear increasing trend in air temperature can be observed for all three basins. As there is strong correlation between precipitation and runoff (Fig. 6), the interannual variability of them are similar. There is no clear trend that can be observed for ET in each basin from the present to the near-future period. However, in the far-future a notable increasing trend is observed for all basins (Fig. 7e1-e3). Figure 7f1-f3 plots the interannual variability of soil moisture. Since there are no clear trends (from the present to the near-future period) identified from precipitation and evapotranspiration, the effect of climate change on soil moisture is relatively less pronounced from this modelling study.

4.4. Projected mean changes

The changes in the seasonal cycles of hydro-meteorological variables in the two projected periods (2015-2039 and 2075–2099) are comparing with that in the reference period (1979-2003). All the results presented here are from the multi-model mean of all simulations driven by the climate forcing data from 5 GCMs for both reference and future periods. The solid lines in Fig. 8 represent the monthly averages and the dashed lines represent the upper and lower bounds of the uncertainty bands as determined from the 10 simulations using the 10 optimal parameter sets (identified by ranking the Nash–Sutcliffe efficiency (NSE)). Figure 9 plots the corresponding percentage changes and Table 5 summarizes these relative changes in the hydro-meteorological variables over three basins on the annual and 6-month (dry season and wet season) basis.

4.4.1. Precipitation

Considering high emission scenario, by the end of 21st century the long-term mean precipitation is projected to increase by 16.3%, 19.8% and 29.6% in the Brahmaputra, Ganges and Meghna basin, respectively (Table 5), in agreement with previous studies which compared GCM simulation results over these regions. For example, Immerzeel (2008) estimated the increase of precipitation in the Brahmaputra basin as 22% and 14% under the SRES A2 and B2 scenarios, respectively. Endo et al. (2012) considered the SRES A1B scenario and estimated the country-wise increase in precipitation as 19.7% and 13% for Bangladesh and India respectively. Based on the present study, for the Brahmaputra and Meghna basins the change of precipitation in dry season (November-April) is 23% and 33.6%, respectively, both are larger than the change in wet season (May-October) (Brahmaputra: 15.1%, Meghna: 29%) (Fig. 9b-c). However, the change of precipitation in dry season in Ganges (3.6%) is lower than that in wet season (21.5%).

4.4.2. Air temperature

The GBM basin will be warmer by the range of 1-4.3°C in the near-future (Brahmaputra: 1.2°C, Ganges: 1.0°C, Meghna: 0.7°C) and far-future (Brahmaputra: 4.8°C, Ganges: 4.1°C, Meghna: 3.8°C), respectively (Table 5). According to the projected changes, the cooler Brahmaputra basin will be significantly warmer by the maximum increase up to 5.9°C in February (Fig. 9d). In Immerzeel (2008), the increase of air temperature in Brahmaputra is projected (under the SRES A2 and B2 scenarios) as 2.3°C ~3.5°C by the end of 21st century. However, The rate of increase over the year is not uniform for all these basins. Temperature will increase more in winter than that in summer (Fig. 9d-f). Therefore, a shorter winter and an extended spring can be expected in the future of the GBM basin, which may significantly affect the crop growing season as well.

4.4.3. Runoff

Long-term mean runoff is projected to be increased by 16.2%, 33.1% and 39.7% in Brahmaputra, Ganges and Meghna, respectively by the end of the century (Table 5). Percentage increase of runoff in Brahmaputra will be quite large in May (about 36.5%), which may be due to the increase of precipitation and also smaller evapotranspiration caused by lower net radiation (Fig. 9g, m). In response to seasonally varying degrees of changes in air temperature, net radiation and evaporation, the changes of runoff in wet season (May-October) (Brahmaputra: 20.3%, Ganges: 36.3%, Meghna: 41.8%) are larger than that in dry season (November-April) (Brahmaputra: 2.9%, Ganges: -2.3%, Meghna: 24.2%) (Fig. 9j-k). Runoff in Meghna shows larger response to precipitation increase, which could lead to higher possibility of floods in this basin and prolonged flooding conditions in Bangladesh. These findings are in general consistent with previous findings. Mirza (2002) reported that the probability of occurrence of 20-year floods are expected to be higher in the Brahmaputra and Meghna Rivers than in Ganges River. However, Mirza et al. (2003) found future change in the peak discharge of the Ganges River (as well as the Meghna River)is expected to be larger than that of the Brahmaputra River.

4.4.4. Evapotranspiration

It can be seen from Fig. 9m-o that the change of ET in near-future is relative low, but increases to be quite large by the end of the century (Brahmaputra: 16.4%, Ganges: 13.6%, Meghna: 12.9%). This is due to the increase of net radiation (Brahmaputra: 5.6%, Ganges: 4.1%, Meghna: 4.4%) as well as the warmer air temperature. Following the seasonal patterns of radiation (Fig. 9g-i) and air temperature (Fig. 9d-f), the change of ET will be considerably larger in dry season

(November-April) (Brahmaputra: 25.6%, Ganges: 19.3%, Meghna: 18.2%) than that in wet season (May-October) (Brahmaputra: 12.9%, Ganges: 10.9%, Meghna: 10.5%).

4.4.5. Soil moisture

Soil moisture is expressed in terms of the water depth per unit area within the spatially varying soil depths (3 ~ 5 m). The change of soil moisture (ranges from 1.5 ~ 6.9% in the far-future) is lower compared to other hydrological quantities, except for the Meghna in April where the soil moisture is projected to increase by 22%. However, the associated uncertainties through all seasons are relatively high compared to other variables (Fig. 8f1-f3).

4.4.6. Net radiation

Net radiation is projected to be increased by >4% for all the seasons except summer in the entire GBM basin by the end of the century (Figure 9g-i). Due to the increase in the future air temperature, the downward long-wave radiation will increase accordingly and lead to the increase in net radiation. However, the change of net radiation in the far-future period is larger in dry season (Brahmaputra: 10.3%, Ganges: 5.3%, Meghna: 6.5%) than wet season (Brahmaputra: 3.1%, Ganges: 3.4%, Meghna: 3%). For the near-future period, net radiation is projected to decrease by <1% through about all seasons due to the smaller increase in air temperature (~1°C) as well as decreased incoming solar radiation (not shown) in this basin.

4.5. Uncertainty in projection due to model parameters

In recent decades, along with the increasing computational power there has been a trend towards increasing complexity of hydrological models to capture natural phenomenon more precisely. However, the increased complexity of hydrological models does not necessarily improve their performance for unobserved conditions due to the uncertainty in the model parameters values (Carpenter and Georgakakos, 2006;Tripp and Niemann, 2008). An increase in complexity may improve the calibration performance due to the increased flexibility in the model behaviour, but the ability to identify correct parameter values is typically reduced (Wagener et al., 2003). Multiple parameter sets can reproduce the observations with the similar accuracy. Another source of uncertainty comes from the assumption of stationary model parameters, which is one of the major limitations in modelling the effects of climate change. Model parameters are commonly estimated under the current climate conditions as a basis for predicting future conditions, but the optimal parameters may not be stationary over time (Mirza and Ahmad, 2005b). Therefore, the uncertainty in future projections due to model parameters specification can be critical (Vaze et al., 2010; Merz et al., 2011; Coron et al., 2012), although it is usually ignored in most climate change impact studies (Lespinas et al., 2014). Results obtained by Vaze et al. (2010) indicated that the model parameter can generally be used for climate impact studies when model is calibrated using more than 20-year of data and where the future precipitation is not more than 15% drier or 20% wetter than that in the calibration period. However, Coron et al. (2012) found a significant level of errors in simulations due to this uncertainty and suggested further research to improve the methods of diagnosing parameter transferability under the changing climate. For the purpose of minimizing this parameter uncertainty the average results from the 10 simulations using 10 optimal parameter sets are considered as the simulation result for the two future periods in this study. Also the propagating uncertainty in simulation results due to the uncertainty in mode parameters will be quantified and compared among various hydrologic variables in this study.

From Fig. 8 where the upper and lower bounds of the uncertainty of hydro-meteorological variables are plotted for all the simulation periods. It can be seen that the uncertainty band of runoff is relatively narrow, which indicates future runoff is well predictable through model simulations in this study. The uncertainty due to model parameters in runoff prediction is lower (the coefficient of variation (CV) ranges between 3 – 7.6% among three basins) than that of other hydrologic variables (Fig. 8d1-d3). In addition, from Fig. 4e it is observed that there is no significant uncertainty in simulated peak discharge for the Brahmaputra and Meghna River. Lower uncertainty in predicting runoff is highly desirable for climate change impact studies, for instance, the flood risk assessment where the runoff estimate (especially the peak flow) is the main focus. However, a relatively wide uncertainty band of runoff can be found in Ganges in wet season (Fig. 8d2), which might be due to that the upstream water use (diversion) in Ganges was not well represented in the model. Notice that the lower uncertainty in runoff prediction relative to other variables is expected as the model is calibrated and validated against observed streamflow at the basin outlet. The uncertainty in ET prediction is also lower (CV: 3.6–11.3%; SD: 0.1–0.4), which can be related to the narrower uncertainty band of net radiation (CV: 1.8–8.6%; SD: 1.8–5.6). On the other hand, the prediction of soil moisture is rather uncertain for all three basins (CV: 14.4–31%; SD: 35–104). Large uncertainty in predicting soil moisture can be a serious issue significant in land use management and agriculture in particular, and this emphasizes the critical importance of having soil moisture observations for constraining model simulations in addition to the issues regarding the identifiability of model parameters.

5 Conclusions

This study presents model analyses of the climate change impact on Ganges-Brahmaputra-Meghna (GBM) basin focusing on (1) the setup of a hydrologic model by integrating the fine-resolution (~0.5 km) DEM data for the accurate river networks delineation to simulate at relatively fine grid resolution (10 km) (2) the calibration and validation of the hydrologic model with long-term observed daily discharge data and (3) the impacts of future climate changes in the basin-scale hydrology. The uncertainties in the future projection stemming from model parameter were also assessed. The time-slice numerical experiments were performed using the model forced by the climatic variables from 5 GCMs (all participating in the

CMIP5) for the present-day (1979–2003), near-future (2015-2039) and the far-future (2075–2099) periods.

The following findings and conclusions were drawn from the model analysis:

- (a) The entire GBM basin is projected to be warmer by the range of 1-4.3°C in the near-future and far-future, respectively. And the cooler Brahmaputra basin will be warmer than the Ganges and Meghna. (b) Considering high emissions scenario, by the end of 21st century the long-term mean precipitation is projected to increase by +16.3, +19.8 and +29.6%, and the long-term mean runoff is projected to increase by +16.2, +33.1 and +39.7% in the Brahmaputra, Ganges and Meghna basin, respectively. (c) The change of ET in near-future is relative low, but increases to be quite large by the end of the century due to the increase of net radiation as well as the warmer air temperature. However, the change will be considerably larger in dry season than that in wet season. (d) The change of soil moisture is lower compared to other hydrological quantities.

- Over all, it is observed that climate change impact on the hydrology of the Meghna basin is larger than that of the other two basins. For example, in the near-future runoff of Meghna is projected to increase 19.1% whereas it is 6.7% and 11.3% for Brahmaputra and Ganges, respectively. In far-future larger increase of precipitation (29.6%) and lower increase of ET (12.9%) and consequently larger increase of runoff (39.7%) lead to higher possibility of floods in this basin.

- The uncertainty due to model parameters in runoff prediction is lower than that of other hydrologic variables. The uncertainty in ET prediction is also lower, which can be related to the narrower uncertainty band of net radiation. On the other hand, the prediction of soil moisture is rather uncertain for all three basins, which can be significant in land use management and agriculture in particular, and this emphasizes the importance of having soil moisture observations for model calibration.

However this study still has some limitations which can be addressed in future research; (a) all results presented here are basin-averaged. The basin-averaged large scale changes and trends are difficult to translate to regional and local scale impacts. Moreover, the changes in averages do not reflect the changes in variability and extremes, (b) anthropogenic and industrial water use in upstream are important factors in altering hydrologic cycle, however, which are not considered in present study due to data constraint, (c) urbanizing watersheds are characterized by rapid land use changes and associated land-scape disturbances can shift the rainfall–runoff relationships away from natural processes. Hydrological changes in future can also be amplified by changing land uses. However, in our study future changes of demography and land uses are not considered.

Acknowledgments. This study is supported by Public Works Research Institute (PWRI), Japan. The first author is indebted to the authority of Nippon Koei Co., Ltd, Japan for the grant from “The Kubota Fund”. Also, thanks are given to A. Hasegawa, T. Sayama for help in data preparation and for suggestions, and to FFWC, BWDB for providing observed hydrological data.

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Table 1: Major characteristics of the Ganges, Brahmaputra and Meghna River basin

Item		Brahmaputra	Ganges	Meghna
Origin and major properties [a]		The Brahmaputra River begins in the glaciers of the Himalayas and travels through China, Bhutan, and India before emptying into the Bay of Bengal in Bangladesh. It is snow-fed braided river and it remains a natural stream with no major hydraulic structures built along its reach.	The Ganges River originates at the Gangotri glaciers in the Himalayas and it passes through Nepal, China, and India and empties into the Bay of Bengal at Bangladesh. It is snowmelt-fed river regulated by upstream India.	The Meghna River is a comparatively smaller, rain-fed, and relatively flashier river that runs through a mountainous region in India before entering Bangladesh.
Basin area (km^2)		583 000[b]	907 000[b]	65 000[b]
		530 000[f,g]	1 087 300[h]	82 000[h]
		543 400[h]	1 000 000[c]	
River length (km)		1 800[b]	2 000[b]	946[b]
		2 900[f]	2 510[c]	
		2 896[a]	2 500[a]	
Elevation (m a.s.l.) [e]	Range	8 ~ 7057	3 ~ 8454	-1 ~ 2579
	Average	3141	864	307
	Area below 500 m:	20%	72%	75%
	Area above 3000 m:	60%	11%	0%
Discharge ($m^3 s^{-1}$)	Station	Bahadurabad	Hardinge bridge	Bhairab bazar
	Lowest	3 430[d]	530[d]	2[d]
	Highest	102 535[d]	70 868[d]	19 900[d]
	Average	20 000[g]	11 300[d]	4 600[d]
Land use	Agricultur	19%	68%	27%

(% area)[i]	e			
	Forest	31%	11%	54%
Basin-averaged Normalized Difference Vegetation Index (NDVI)[j]		0.38	0.41	0.65
Total number of dams (both for hydropower and irrigation purpose)[k]		6	75	-

[a] Moffitt et al. (2011)
[b] Nishat and Faisal (2000)
[c] Abrams (2003)
[d] BWDB (2012)
[e] Estimated from SRTM DEM data by Lehner et al. (2006)
[f] Gain et al. (2011)
[g] Immerzeel (2008)
[h] FAO-AQUASTAT (2014)
[i] Estimated from Tateishi et al. (2014)
[j] Estimated from NEO (2014)
[k] Lehner et al. (2008)

Table 2. Basic input data used in this study

Type	Description	Source/Reference(s)	Original spatial resolution	Period	Remarks
Physical Data	Digital Elevation Map (DEM)	HydroSHEDS[a] (HydroSHEDS, 2014)	15″ (~0.5 km)	-	Global data
	Basin mask	HydroSHEDS[a] (HydroSHEDS, 2014)	30″ (~1 km)	-	
Meteorological data	rainfall, snowfall, surface pressure, air temperature, specific humidity, wind speed, long-wave downward radiation, shortwave downward radiation	WFD[b] (Weedon et al., 2010;Weedon et al., 2011)	0.5°	1980-2001	5′ (~10 km-mesh) data has been prepared by linear interpolating for this study
	albedo	GSWP2[c]	1°	1980-1990	Mean monthly 5′ (~10 km-mesh) data has been prepared for this study
Hydrologic data	water level discharge	Bangladesh Water Development Board (BWDB)	Gauged	1980-2012	water level (daily), discharge (weekly) data at outlets of three basins, i.e. the Ganges basin at Hardinge Bridge, the Brahmaputra basin at Bahadurabad, and the Meghna basin at Bhairab Bazar obtained from

					BWDB.
	discharge	Global Runoff Data Centre (GRDC)	Gauged	1949-1973 (Farakka), 1975-1979 (Pandu), 1969-1992 (Teesta) with missing data	discharge (monthly) data at three upstream stations, i.e. at Farakka (Ganges), Pandu (Brahmaputra) and Teesta (Brahmaputra).
GCM data	rainfall, snowfall, surface pressure, air temperature, specific humidity, wind speed, long-wave downward radiation, shortwave downward radiation	MRI-AGCM 3.2S[d]	0.25° (~20 km-mesh)	1979-2003 , 2015-2039 ,2075-2099	bias of precipitation dataset has been corrected by multiplying using monthly correction coefficient (ratio between basin averaged long term monthly mean precipitation from WFD and that from each GCM) for each GBM basins
		MIROC5	1.41×1.39°		
		MIROC-ESM	2.81×2.77°		
		MRI-CGCM3	1.125×1.11°		
		HadGEM2-ES	1.875×1.25°		

[a]HydroSHEDS is Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales,

[b]WFD is WATCH forcing data,

[c]GSWP2 is Second Global Soil Wetness Project,

[d]MRI-AGCM is Meteorological Research Institute-Atmospheric General Circulation Model

Table 3. Basic information of the streamflow validation stations in the GBM basins

Basin name	Brahmaputra			Ganges		Meghna
Station name	Bahadurabad	Pandu	Teesta	Hardinge bridge	Farakka	Bhairab bazar
Latitude	25.18° N	26.13° N	25.75° N	24.08° N	25° N	25.75° N
Longitude	89.67° E	91.7° E	89.5° E	89.03° E	87.92° E	89.5° E
Drainage area (km^2)	583 000	405 000	12 358	907 000	835 000	65 000
Available observed data period (with missing)	1980-2001	1975-1979	1969-1992	1980-2001	1949-1973	1980-2001

Table 4. The 22-year (1980-2001) averages of the meteorological (from the WFD forcing data) and hydrologic variables in the GBM river basins.

	Unit	**Brahmaputra**	**Ganges**	**Meghna**
(a) Meteorological variables				
Precipitation (Prcp)	mm $year^{-1}$	1609	1157	3212
Temperature (Tair)	°C	9.1	21.7	23.0
Net radiation (Net rad)	W m^{-2}	31	74	84
Specific humidity	g/kg	9.3	11.8	14.4
(b) Hydrological variables				
Runoff	mm $year^{-1}$	1360	406	2193
Evapotranspiration (ET)	mm $year^{-1}$	251	748	1000
Potential Evapotranspiration (PET)	mm $year^{-1}$	415	2359	1689

Table 5. The 10-simulation average of annual mean and percentage changes of hydrological and meteorological variables.

Variable	Period	Brahmaputra annual mean	Brahmaputra % change (Tair: °C) dry season (November-April)	wet season (May-October)	annual	Ganges annual mean	Ganges % change (Tair: °C) dry season (November-April)	wet season (May-October)	annual	Meghna annual mean	Meghna % change (Tair: °C) dry season (November-April)	wet season (May-October)	annual
(a) Meteorological variables													
Pricipitation (mm year^{-1})	present-day (1979-2003)	1632	-	-	-	1154	-	-	-	3192	-	-	-
	near-future (2015-2039)	1720	4.2	5.6	5.4	1218	-0.1	6.2	5.6	3598	11.4	12.9	12.7
	far-future (2075-2099)	1897	23.0	15.1	16.3	1383	3.6	21.5	19.8	4139	33.6	29.0	29.6
Tair (°C)	present-day (1979-2003)	5.5	-	-	-	21.7	-	-	-	23.0	-	-	-
	near-future (2015-2039)	6.7	1.4	1.0	1.2	22.8	1.1	0.9	1.0	23.7	0.8	0.6	0.7
	far-future (2075-2099)	10.3	5.5	4.1	4.8	25.9	4.6	3.7	4.1	26.8	4.3	3.4	3.8
Net radiation (W m^{-2})	present-day (1979-2003)	63	-	-	-	97	-	-	-	114	-	-	-
	near-future (2015-2039)	62	2.0	-1.6	-0.4	97	-0.2	-0.9	-0.7	112	-0.4	-2.2	-1.5
	far-future (2075-2099)	66	10.3	3.1	5.6	101	5.3	3.4	4.1	119	6.5	3.0	4.4
(b) Hydrological variables													

Total runoff (mm year^{-1})	present-day (1979-2003)	1166	-	-	-	372	-	-	-	1999	-	-	-
	near-future (2015-2039)	1244	0.5	8.6	6.7	414	2.5	12.1	11.3	2380	10.5	20.2	19.1
	far-future (2075-2099)	1355	2.9	20.3	16.2	495	-2.3	36.3	33.1	2793	24.2	41.8	39.7
ET (mm year^{-1})	present-day (1979-2003)	467	-	-	-	785	-	-	-	1193	-	-	-
	near-future (2015-2039)	477	5.5	0.9	2.1	808	4.9	2.1	3.0	1216	5.2	0.4	1.9
	far-future (2075-2099)	543	25.6	12.9	16.4	892	19.3	10.9	13.6	1347	18.2	10.5	12.9
Soil moisture (mm)	present-day (1979-2003)	335	-	-	-	186	-	-	-	336	-	-	-
	near-future (2015-2039)	338	0.4	1.2	0.9	192	2.7	3.4	3.1	354	6.6	5.1	5.5
	far-future (2075-2099)	340	0.2	2.3	1.5	197	0.4	8.3	5.8	359	6.7	6.9	6.9

Table 6. Statistical indices (the coefficient of variation (CV) and standard deviation (SD)) of the uncertainty in model simulations due to the uncertainty in model parameters

Variable	Period	Brahmaputra		Ganges		Meghna	
		Coefficient of variation (CV) of mean (Fig.8) (%)	Standard deviation (SD) of mean (Fig.8)	Coefficient of variation (CV) of mean (Fig.8) (%)	Standard deviation (SD) of mean (Fig.8)	Coefficient of variation (CV) of mean (Fig.8) (%)	Standard deviation (SD) of mean (Fig.8)
Net radiation	present-day	8.6	5.4	2.0	2.0	2.1	2.4
	near-future	8.6	5.4	1.9	1.9	2.1	2.3
	far-future	8.4	5.6	1.8	1.8	2.0	2.4
Total runoff	present-day	3.2	0.1	7.6	0.1	6.7	0.4
	near-future	3.0	0.1	7.2	0.1	5.4	0.4
	far-future	3.1	0.1	6.6	0.1	4.6	0.4
ET	present-day	7.9	0.1	3.6	0.1	11.3	0.4
	near-future	7.9	0.1	3.7	0.1	10.6	0.4
	far-future	7.8	0.1	3.7	0.1	9.7	0.4
Soil moisture	present-day	31.0	103.7	18.5	34.5	15.9	53.5
	near-future	30.8	104.1	18.5	35.5	15.4	54.5
	far-future	30.5	103.7	18.3	36.1	14.4	51.6

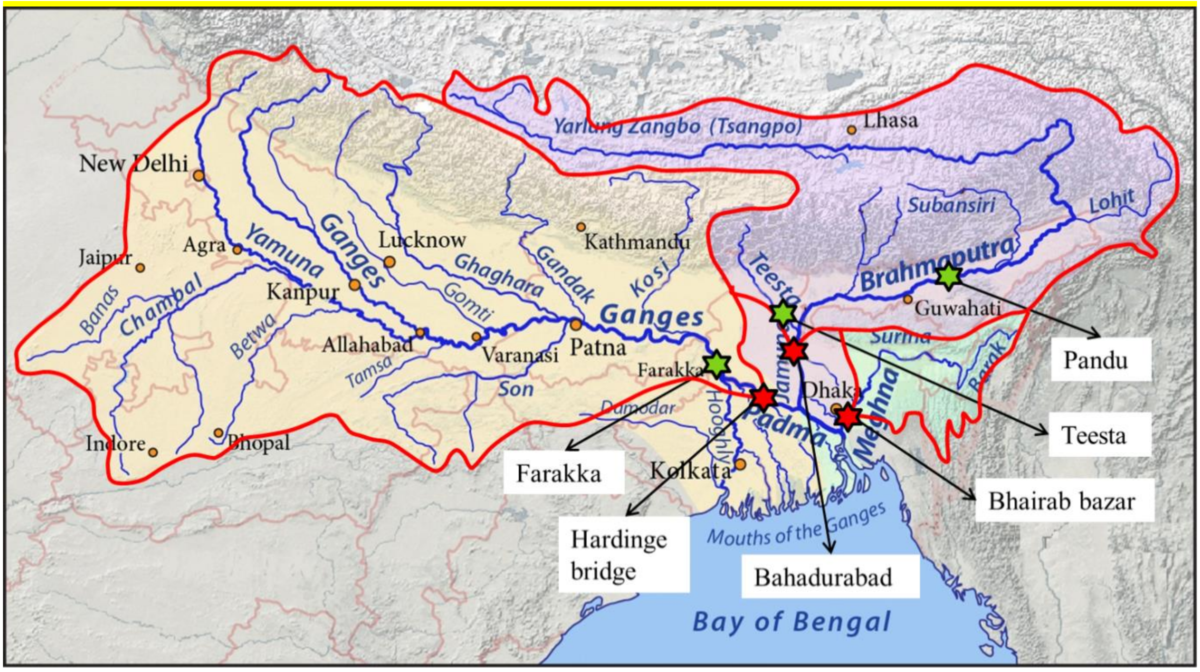

Figure 1. The boundary of the Ganges-Brahmaputra-Meghna (GBM) River basin (thick red line), the three outlets (red star): Hardinge bridge, Bahadurabad and Bhairab bazar for the Ganges, Brahmaputra and Meghna River basin, respectively. Green stars indicate the locations of three additional upstream stations; Farakka, Pandu and Teesta. (modified from Pfly, 2011).

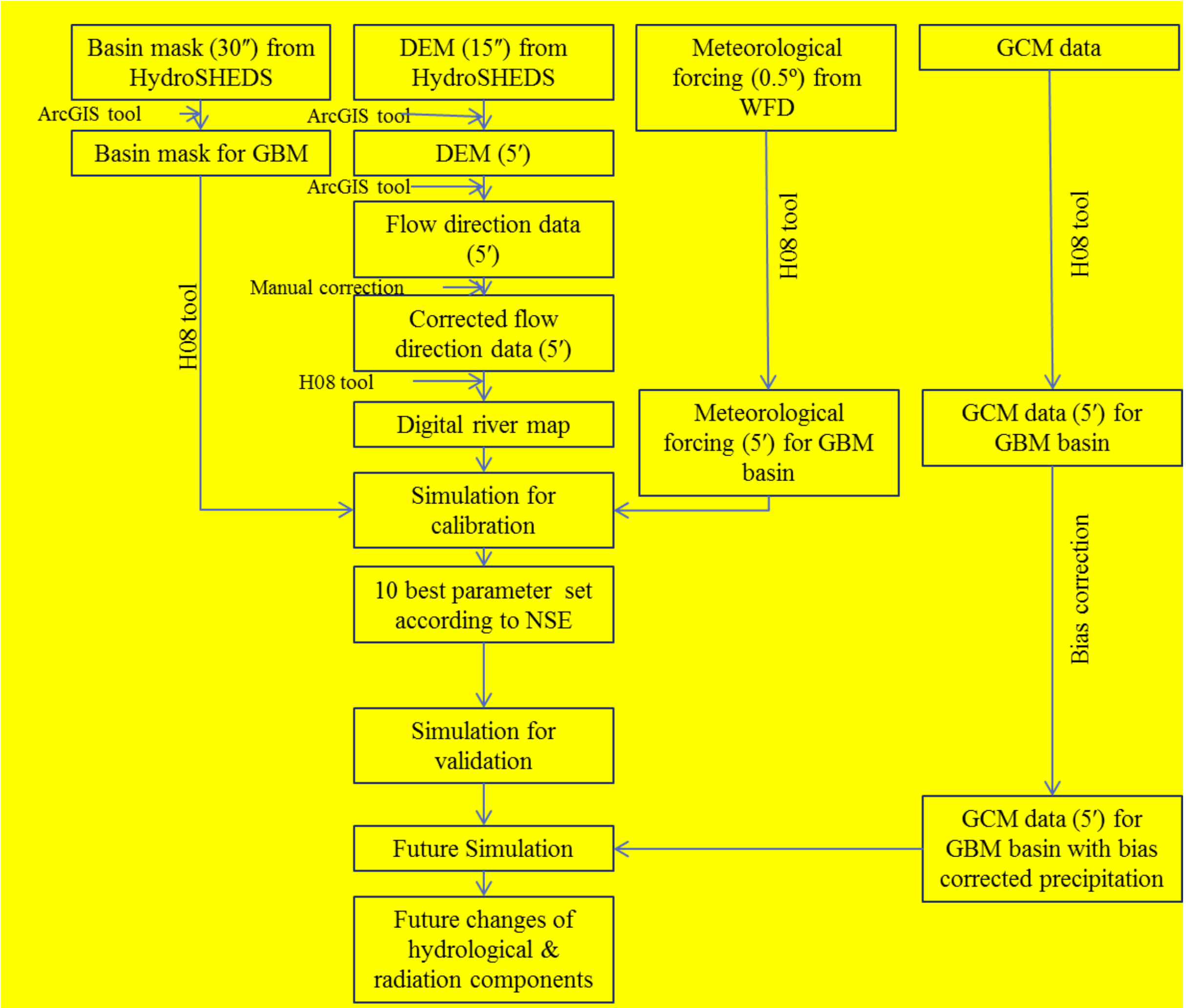

Figure 2. Flow chart of the methodology used in this study.

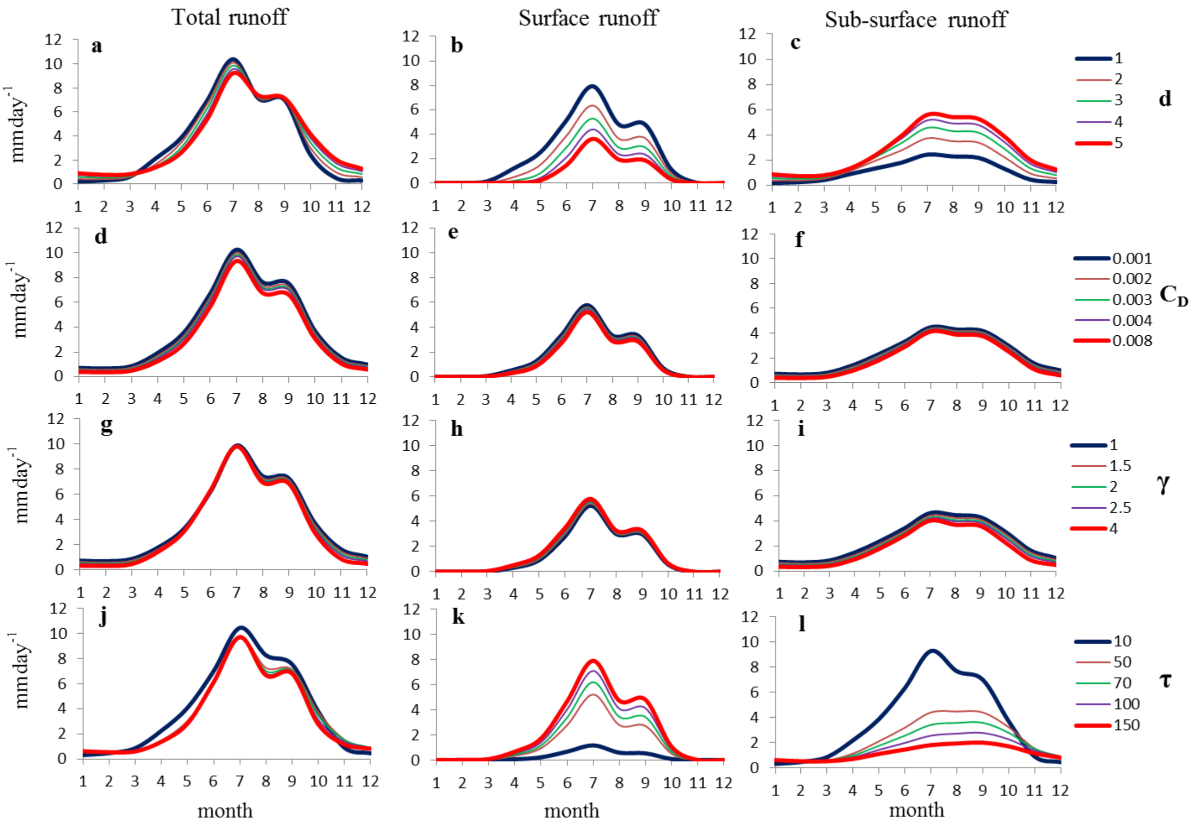

Figure 3. The 11-year (1980–1990) mean seasonal cycles of the simulated total runoff, surface runoff and sub-surface runoff (unit: mm day^{-1}) in the Brahmaputra basin. Each of the five lines in each panel represents the average of 5^3 (=125) runs with one of the four calibration parameters fixed at a given reasonable value.

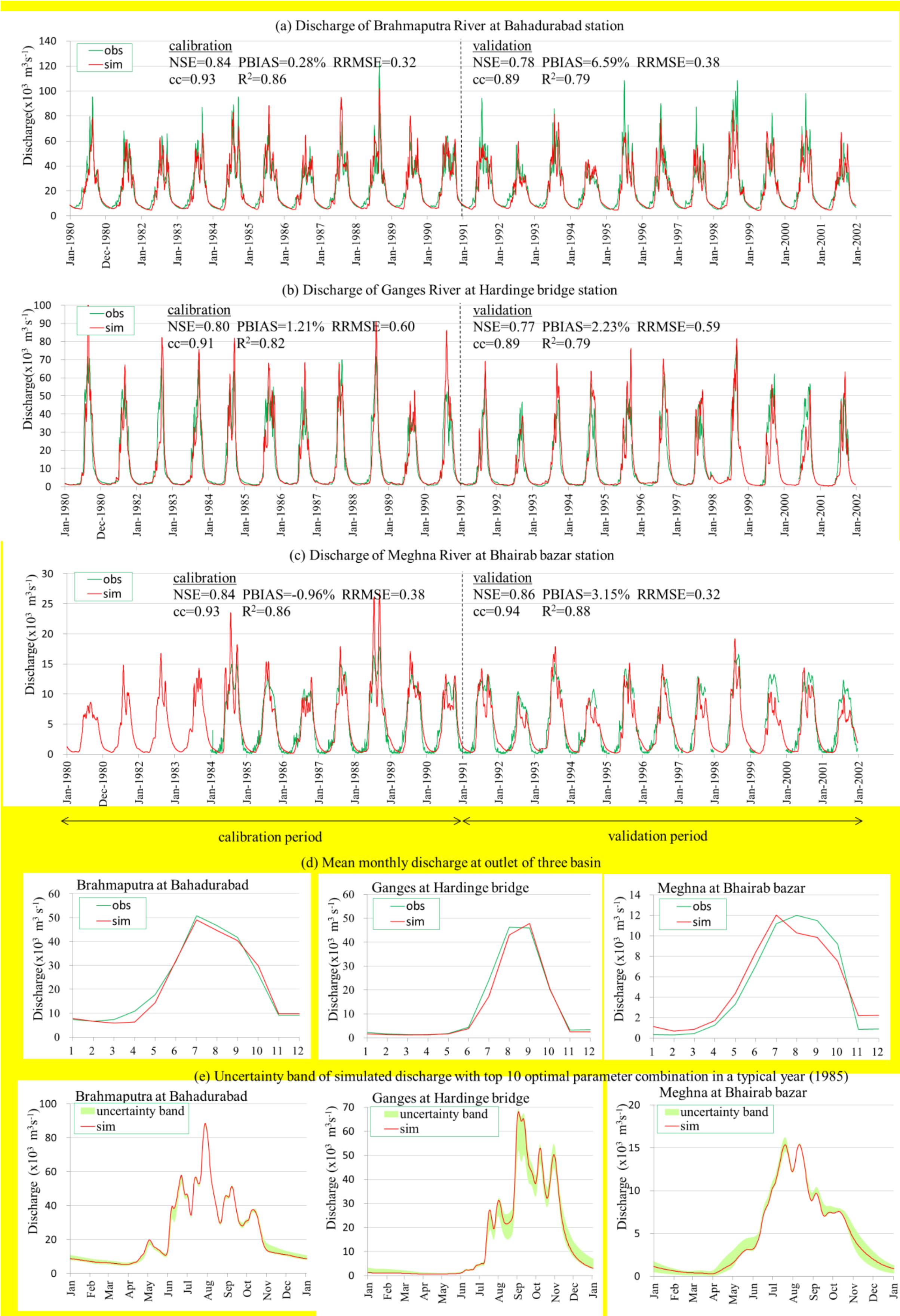
(a) Discharge of Brahmaputra River at Bahadurabad station
calibration
NSE=0.84 PBIAS=0.28% RRMSE=0.32
cc=0.93 R2=0.86
validation
NSE=0.78 PBIAS=6.59% RRMSE=0.38
cc=0.89 R2=0.79
obs
sim
Discharge(x10^3 m^3s^-1)
(b) Discharge of Ganges River at Hardinge bridge station
calibration
NSE=0.80 PBIAS=1.21% RRMSE=0.60
cc=0.91 R2=0.82
validation
NSE=0.77 PBIAS=2.23% RRMSE=0.59
cc=0.89 R2=0.79
(c) Discharge of Meghna River at Bhairab bazar station
calibration
NSE=0.84 PBIAS=-0.96% RRMSE=0.38
cc=0.93 R2=0.86
validation
NSE=0.86 PBIAS=3.15% RRMSE=0.32
cc=0.94 R2=0.88
calibration period
validation period
(d) Mean monthly discharge at outlet of three basin
Brahmaputra at Bahadurabad
Ganges at Hardinge bridge
Meghna at Bhairab bazar
(e) Uncertainty band of simulated discharge with top 10 optimal parameter combination in a typical year (1985)
uncertainty band
sim
Discharge (x10^3 m^3s^-1)

Figure 4. The simulated discharges (red line) using the WFD forcing data (both calibration and validation period) compared with observations (green line) at outlets of the (a) Brahmaputra, (b) Ganges, (c) Meghna River, (d) mean monthly (1980-2001) simulated discharges compared with that of observations at outlets, (e) simulated discharges by using the 10 optimal parameter sets (red line) and the associated uncertainty bands (green shading) in a typical year (1985). Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), relative Root-Mean Square Error (RRMSE), correlation coefficient (cc) and coefficient of determination (R^2) for both calibration and validation period are noted at sub-plot (a), (b) and (c).

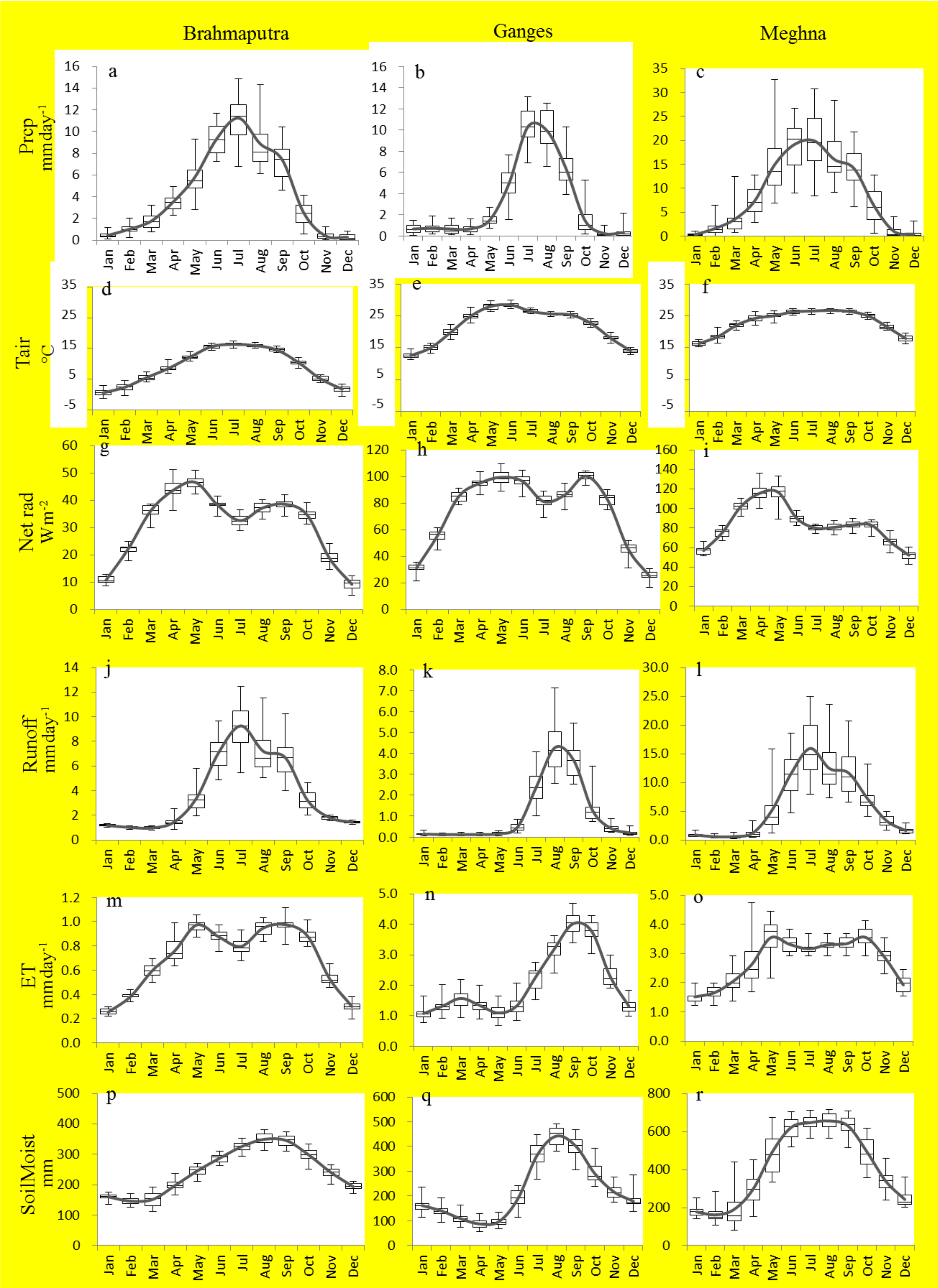

Figure 5 (a)-(r). Seasonal cycle of climatic and hydrologic quantities during 1980-2001. Box-and-whisker plots indicate minimum and maximum (whiskers), 25th and 75th percentiles (box ends), and median (black solid middle bar). Solid curve line represents interannual average value. All abbreviated terms here refer to Table 4.

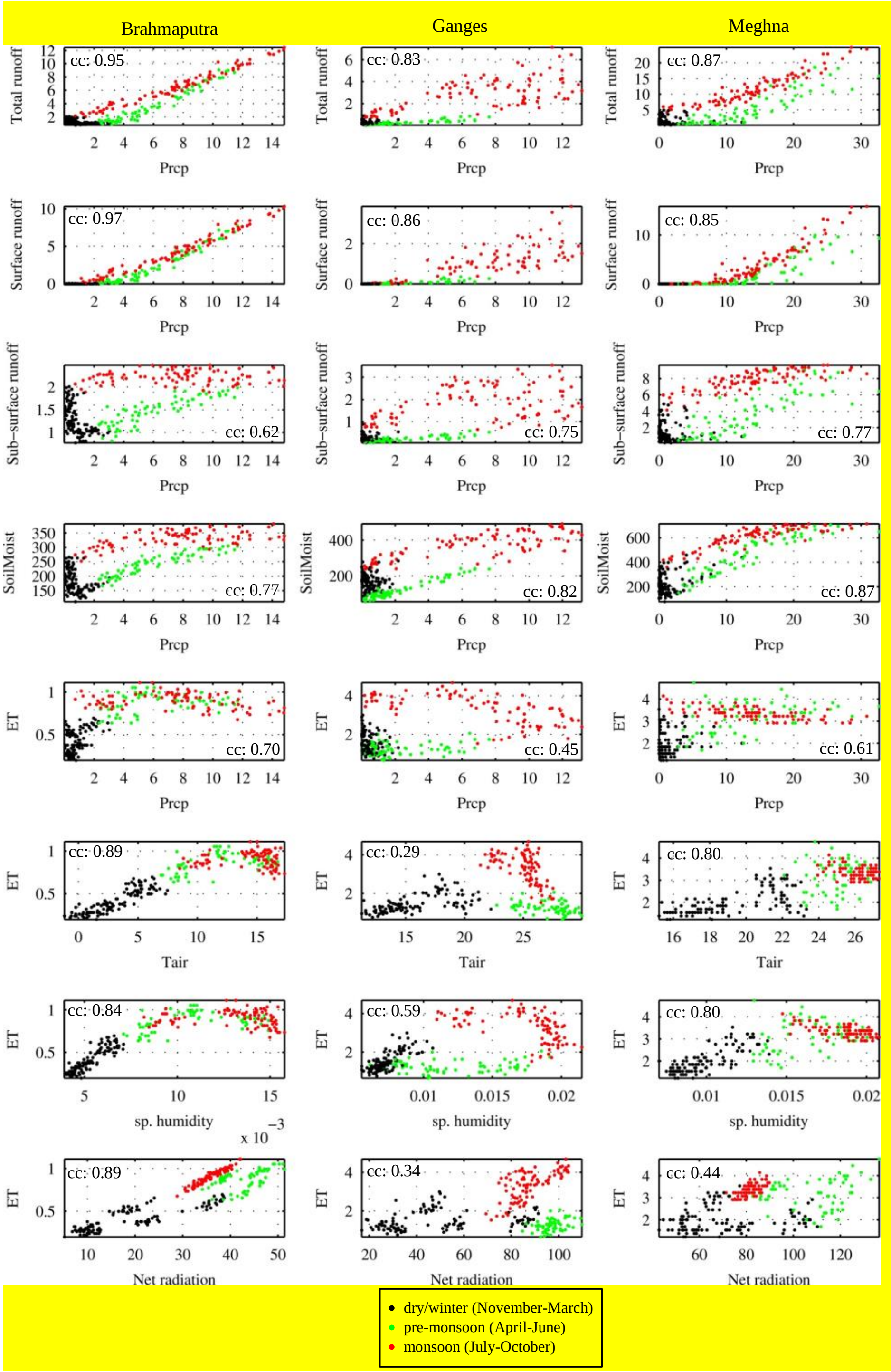

Figure 6. The correlation between the monthly means of meteorological variables (WFD) and that of hydrological variables for the Brahmaputra, Ganges and Meghna basins. Three different colors represent the data in three different seasons: Black: dry/winter (November-March); Green: pre-monsoon (April-Jun); Red: monsoon (July-October). The correlation coefficient (cc) for each pair (all 3 seasons together) is noted at each sub-plot. The units are mm day^{-1} for Prec, ET, runoff , mm for SoilMoist, °C for Tair, and W m^{-2} for net radiation. All abbreviated terms here are referred to Table 4.

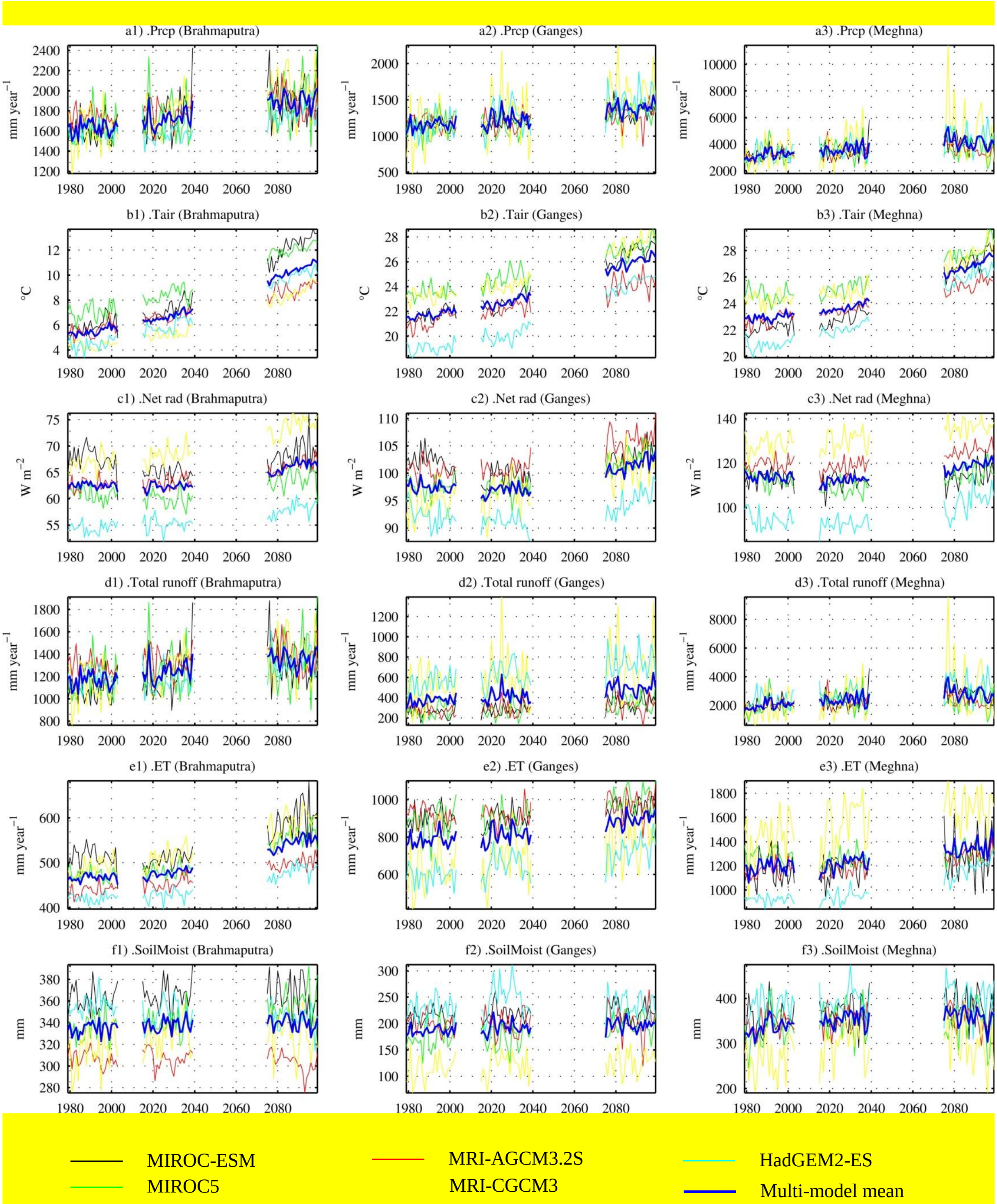

Figure 7 (a1-f3). Interannual variation of mean of meteorological and hydrological variables of 5 GCMs for present-day (1979-2003), near-future (2015-2039) and far-future (2075-2099). Thick blue lines represent the means of 5 GCMs.

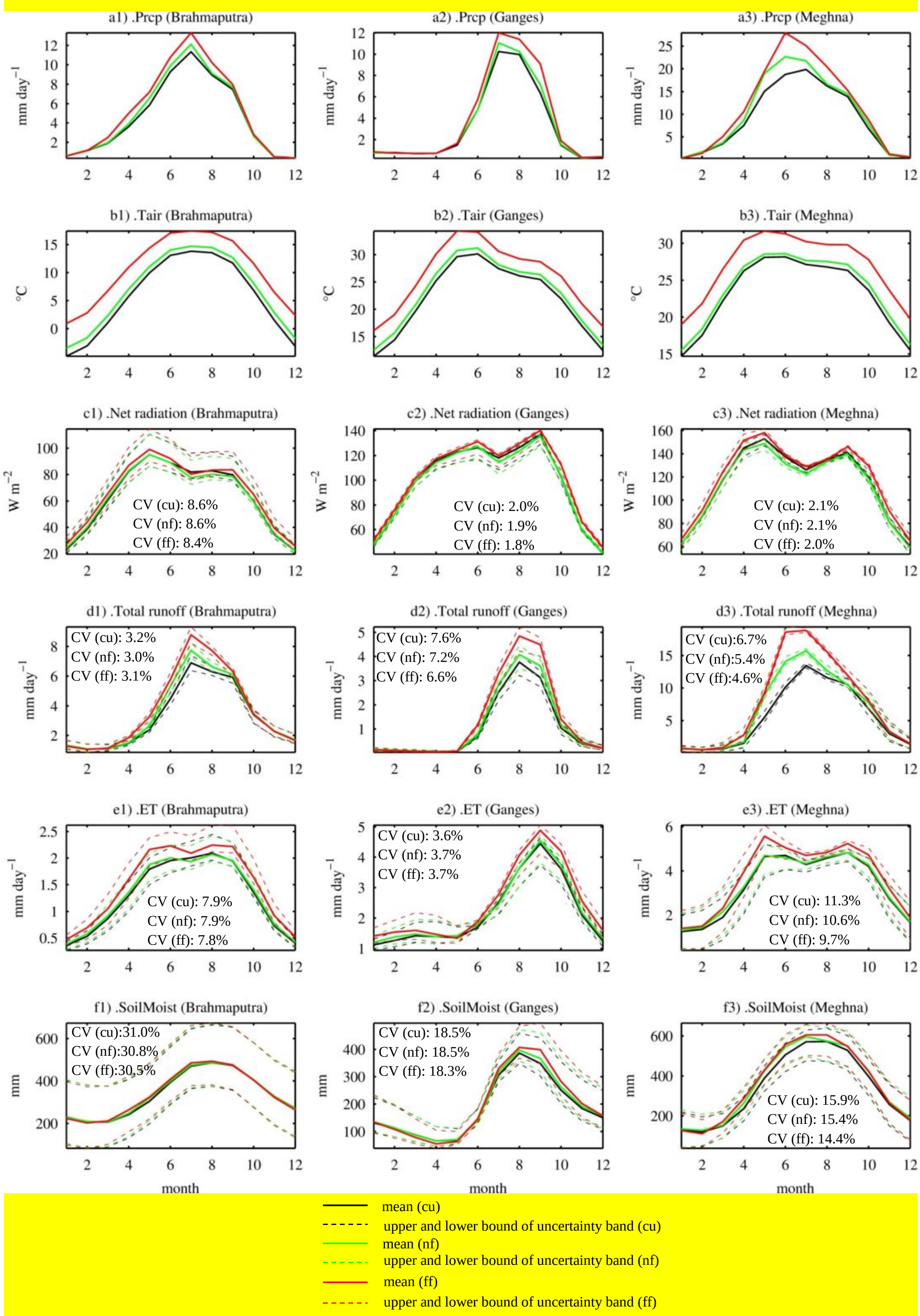

Figure 8 (a1)-(f3). The mean (solid line), upper and lower bounds (dashed line) of the uncertainty band of the hydrological quantities and net radiation components for the present-day (black), near-future (green) and far-future (red) simulations as determined found from 10 simulation result with considering 10 optimal parameter set according to Nash–Sutcliffe efficiency (NSE) (cu: present-day, nf: near-future, ff: far-future). Coefficient of variations (CV) for all periods (Table 6) are noted on each sub-plot.

Figure 9 (a)-(r). Percentage changes in the monthly means of the climatic and hydrologic quantities from the present-day period to the near-future and far-future periods. The dashed lines represent the annual mean changes.

Appendix A: Model validation at three upstream station

The model performance was further evaluated by comparing the simulated monthly streamflow with the observed data from the Global Runoff Data Centre (GRDC) at three upstream gauging stations (Farakka, Pandu and Teesta) in the GBM basin. The locations and drainage areas of these three stations are summarized in Table 3. Although the available data period do not cover the study period 1980-2001 (except for the Teesta which has the data from 1985-1991), the mean seasonal cycle and the mean, maximum, minimum, and the standard deviation of the streamflow are compared in Figure A1 and Table A1. It can be seen that the mean seasonal cycle of simulated streamflow matches well with the corresponding GRDC data (Fig. A1d-f). Also the agreement of the simulated and observed 1985-1991 monthly streamflow at the Teesta station of the Brahmaputra basin is excellent (Fig. A1c).

Table A1. Comparison between observed (data source: GRDC) and simulated discharge ($m^3 s^{-1}$) at the Farakka gauging station in the Ganges basin, and Pandu and Teesta stations in the Brahmaputra basin.

Basin	Ganges		Brahmaputra		Brahmaputra	
Station	Farakka		Pandu		Teesta	
Data type	observed	simulated	observed	simulated	observed	simulated
Data period (with missing)	1949-1973	1980-2001	1975-1979	1980-2001	1969-1992	1980-2001
Mean	12 037	11 399	18 818	15 868	915	920
Maximum	65 072	69 715	49 210	46 381	3 622	4 219
Minimum	1 181	414	4 367	3 693	10	122
Standard deviation	14 762	15 518	12 073	11 709	902	948

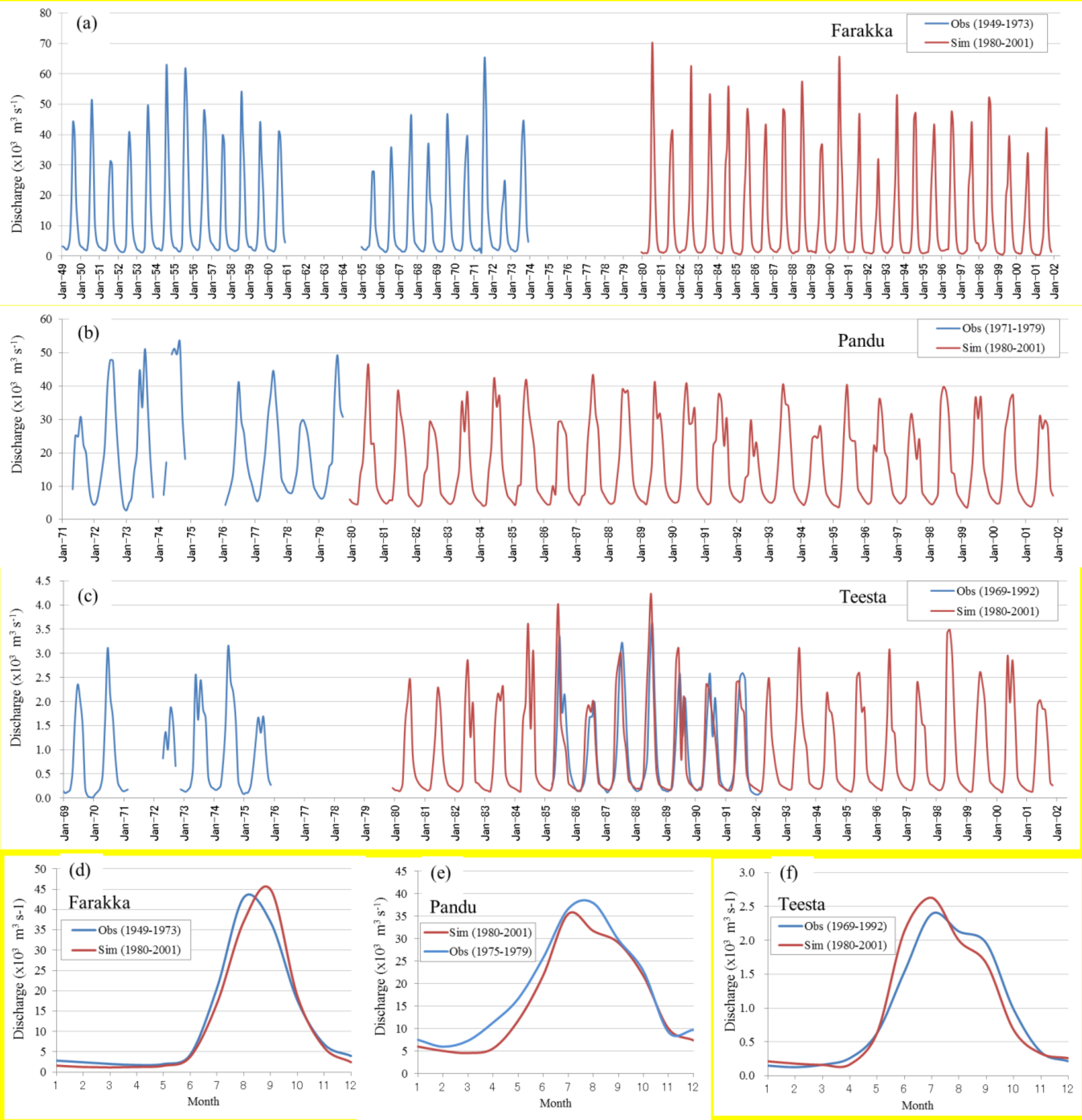

Figure A1. Comparisons between simulated (magenta line) and observed GRDC (blue line) data for (a-c) the monthly time series of discharges and (d-f) long-term mean seasonal cycles at the Farakka gauging station in the Ganges basin and the Pundu and Teesta stations in the Brahmaputra basin.

Appendix B:

Table B1: CMIP5 climate models used in the analysis

Model name	Modelling centre	Scenario	Nominal horizontal resolution
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	RCP 8.5	2.81 × 2.77°
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	RCP 8.5	1.41×1.39°
MRI-AGCM3.2S	Meteorological Research Institute (MRI), Japan and Japan Meteorological Agency (JMA), Japan	SRES A1B	0.25×0.25°
MRI-CGCM3	Meteorological Research Institute (MRI), Japan	RCP 8.5	1.125× 1.11°
HadGEM2-ES	Met Office Hadley Centre, UK	RCP 8.5	1.875× 1.25°