Author's Response to Comments by Referee #2

The authors thank the referee for providing useful and thought provoking comments on the manuscript.

C: Page 2206, lines 23-26: It is not clear how naturalized flows were obtained? Also provide a reference, if available.

AR: Naturalized flows for the upstream and midstream regions were obtained by adding the canal diversions to the observed streamflow. Description for this is presented in the manuscript (Pg. 2206, lines 23-26), "*Along with Q_{obs}, data corresponding to various diversion channels is also procured to convert the observed (regulated) flow to natural flow. The flow data thus obtained ($Q_{n\text{-}obs}$) is used for model calibration and validation."*

Conversion of observed flow to naturalized flow is demonstrated through an example presented in Table A1 (in this document) for the Ankinghat station (Fig. 1 in manuscript). Between Bhimgodha and Ankinghat stations, there are diversions such as Upper Ganga Canal (UGC), Madhya Ganga Canal (MGC) and Lower Ganga Canal (LGC) (Fig. 1 in manuscript) that divert the water from the main Ganga River. The data on diversions to these canals was procured from the Central Water Commission (CWC) and added to the flow observed at Ankinghat station thereby converting the observed streamflow to naturalized flow.

C: Page 2207, lines 6-10: My understanding is that the wind speed data for all the GCMs used in this study are not available, right? If so, then how did you obtain it for all the models?

AR: The zonal (u-wind) component of wind speed was available for all the GCMs considered in the study at the time of data procurement. Data was downloaded from the CORDEX web portal server located at http://cccr.tropmet.res.in:8080/. It is noticed that this server is not accessible for some time now. However, this data is still available for download from CCCR FTP server located at ftp://cccr.tropmet.res.in/. Data corresponding to various meteorological variables considered in the study for all the GCMs was downloaded during July 2014.

Page 2207, lines 18-21: Was the bias correction from Wood et al. (2002) applied on a daily basis? Provide details.

AR: Yes, the bias correction was applied on a daily basis. Since the hydrologic model was

executed at daily time step, bias correction of meteorological variables was carried out at daily scale before providing them as an input to the hydrologic model. To perform bias correction, the following steps are implemented:

(i) A distribution function is fit to the observed daily data and individual GCM data.

(ii) The CDF value, $F_{GCM}(x)$ of a GCM simulation is identified for a given x and the corresponding observed value x′ is obtained from the observed CDF, $F_{obs}(x')$, such that $F_{obs}(x') = F_{GCM}(x)$

(iii) The GCM value x is then replaced with the observed value x′ on the CDF of GCM.

Details pertaining to the bias correction will be added in the revised manuscript.

C: Pages 2207, lines 28 onwards: Did you compare the correlations between GCMs precipitation to the observed data? GCM simulations cannot produce observational sequence of events so the skill must be evaluated using climatology rather than the time series. Clarify.

AR: Yes, correlation between GCM precipitation and observed precipitation was obtained (pl. see the Taylor diagram, Fig.2 in the manuscript). The authors agree with the reviewer that GCMs do not exactly reproduce the observational sequence of events. However, since the analysis is presented at decadal scale, the need of presenting the climatology at monthly scale was not considered. Instead, correlation coefficient was considered as a measure to show agreement between the GCM simulations and the observed data. Additional analysis of climatology presented below will be added in the revised manuscript.

Figure A1 (in this document) shows the climatology for different GCMs along with the observed climatology for monthly precipitation from 1971-2005 for one of the grid cells within the UGB. The observed and GCM climatology at monthly scale for time period 1971-2005 is represented following Wood et al. (2002). It can be observed from Fig. A1 that the GCMs successfully reproduce the mean and variance of the rainfall climatology for most of the months. However, for post-monsoon period (i.e. October, November and December) the GCMs overestimate the rainfall compared to the observed rainfall. Similar analysis was carried out on maximum and minimum temperature (Fig. A2 and A3 respectively). It was observed that GCMs could successfully reproduce the observed climatology for maximum and minimum temperature across

all the months. Other grids within the UGB demonstrated similar patterns for both rainfall and temperature.

C: Page 2208, lines 24-27: It is incorrect to say that only B, Ws and Ds are the only unknown parameters in this study. How about the soil depths as they can vary in different topographical conditions?

AR: The authors agree with the reviewer that apart from B, Ds and Ws, soil depth has also been considered as calibration parameter in various earlier studies. However, for the present study, soil depths (upto three layers) were obtained along with the digitized soil map from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) for the study region. Therefore, soil depths are not considered as a calibration parameter and only B, Ds and Ws are considered for calibration.

C: Page 2214, lines 12-15: Is scenario based uncertainty minimum over all the time periods? Explain.

AR: Scenario based uncertainty is observed to be minimum for all the variables as the complete time series from 2010-2100 is considered to address this aspect. Scenario based uncertainty is determined by following the approach of Maurer and Duffy (2005) and Maurer (2007). In this approach, a t-test is performed to test equality of means between the ensemble time series of a hydrologic variable corresponding to RCP 4.5 and RCP 8.5 scenarios. Hypothesis testing is done against the null hypothesis that the means obtained for the two scenarios are not different. In the present study, ensemble time series for RCP 4.5 and RCP 8.5 scenarios is considered at annual scale for the entire time period (2010-2100) to check for the equality of means.

For rainfall and T_{min}, it is observed that the means are not significantly different for the two scenarios across all the three regions, which indicate that the scenario based uncertainty is less in the case of these variables. For T_{max} across the entire time series, upstream and downstream regions did not show statistically significant change in the means for RCP 4.5 and RCP 8.5 scenarios indicating that scenario based uncertainty is less for these two regions. However, in the midstream region, statistically significant difference in the means of RCP 4.5 and RCP 8.5 scenarios is observed, indicating the presence of large scenario based uncertainty in T_{max} for this region. For the ensemble streamflow series obtained for RCP 4.5 and RCP 8.5 scenarios, moderate change in the means of two scenarios is noted for the midstream region indicating presence of scenario based uncertainty in the streamflow for this region. This is briefly

mentioned in the manuscript (Pg. 2214, lines 12-15; Pg. 2218 lines 1-4).

C: Page 2220, lines 12-15: The combined response of LU and climate conditions (Qint) may be non-linear. Therefore, Qint – Qclim may not yield contribution of LU alone. Explain. Also state the assumptions made.

AR: The authors thank the reviewer for this comment. The authors agree with the reviewer that the combined response of LU and climate on streamflow may be non-linear. However in the present study, a linear response is assumed. This assumption renders the analysis more general and applicable to other basins. It is to be noted that the only difference in the VIC model simulations between the scenarios Q_{int} and Q_{clim} is that the LU is held constant in case of Q_{clim} whereas both land use and climate are changing with time in the case of Q_{int}. All other parameters are kept same in the two simulations. Hence it can be expected that the difference in the output of the two simulations is due to the contribution of LU alone.

Consideration of non-linearity in response may involve developing empirical relationships between LU, climate and streamflow that may make the approach case-specific. This discussion will now be added in the revised manuscript.

C: Both Introduction and Conclusion sections can be improved.

AR: As suggested by the reviewer, introduction and conclusion sections will be improved in the revised manuscript.

C: The limitations of this study needs to be discussed.

AR: The following limitations of the present study will be mentioned in the revised manuscript:

1. The methodology is applied considering the observed (historical) changes in LU. There is a need to look into the future projections of LU and its subsequent impact on the streamflow.

2. Meteorological variables from only 6 GCMs are used. There is a need to consider more GCMs to address the issue of model based uncertainty more comprehensively

3. There is a need to look into the scenario based uncertainty for different time slices in future.

4. Linearity is assumed to segregate the response of LU and climate from streamflow.

C: The VIC model uses corn as a reference crop. But the crop parameters for the crops grown in the UGB will be different than the vegetation parameters of corn. How does that

affect your results?

AR: In the present study, vegetation parameters corresponding to corn are not considered. For UGB, it is observed from the agricultural statistics (http://mospi.nic.in/Mospi_New/site/India_Statistics.aspx) that major crops grown are wheat during the rabi season (October-March) and rice and millets during the kharif season (July-October). Furthermore, in the upstream part of the UGB, sugarcane is also grown which is planted mostly during the month of March and harvested during October. Therefore vegetation parameters based on these four crops are given as input in relevant grid cells. For example, let's say in a grid, rice is grown during kharif season and wheat is grown during rabi season. Rice can grow upto a height of 1m while wheat may grow upto 1.5m. Therefore the vegetation parameters such as roughness (0.123*vegetation height) and displacement (0.67*vegetation height) are obtained using the above mentioned information. Pl. see the table below for reference.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Roughness	0.123	0.154	0.185	0.012	0.012	0.012	0.031	0.062	0.123	0.031	0.062	0.092
Displacement	0.67	0.838	1.005	0.067	0.067	0.067	0.168	0.335	0.67	0.168	0.335	0.503

This discussion will be presented in the revised manuscript.

C: It should be mentioned in the text that the crops grown in the UGB are rainfed, right?

AR: UGB contains both rain fed as well as irrigated crops. In the present work, the need to separate rain fed crops from irrigated crops is not considered as the overall objective of the paper is to understand and isolate the impact of LU and climate on streamflow irrespective of the crop category.

Table A1 Conversion of observed flow at Ankinghat station to naturalized flow for the year 1977

	Observed streamflow (cumecs)	Diversions to UGC* (cumecs)	Diversions to MGC* (cumecs)	Diversions to LGC* (cumecs)	Naturalized flow (cumecs)
January	198.363	178.679	-	145.945	522.987
February	192.634	154.015	-	150.249	496.899
March	352.040	141.018	-	122.867	615.925
April	178.663	237.295	-	67.875	483.834
May	186.468	227.866	-	51.593	465.927
June	46.420	267.169	76.455	151.070	541.115
July	2907.691	181.001	141.584	190.544	3420.821
August	3638.817	144.246	155.743	189.978	4128.783
September	3046.827	178.623	113.267	194.339	3533.056
October	1010.063	214.613	-	237.777	1462.453
November	327.557	225.714	-	162.142	715.413
December	225.741	224.241	-	188.902	638.884

* UGC: Upper Ganga Canal; MGC: Madhya Ganga Canal; LGC: Lower Ganga Canal

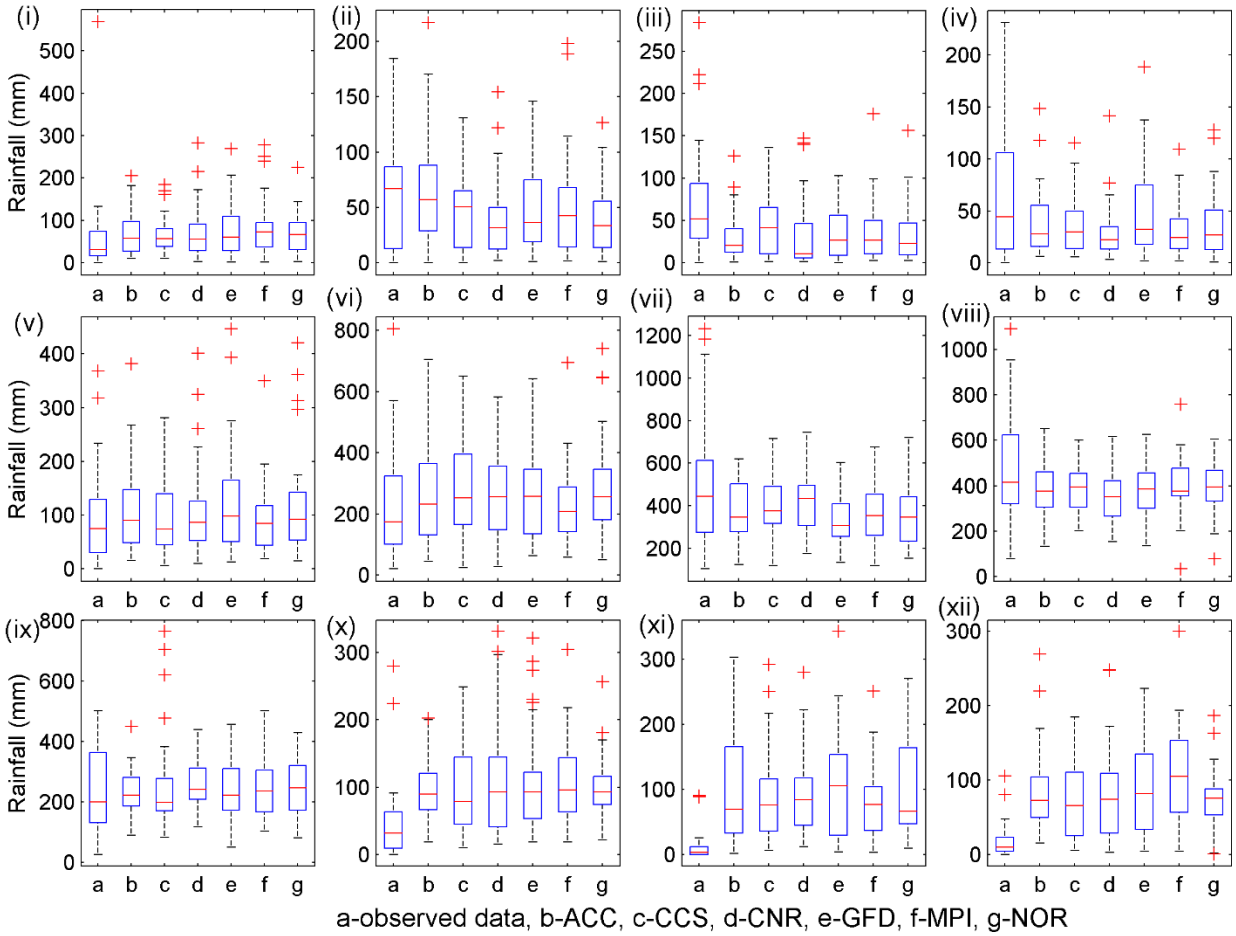

Figure A1. GCMs climatology compared with observed climatology for monthly precipitation from 1971-2005 (represented from January-December as i-xii)

* ACC; CCS; CNR; GFD; MPI and NOR are abbreviations for various climate models considered in the study. Full forms can be obtained from the manuscript (Table 1).

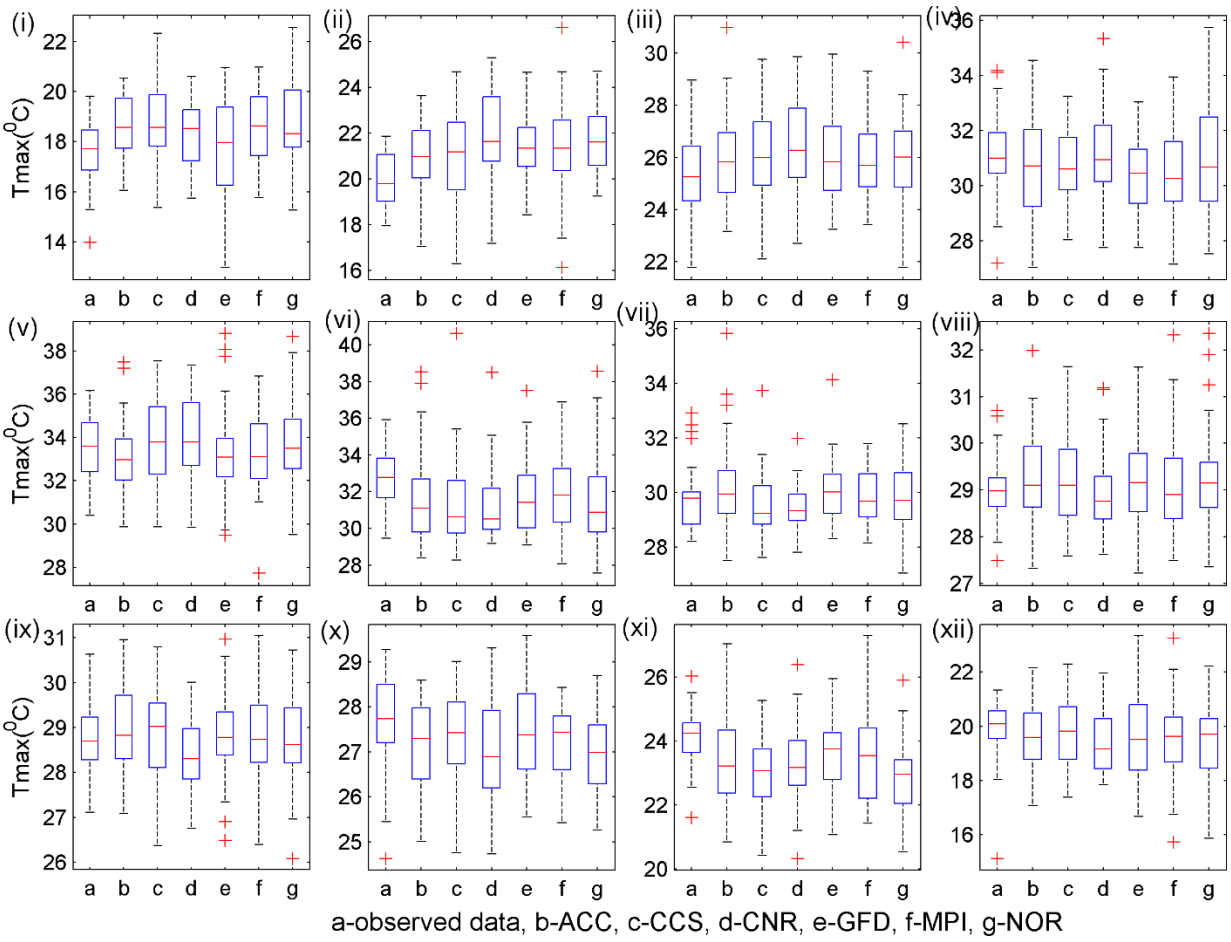

Figure A2. GCMs climatology compared with observed climatology for monthly maximum temperature from 1971-2005 (represented from January-December as i-xii)

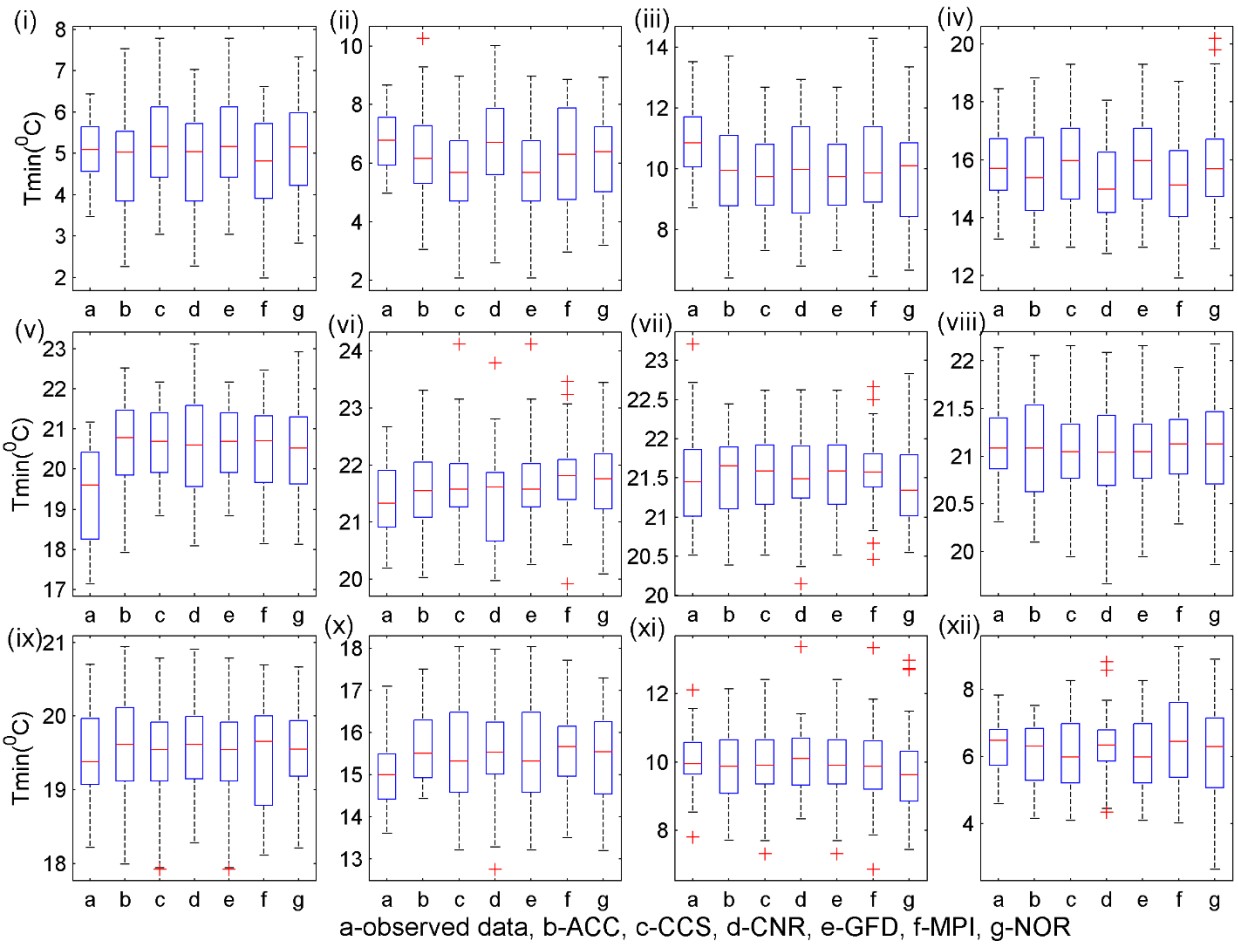

Figure A3. GCMs climatology compared with observed climatology for monthly minimum temperature from 1971-2005 (represented from January-December as i-xii)