Supplement of Hydrol. Earth Syst. Sci., 26, 5737–5756, 2022
https://doi.org/10.5194/hess-26-5737-2022-supplement

Hydrology and Earth System Sciences
Open Access

Supplement of

Risks of seasonal extreme rainfall events in Bangladesh under 1.5 and 2.0 °C warmer worlds – how anthropogenic aerosols change the story

Ruksana H. Rimi et al.

Correspondence to: Ruksana H. Rimi (rimi_esc@yahoo.com) and Karsten Haustein (karsten.haustein@uni-leipzig.de)

Table S1: Basic information about the two observation data sets

Product Name	Product version	Spatial Resolution	Time Scale	Source/reference
APHRODITE	Monsoon Asia (MA) V1901	0.5°X 0.5°	1998-2015	Yatagai et al., 2012. Available at: http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-11-00122.1
CPC	CPC daily rainfall	0.5°X 0.5°	1979-2016	Chen, M. and Xie, P. 2008. Available at: ftp://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_CONUS/DOCU/Chen_et_al_2008_Daily_Gauge_Anal.pdf

Table S2: As per actual climate model ensemble during 2006-2015 - the wettest and driest two years over the four sub-regions.

	pre-monsoon season (MAM)		monsoon season (JJAS)	
Sub-regions	Wettest years	Driest years	Wettest years	Driest years
Sub-region 1 (north-west region)	2008, 2011	2009, 2014	2008, 2009	2013, 2014
Sub-region 2 (north-east region)	2008, 2015	2009, 2014	2008, 2012	2006, 2013
Sub-region 3 (south-west region)	2008, 2012	2009, 2014	2008, 2014	2011, 2013
Sub-region 4 (south-east region)	2008, 2015	2009, 2013	2008, 2014	2011, 2013

Table S3: Basic information about the four HAPPI AGCMs used in this study (adapted from Chevuturi et al., 2018)

Model Name	Organization	Spatial Resolution	Available Ensemble Members	Reference
Community Atmosphere Model 4-2 (ETH_CAM4)	ETH, Federal Institute of Technology; Zurich, Switzerland.	2° × 2° (96 ×144)	501	Neale et al., (2013)
Canadian Fourth generation atmospheric global climate model (CanAM4)	Canadian Centre for Climate Modeling and Analysis; Victoria, Canada.	T42 (64 ×128)	100	von Salzen et al., (2013)
Model for interdisciplinary research on climate 5 (MIROC5)	Atmosphere and Ocean Research Institute (AORId), University of Tokyo; Chiba, Japan. National Institute for Environmental Studies (NIES); Ibaraki, Japan. Japan Agency for Marine-Earth Science and Technology (JAMSTEC); Kanagawa, Japan.	150 × 150 km (128× 256)	100	Watanabe et al., (2010) Shiogama et al., (2014)
Norwegian earth system model 1 (NorESM1)	NorESM Climate modeling Consortium (NCC), Norway.	1.25×0.94∘ (192× 288)	125	Bentsen et al., (2013); Iversen et al. (2013); Kirkevåg et al. (2013)

Table S4: The risk ratios with associated uncertainty ranges (in brackets) for four MAM rainfall events.

Return periods	Sub-region 1 (north-west region) – pre-monsoon season			
	ACT/NAT	HAPPI1.5/NAT	HAPPI2.0/NAT	GHG/ACT
10 years	1.1	1.5	1.8	1.4
	(0.9-1.2)	(1.2-1.6)	(1.5-2.0)	(1.2-1.6)
20 years	1.2	2.1	2.5	1.9
	(0.9-1.5)	(1.6-2.8)	(1.9-3.4)	(1.6-2.2)
50 years	1.1	2.5	3.1	2.5
	(0.7-1.5)	(1.8-3.8)	(2.0-4.5)	(1.9-3.8)
100 years	1.1	**4**	**3.9**	**3.3**
	(0.6-2.1)	**(2.0-7.0)**	**(2.1-6.8)**	**(1.9-5.9)**
Return periods	**Sub-region 2 (north-east region) – pre-monsoon season**			
	ACT/NAT	ACT/NAT	ACT/NAT	ACT/NAT
10 years	1.6	1.9	2.5	1.1
	(1.3-1.9)	(1.5-2.3)	(2.0-2.9)	(1.0-1.2)
20 years	1.5	2.1	3	1.4
	(1.2-2.0)	(1.6-2.8)	(2.2-3.9)	(1.0-1.9)
50 years	1.7	2.4	2.8	1.2
	(1.1-2.2)	(1.7-3.4)	(1.9-4.0)	(0.9-1.9)
100 years	1.9	**3.2**	**2.9**	1.9
	(1.1-3.1)	**(2.0-5.3)**	**(1.9-4.5)**	(1.0-3.2)
Return periods	**Sub-region 3 (south-west region) – pre-monsoon season**			
	ACT/NAT	HAPPI1.5/NAT	HAPPI2.0/NAT	GHG/ACT
10 years	1	1.1	1.4	1.1
	(0.9-1.1)	(1.0-1.3)	(1.2-1.6)	(1.0-1.3)
20 years	1.1	1.3	1.6	1.2
	(0.9-1.2)	(1.1-1.8)	(1.3-2.1)	(0.9-1.4)
50 years	1.2	1.5	2.5	1.5
	(0.9-1.8)	(1.2-2.1)	(1.9-3.8)	(1.0-2.0)
100 years	1.5	2	**3.1**	1.5
	(0.9-2.8)	(1.0-3.0)	**(1.9-5.2)**	(0.9-2.4)
Return periods	**Sub-region 4 (south-east region) – pre-monsoon season**			
	ACT/NAT	HAPPI1.5/NAT	HAPPI2.0/NAT	GHG/ACT
10 years	1.1	1.4	1.5	1.3
	(1.0-1.3)	(1.2-1.5)	(1.3-1.6)	(1.0-1.5)
20 years	1.3	1.9	1.7	1.4
	(1.0-1.6)	(1.3-2.3)	(1.2-2.1)	(1.0-1.6)
50 years	2.1	2.2	2.2	1.6
	(1.4-3.0)	(1.5-3.2)	(1.6-3.2)	(1.0-2.2)
100 years	1.7	**2.5**	2.1	1.7
	(0.9-2.9)	**(1.6-4.0)**	(1.2-3.3)	(0.9-2.3)

Table S4.1: The risk ratios with associated uncertainty ranges (in brackets) for four JJAS rainfall events.

Return periods	**Sub-region 1 (north-west region) – monsoon season**			
	ACT/NAT	HAPPI1.5/NAT	HAPPI2.0/NAT	GHG/ACT
10 years	1.7	2.5	2.3	1.3
	(1.5-2.0)	(2.1-2.9)	(2.0-2.6)	(1.0-1.5)
20 years	2.3	**3.7**	**3.2**	1.5
	(1.9-2.9)	**(2.9-4.5)**	**(2.5-4.0)**	(1.1-1.9)
50 years	2.1	**3.8**	**3.3**	1.5
	(1.5-2.9)	**(2.8-4.9)**	**(2.6-4.6)**	(1.1-2.1)
100 years	1.6	**4**	**3.8**	2
	(1.0-2.5)	**(2.5-6.3)**	**(2.3-6.0)**	(1.2-3.7)
Return periods	**Sub-region 2 (north-east region) – monsoon season**			
	ACT/NAT	ACT/NAT	ACT/NAT	ACT/NAT
10 years	1.8	1.8	1.8	1.8
	(1.5-2.1)	(1.5-2.1)	(1.5-2.1)	(1.5-2.1)
20 years	1.5	1.5	1.5	1.5
	(1.1-1.9)	(1.1-1.9)	(1.1-1.9)	(1.1-1.9)
50 years	1.3	1.3	1.3	1.3
	(0.9-1.9)	(0.9-1.9)	(0.9-1.9)	(0.9-1.9)
100 years	1.8	1.8	1.8	1.8
	(1.0-3.0)	(1.0-3.0)	(1.0-3.0)	(1.0-3.0)
Return periods	**Sub-region 3 (south-west region) – monsoon season**			
	ACT/NAT	HAPPI1.5/NAT	HAPPI2.0/NAT	GHG/ACT
10 years	1.6	1.5	2	1
	(1.4-1.9)	(1.3-1.7)	(1.7-2.2)	(0.8-1.2)
20 years	2	1.9	2.5	1.1
	(1.8-2.2)	(1.4-2.3)	(2.0-3.0)	(0.8-1.8)
50 years	2.1	1.9	2.1	1.2
	(1.7-2.5)	(1.2-2.6)	(1.5-2.8)	(0.7-1.9)
100 years	2.2	2.3	2.2	1.3
	(1.6-3.1)	(1.3-3.6)	(1.3-3.8)	(0.5-2.2)
Return periods	**Sub-region 4 (south-east region) – monsoon season**			
	ACT/NAT	HAPPI1.5/NAT	HAPPI2.0/NAT	GHG/ACT
10 years	1.9	2.1	2.3	1
	(1.6-2.1)	(1.9-2.5)	(2.0-2.8)	(0.9-1.2)
20 years	2	2.3	**2.9**	1.1
	(1.5-2.5)	(1.8-2.8)	**(2.2-3.8)**	(0.9-1.5)
50 years	2.5	2.6	**3.9**	0.9
	(1.9-3.5)	(1.9-3.7)	**(2.9-5.5)**	(0.5-1.2)
100 years	**3.9**	**4.1**	**5.5**	0.9
	(2.6-5.8)	**(2.2-5.3)**	**(3.5-7.8)**	(0.3-1.8)

Supplementary Figures:

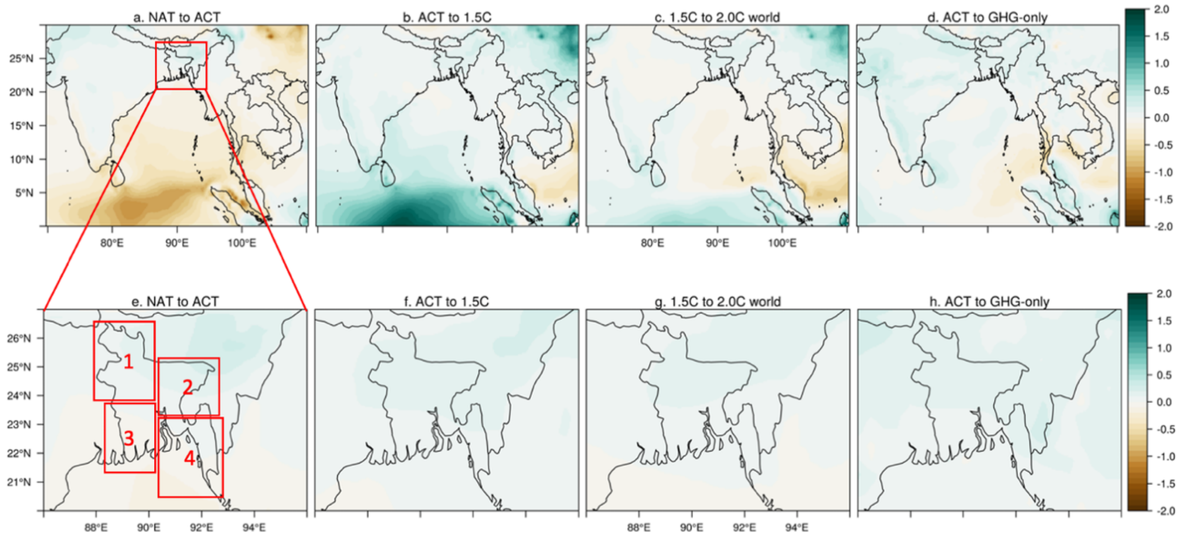

Figure S1: Relative change in standardized precipitation index (SPI) of MAM mean rainfall between different forcing scenarios. The top row (panels a-d) shows the regional SPI changes over central parts of the South Asia (SA) while, bottom row (panels e-h) shows the SPI changes over Bangladesh. The four boxes (1-4) on top of the panel e represent the four sub-regions of Bangladesh. a. ACT rainfall SPI relative to NAT over SA b. ACT rainfall SPI relative to HAPPI 1.5 over SA c. HAPPI 1.5 rainfall SPI relative to HAPPI 2.0 over SA d. ACT rainfall SPI relative to GHG-only over SA.

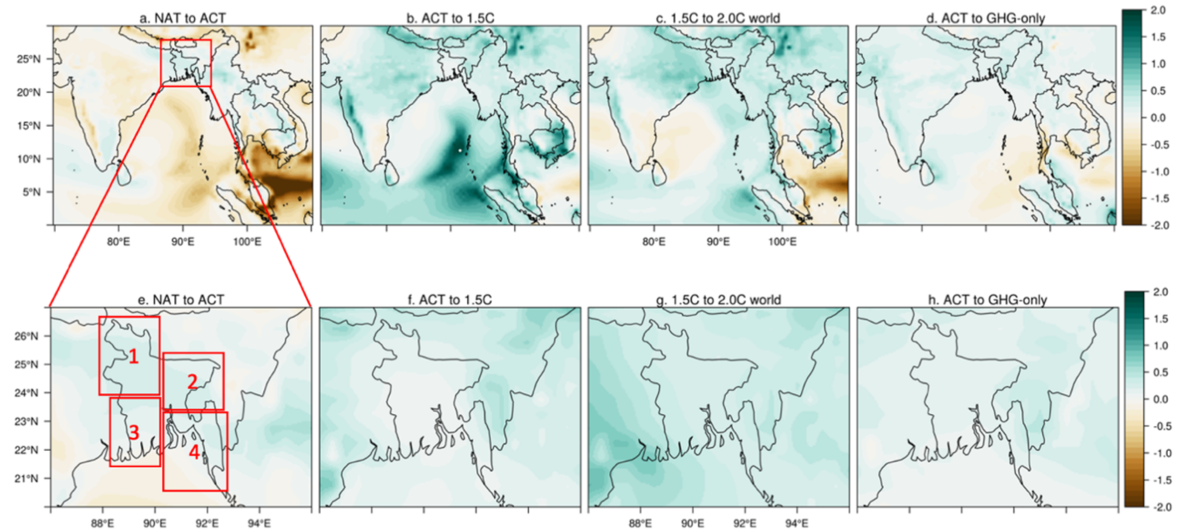

Figure S2: Same as Fig. S1, but for SPI changes in JJAS mean rainfall. This figure shows that the apparently non-linear response between panels of a, b, and c (or, e, f, g) can be explained by the response for aerosols in the panel d (or, h).

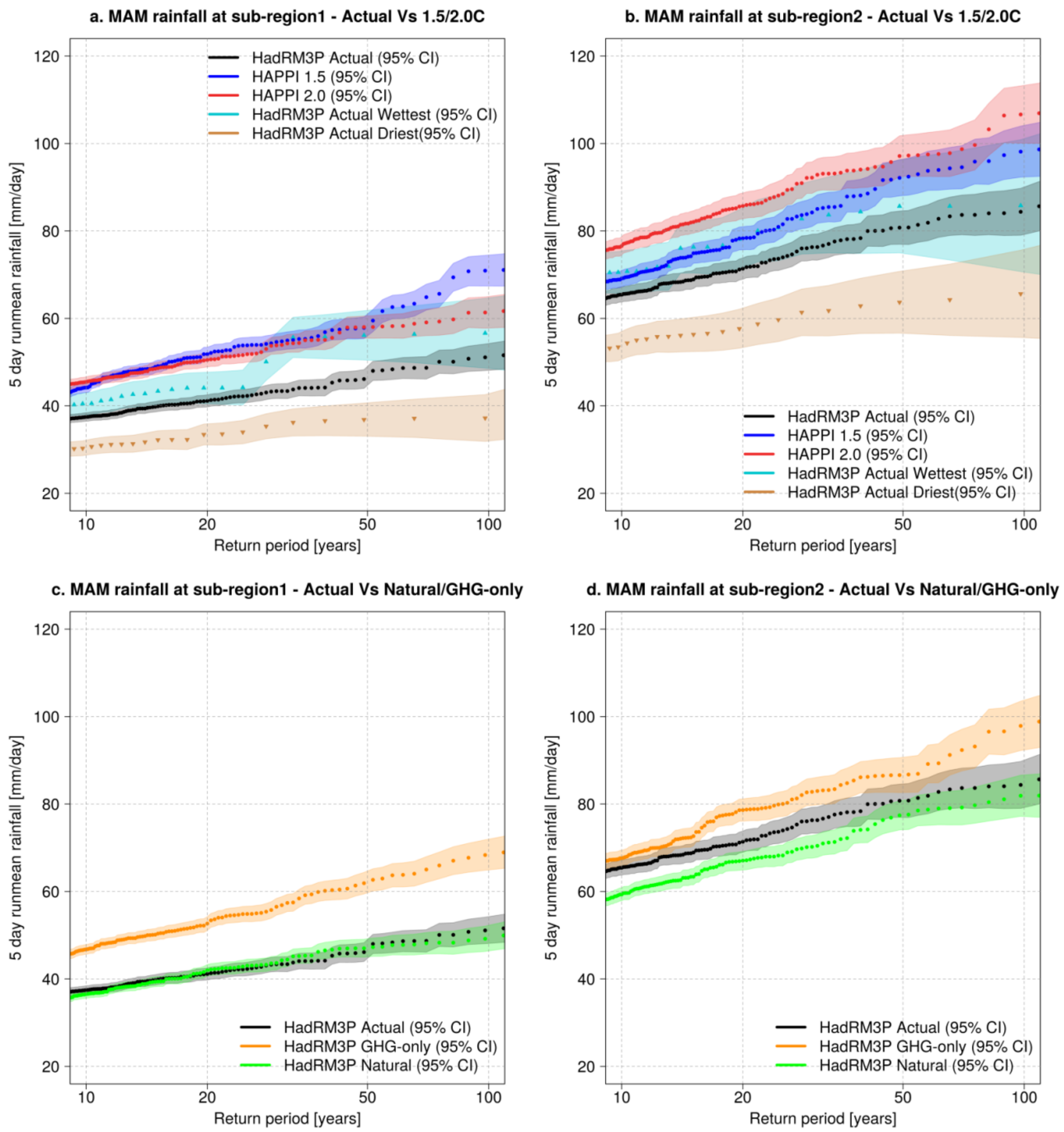

Figure S3: Return time plots for MAM five day mean rainfall under different forcing scenarios over the sub-regions 1 and 2 of Bangladesh. The ACT (black), ACT highest (sky-blue), ACT lowest (grey), NAT (green) and GHG-only (orange) ensembles are compared with the HAPPI 1.5 (blue) and HAPPI 2.0 (red) ensembles.

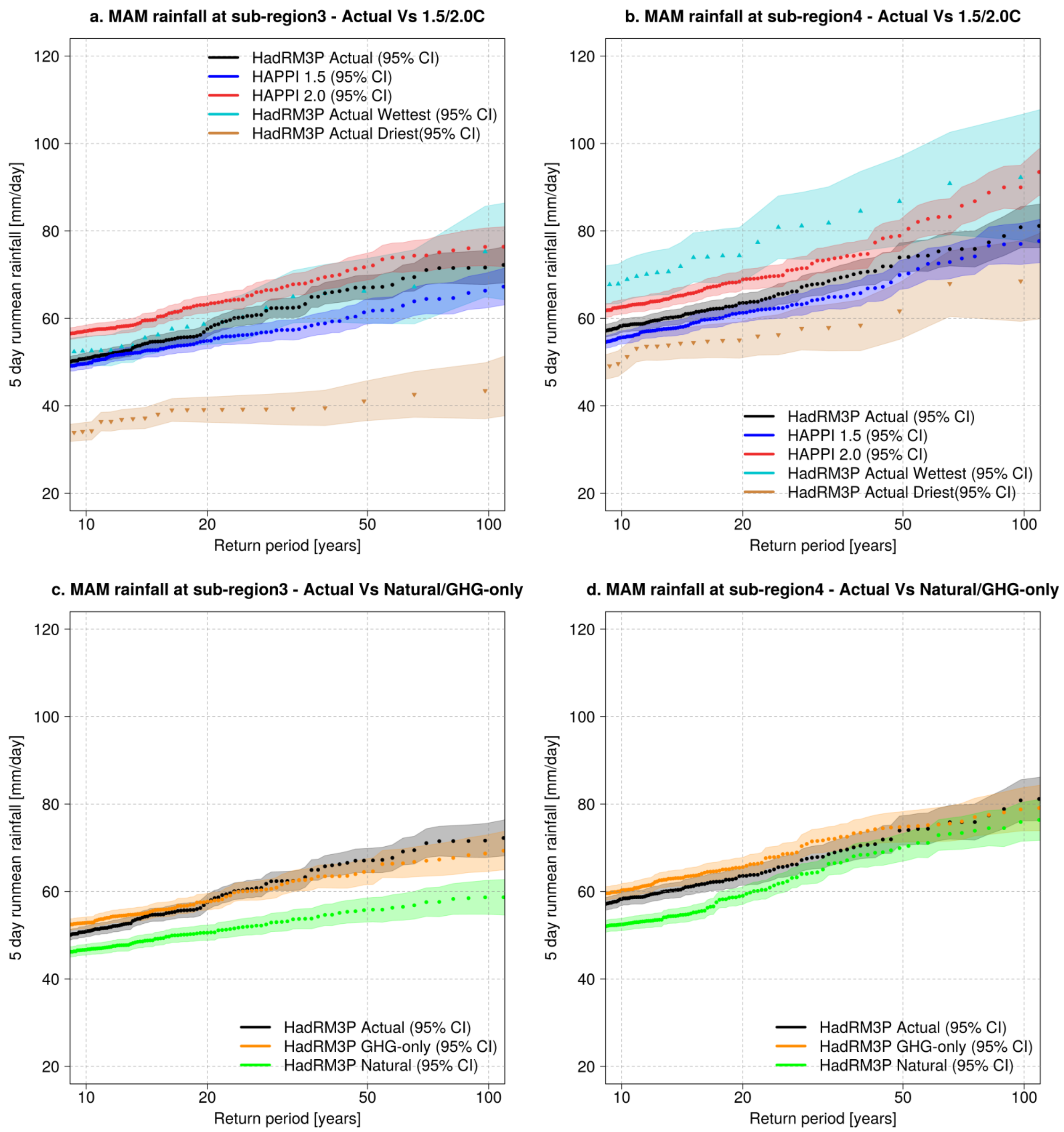

Figure S4: Same as Fig. S3, but for return time plots for MAM five day mean rainfall under different forcing scenarios over the sub-regions 3 and 4 of Bangladesh.

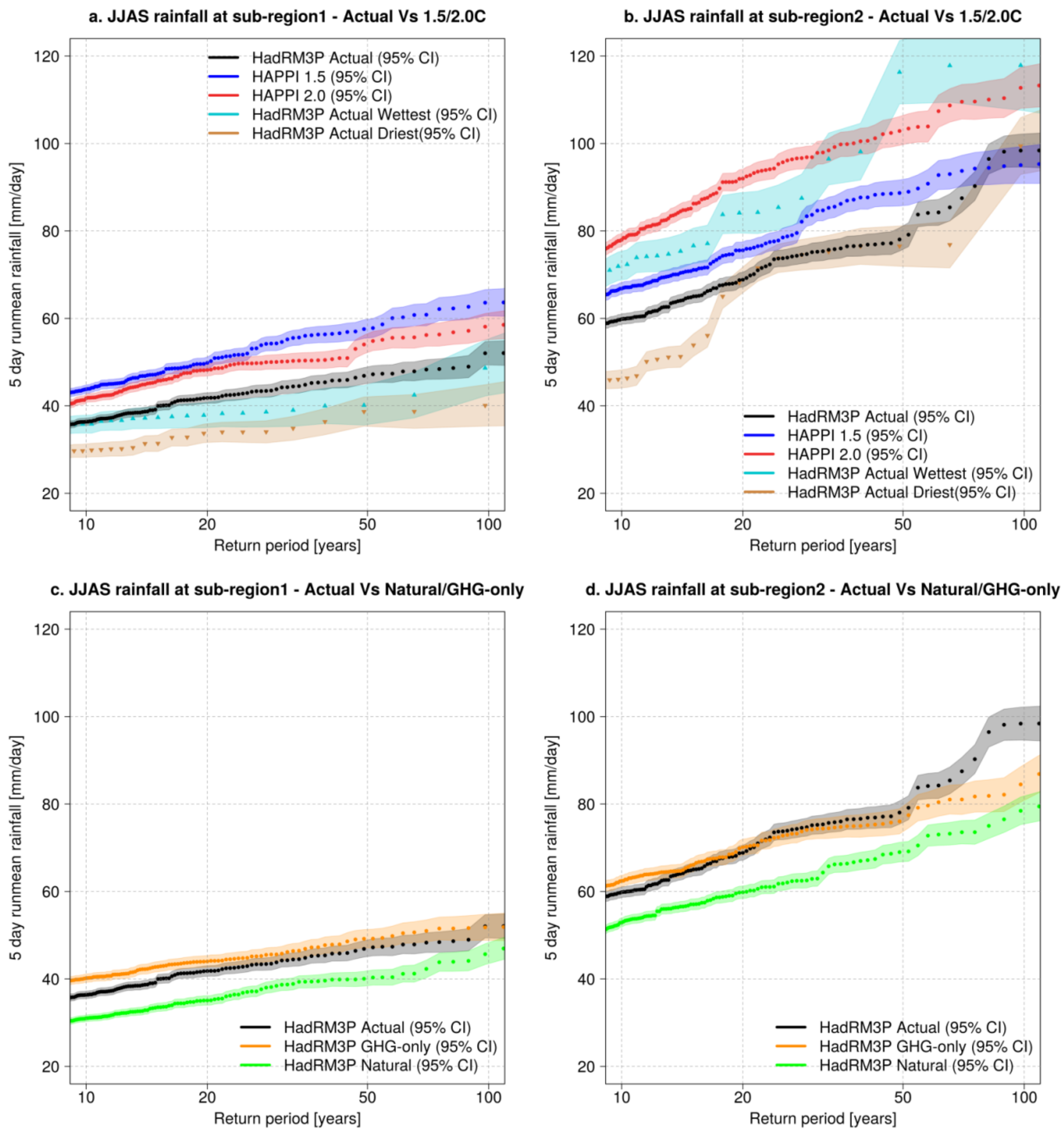

Figure S5: Return time plots for JJAS five day mean rainfall different forcing scenarios over the sub-regions 1 and 2 of Bangladesh. The ACT (black), ACT highest (sky-blue), ACT lowest (grey), NAT (green) and GHG-only (orange) ensembles are compared with the HAPPI 1.5 (blue) and HAPPI 2.0 (red) ensembles. The risks of extreme rainfall events are evidently increasing between different forcing scenarios over sub-region 2.

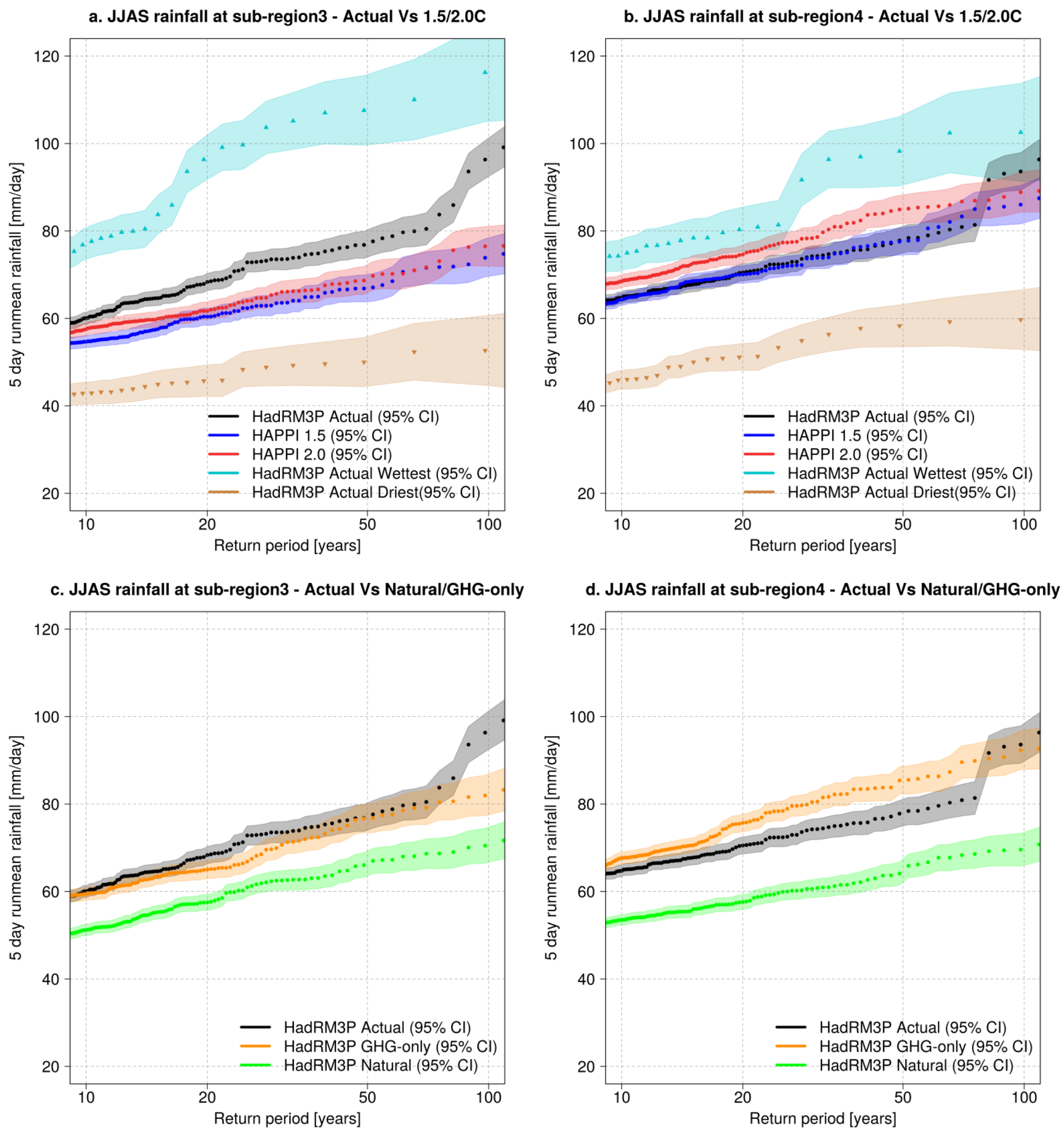

Figure S6: Same as Fig. S5, but for return time plots for JJAS five day mean rainfall under different forcing scenarios over the sub-regions 3 and 4 of Bangladesh.

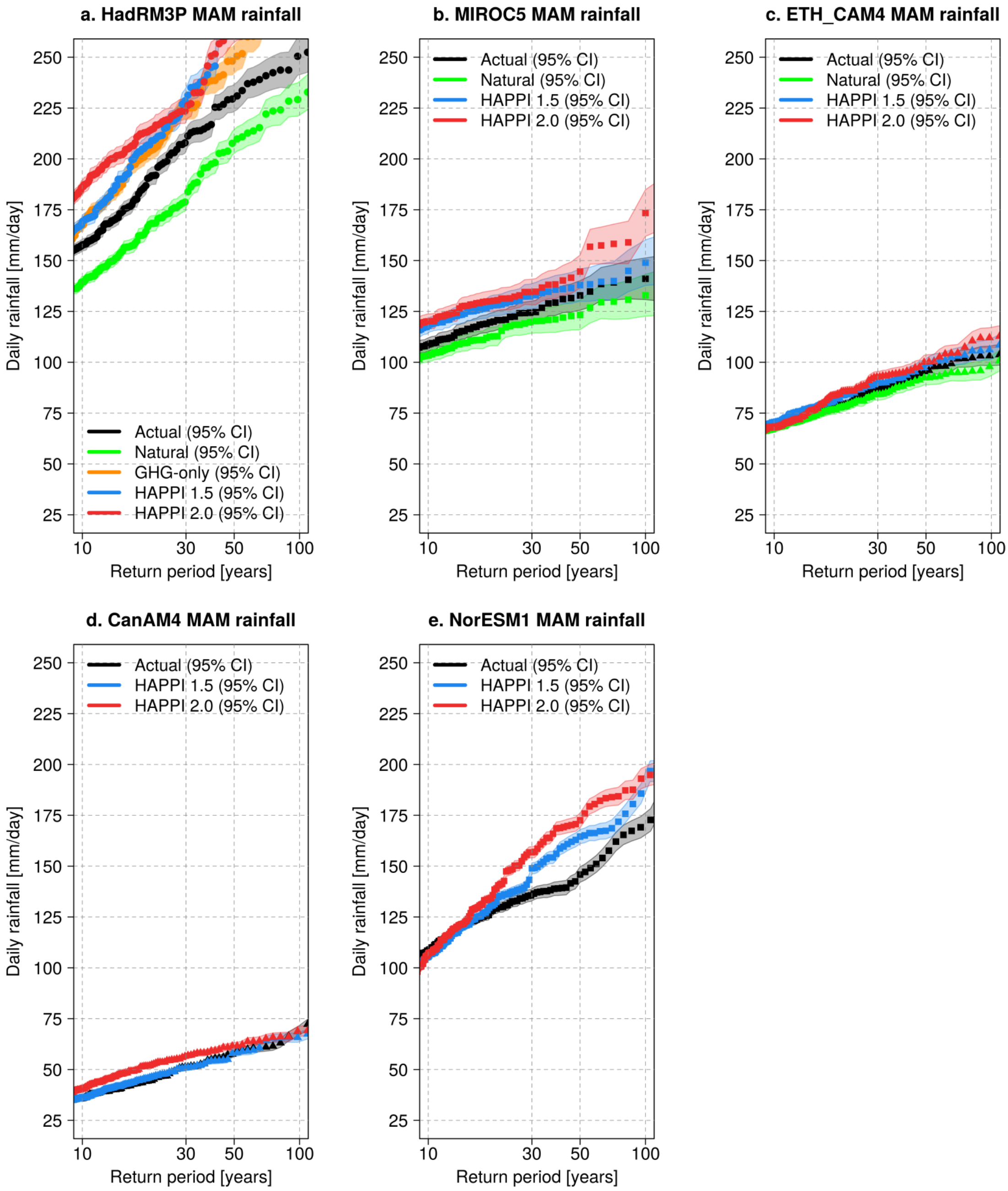

Figure S7: Comparative return periods (10–100 year events) of MAM daily rainfall (mm/day) over sub-region 2 during 1986-2015 as per (a) HadRM3P, (b) MIROC5, (c) ETH_CAM4, (d) CanAM4 and (e) NorESM1 models. ACT, NAT, GHG-only, plus HAPPI 1.5 and HAPPI 2.0 model ensembles are shown in black, green, orange, blue and red colours respectively.

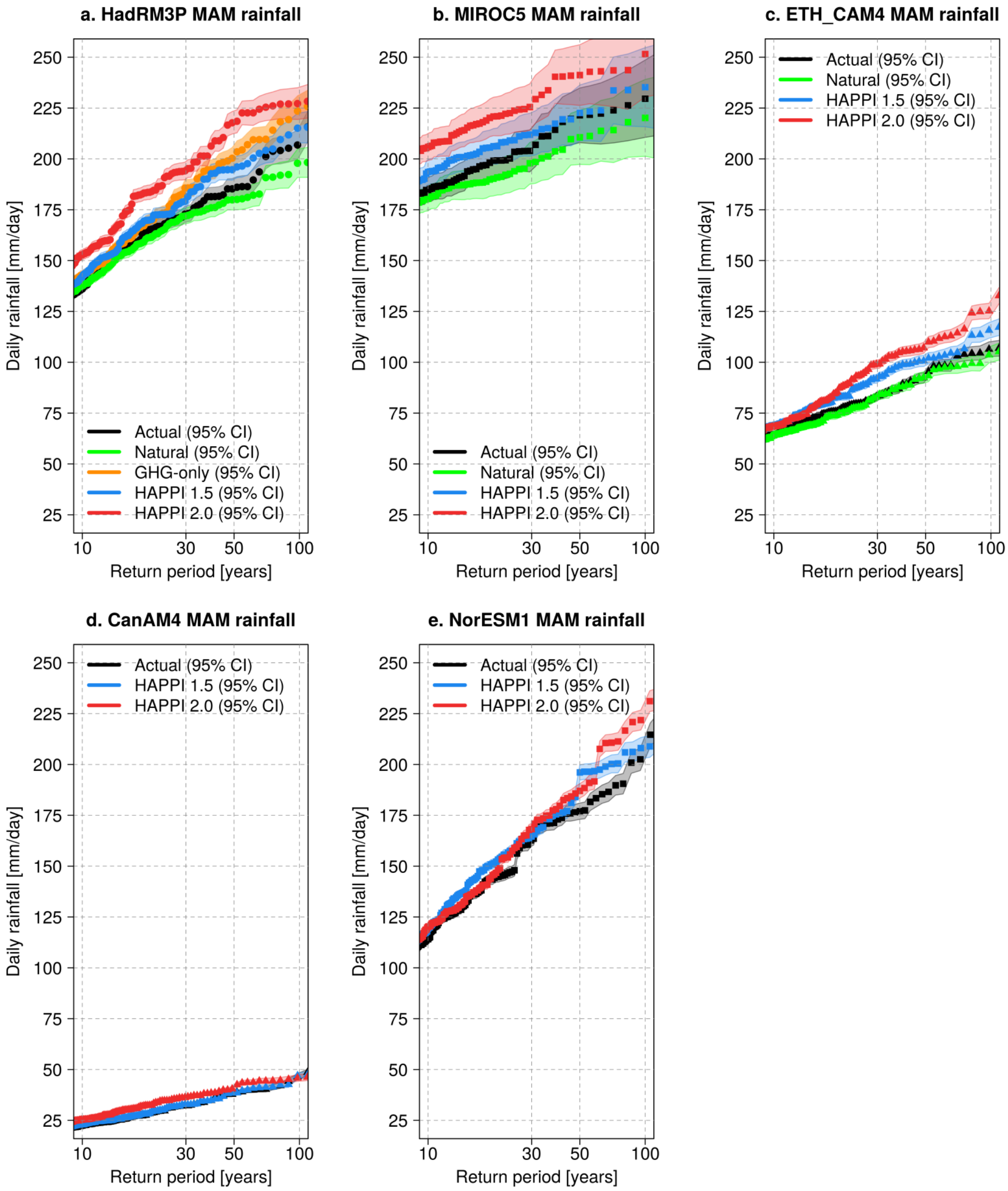

Figure S8: Same as Figure S7 but for sub-region 3.

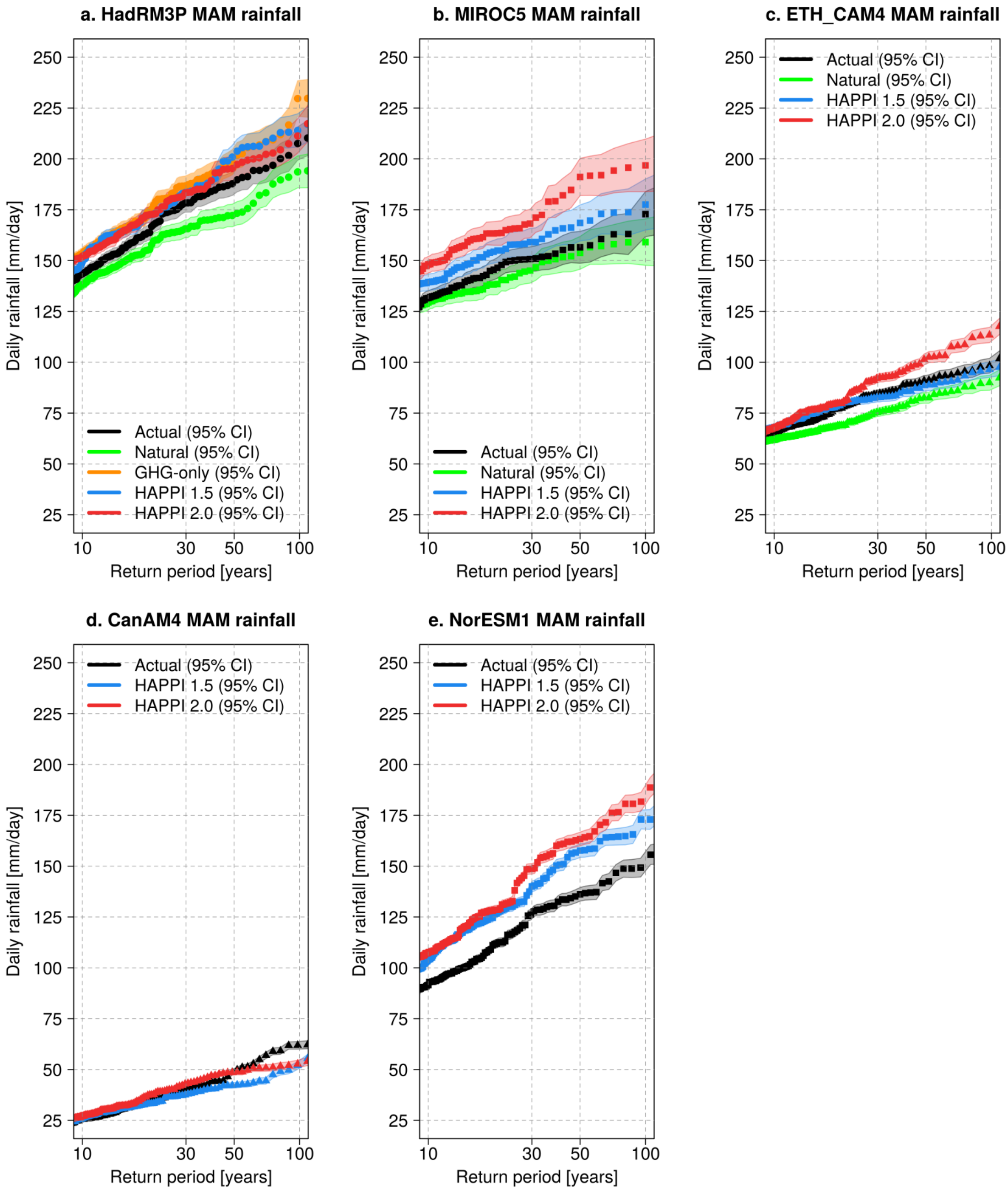

Figure S9: Same as Figure S7 but for sub-region 4.

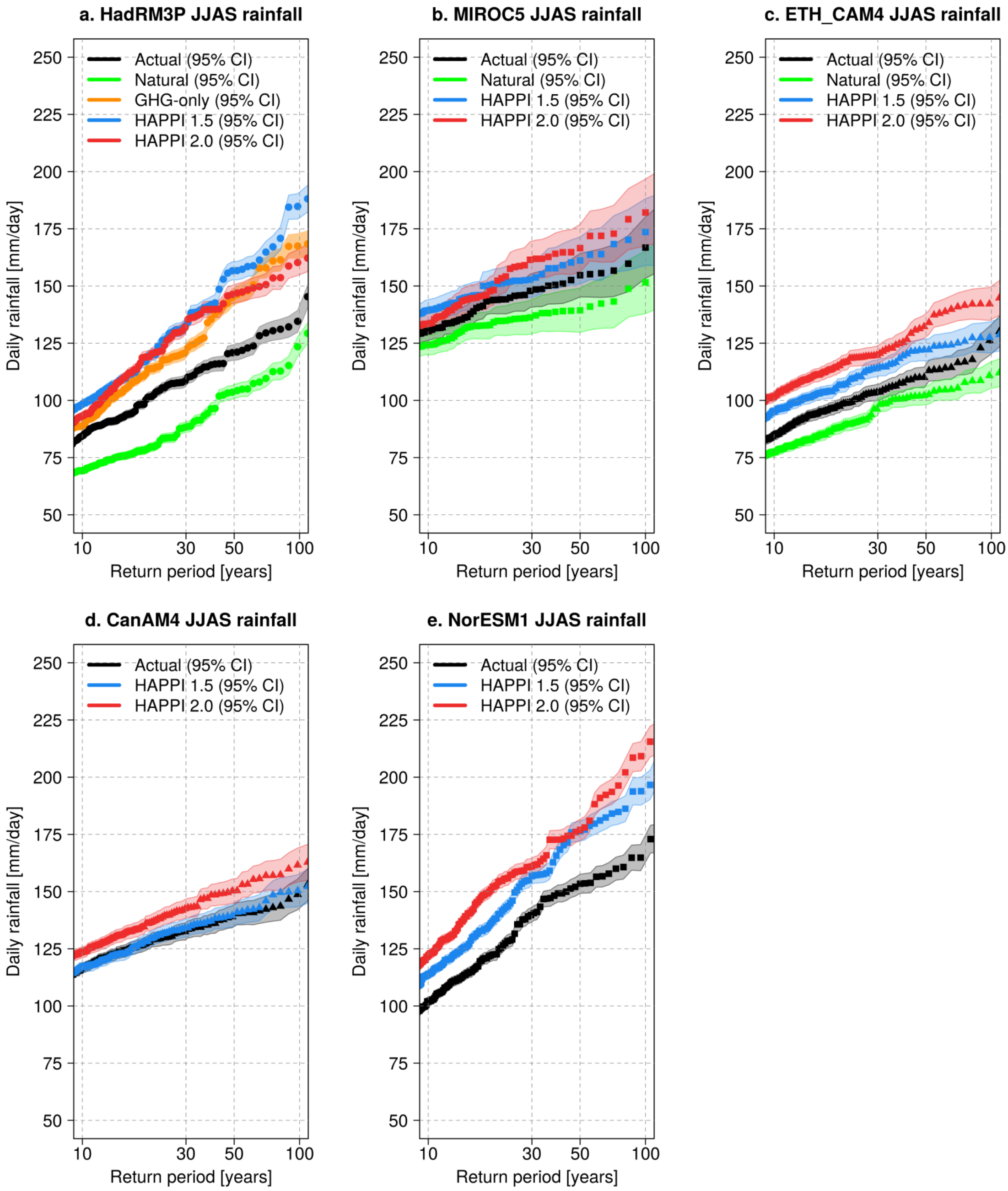

Figure S10: Comparative return periods (10-100 year events) of JJAS daily rainfall (mm/day) over sub-region 1 during 1986-2015 as per (a) HadRM3P, (b) MIROC5, (c) ETH_CAM4, (d) CanAM4 and (e) NorESM1 models. ACT, NAT, GHG-only, plus HAPPI 1.5 and HAPPI 2.0 model ensembles are shown in black, green, orange, blue and red colours respectively.

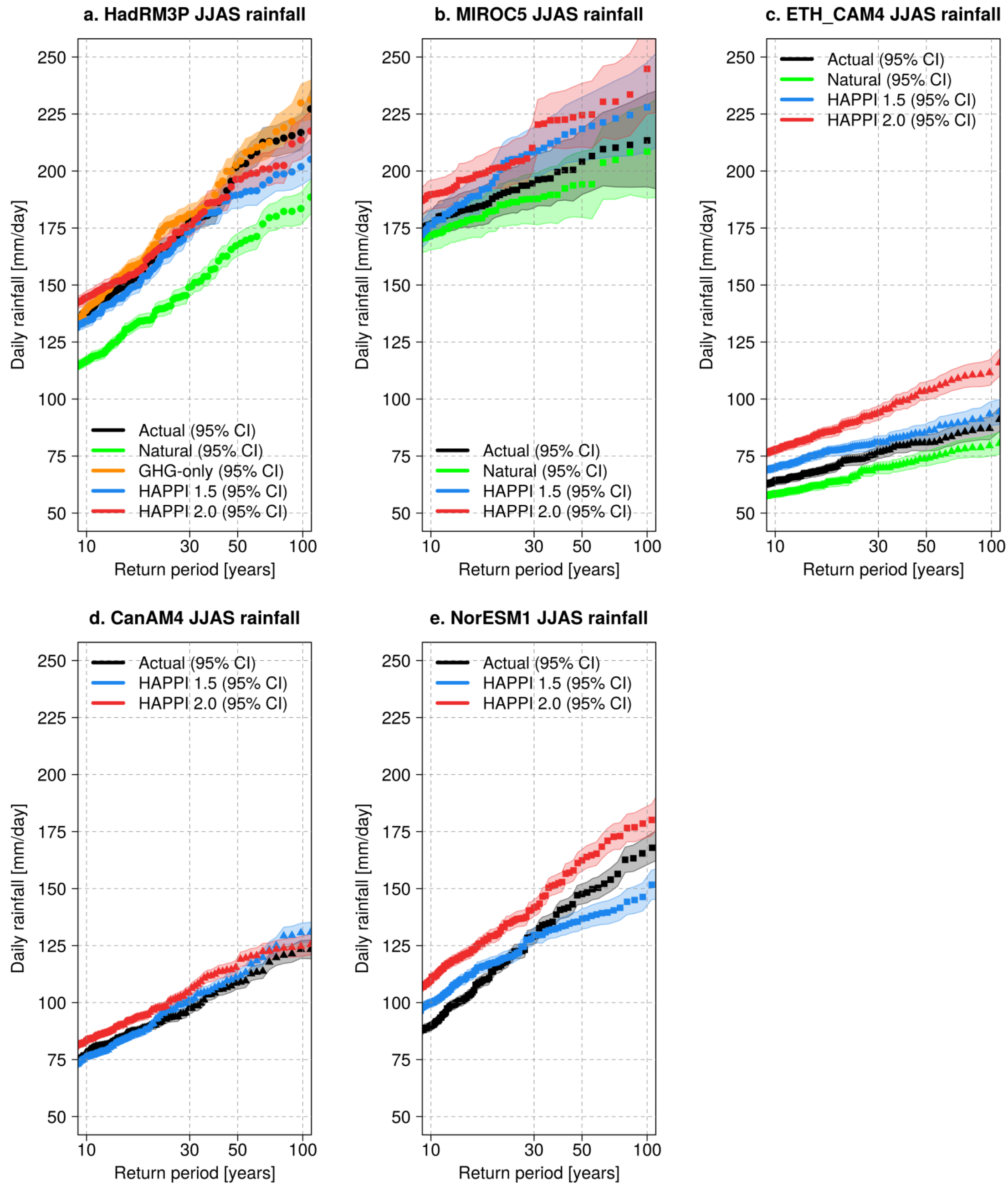

Figure S11: Same as Figure S9 but for sub-region 3.

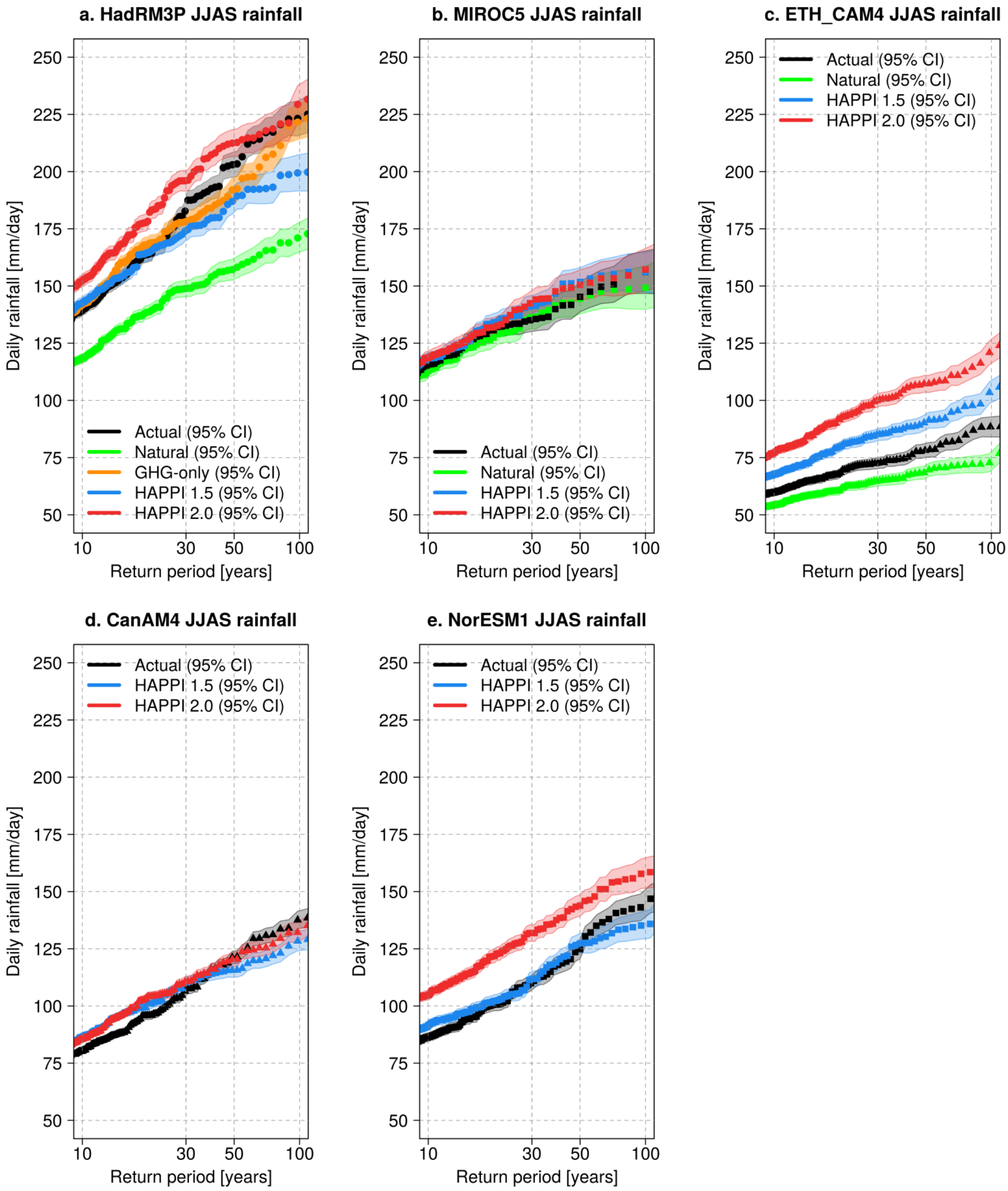

Figure S12: Same as Figure S9 but for sub-region 4.

Supplementary Text

Prescribed fields of Sulphur dioxide (SO_2) emission data in the model

A major source of uncertainty in climate model studies is the representation of SO_2 emissions. The climate models in general use historical data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and representative concentration pathway (RCP) data. But the problem is that after 2005, the contribution from observational data stops.

To overcome this problem, a more recent SO_2 emission data from the ECLIPSE v5a (Klimont *et al.*, 2013) global emissions dataset is used to prescribe the fields in the model used in weather@home. Five yearly data estimates and projections are taken from the ECLIPSE dataset and interpolated using conservative method both spatially onto an N96 global grid (1.875° longitude x 1.25° latitude) and temporally into monthly emissions data. More details of the method for the conversion of SO_2 data in terms of sulphur emissions in kg/m2/s can be made available on request from Sarah Sparrow.

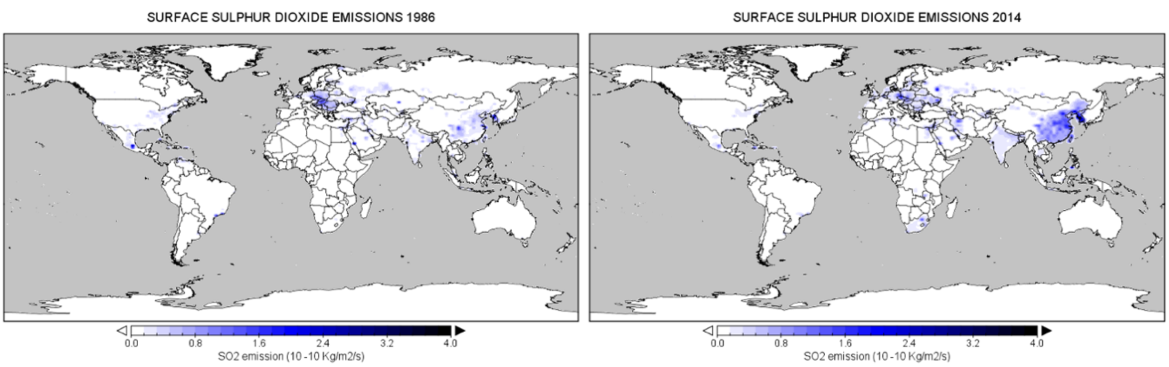

Figure S13: Prescribed field of surface SO_2 emissions in the model in 1986 (left panel) and 2014 (right panel).

Figure S13 shows the prescribed SO_2 fields in the model in two different years of 1986 and 2014 and indicates how the distribution of SO_2 emissions changes in both spatial and temporal scales. Such variability of the SO_2 emissions in the model is prerequisite for having meaningful propagation of aerosol impacts on rainfall events at regional scales.

Analytic methods:

1. **Percentage Change (dPercent)** in seasonal mean precipitation is calculated for one forcing scenario relative to another forcing scenario to indicate the magnitude of change between the scenarios across the study region. This approach enables the identification of areas at risk of becoming wetter or drier. For instance, the dPercent for ACT relative to NAT in monsoon (JJAS) season is calculated as:

$$\text{dPercent}_{\text{ACT relative to NAT}} = \left[\frac{\text{JJAS precipitation in ACT - JJAS precipitation in NAT}}{\text{Mean JJAS precipitation in ACT}}\right] \times 100$$

   The multi-year monthly means of JJAS months for each decadal model ensemble is used to calculate the dPercent in all cases. The dPercent for pre-monsoon (MAM) season is calculated using the same approach.

2. The **Standardized Precipitation Index (SPI)** (Mckee *et al.*, 1993; McKee *et al.*, 1995) is a simple, flexible index which is powerful to effectively analyse both wet and dry periods. SPI is widely used for assessing wetting/drying effects (e.g., Du et al., 2013; Li et al., 2015, 2008; Mahfouz et al., 2016). Precipitation data is the only required input parameter to calculate the SPI and this can be computed for multiple timescales from 1 to 24 months (WMO, 2012).

   For example, SPI for monsoon precipitation during JJAS months in GHG only climate model ensemble (denoted as GHG-only) relative to actual climate model ensemble (denoted as ACT) is calculated by the following equation:

$$\text{SPI}_{\text{GHG-only relative to Act}} = \frac{\text{JJAS precipitation in GHG-only - JJAS precipitation in ACT}}{\text{Standard deviation of JJAS precipitation in ACT}}$$

   The multi-year monthly means of JJAS months for each model ensemble is used to calculate the SPI in all cases. An SPI index value greater than 2.0 indicates areas are extremely wet, 1.5 to 1.99 indicates very wet; 1.0 to 1.49 moderately wet; -0.99 to 0.99 near normal; -1.0 to -1.49 moderately dry; -1.5 to -1.99 severely dry; and -2 and less indicate areas to be extremely dry (WMO, 2012).