Supplementary material for "The control of climate sensitivity on variability and change of summer runoff from two glacierised Himalayan catchments"

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Table S1. Details of the hydrometeorological observations used in this study. All hydro-meteorological data of upper Dudhkoshi catchment (Chevallier et al., 2017) are accessible from http://www.papredata.org/.

Parameters (station name)	Sensor	Accuracy (Range)	Data availability
Chandra catchment (Pratap et al., 2019; Singh et al., 2020)			
Runoff (Tandi)	YSI radar	± 2 mm	26Th June, 2016 to 30th Oct, 2018 (with gaps)
Precipitation (Himansh)	OTT Pluvio precipitation bucket	± 0.05 mm	18th Oct, 2015 to 5th Oct, 2018 (with gaps)
2m air temperature (Himansh)	Campbell HC2S3	±0.1°C (−50 to + 60 °C)	18th Oct, 2015 to 5th Oct, 2018 (with gaps)
Incoming shortwave radiation (Himansh)	Kipp and Zonen four component net radiometer	< 5%–day total (305–2800 nm, 0–2000 Wm^{-2})	18th Oct, 2015 to 5th Oct, 2018 (with gaps)
Upper Dudhkoshi catchment (Chevallier et al., 2017; Sherpa et al., 2017)			
Runoff (Phadking)	Campbell sensor (details not available)		7th April 2010 to 16th April 2017
Precipitation (Phadking)	Campbell sensor (details not available)		7th April 2010 to 23th April 2017 (with gaps)
2m air temperature (Phadking)	Campbell sensor (details not available)		7th April 2010 to 23th April 2017 (with gaps)
2m air temperature (Changri Nup)	Vaisala HMP45C	±0.2°C	1st Nov, 2010 to 30th Nov, 2014
Incoming shortwave radiation (Changri Nup)	Kipp and Zonen CNR4	±3%–day total (0.305–2.8 μm)	1st Nov, 2010 to 30th Nov, 2014

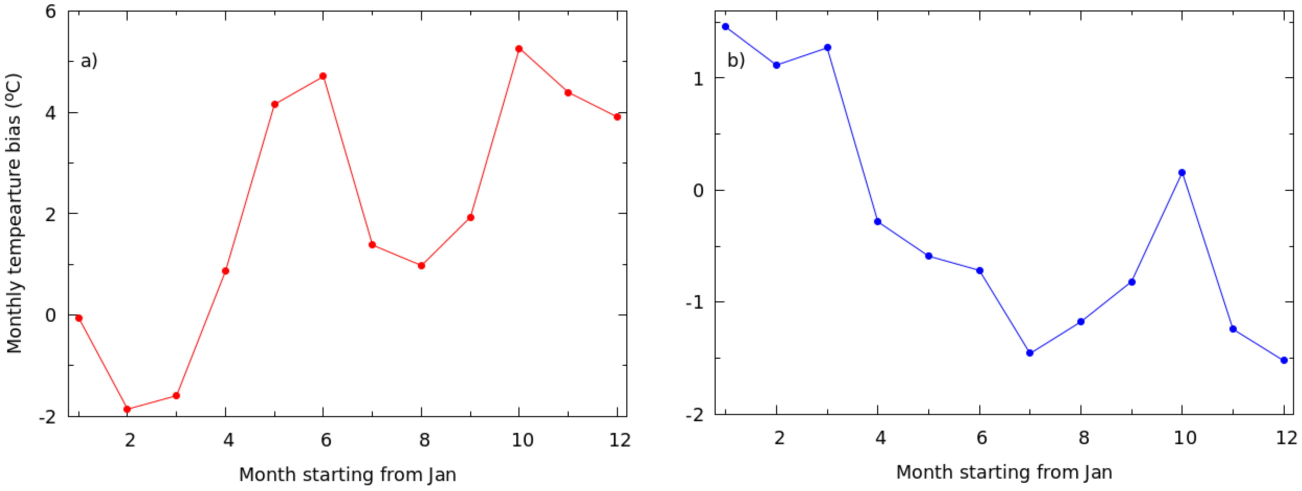

Figure S1. Mean monthly bias in ERA5 2m air temperature for (a) Chandra, and (b) upper Dudhkoshi catchments with respect to the corresponding stations (Himansh and Phadking, respectively).

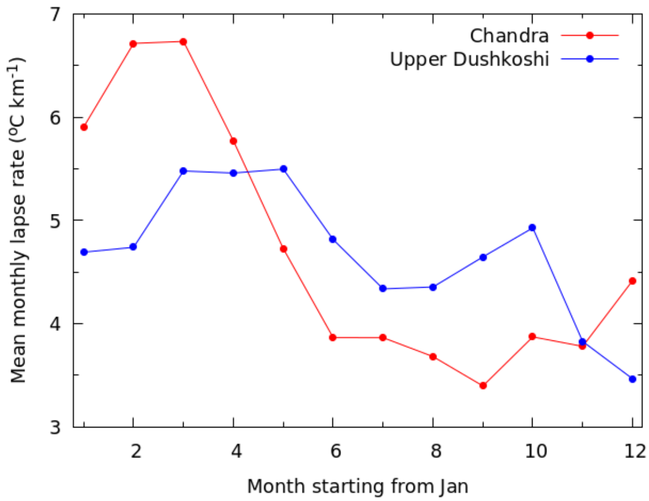

Figure S2. The mean monthly temperature lapse rates for Chandra (red symbols + line) and upper Dudhkoshi (blue symbols + line) catchments. In Chandra catchment the lapse rate was computed at the gridbox containing Himansh station from the ERA5 data (1980–2018) using temperature from four near-neighbour gridboxes. The mean annual lapse rate in Chandra catchment was 4.7±1.2 °C km^{-1}, consistent with the available mean annual lapse rate estimates of 4.4–6.4 °C km^{-1} (Azam et al., 2014; Pratap et al., 2019). In upper Dudhkoshi catchment, data from two stations Phadking and Changri Nup over the period 2013–2016 were used compute the lapse rate. The mean annual lapse rate was 4.6±0.6 °C km^{-1} which was consistent with the previously reported value of 4.6 °C km^{-1} (Pokhrel et al., 2014) from the same catchment. In this catchment, the lapse rate derived from ERA5 was significantly larger than the observed value.

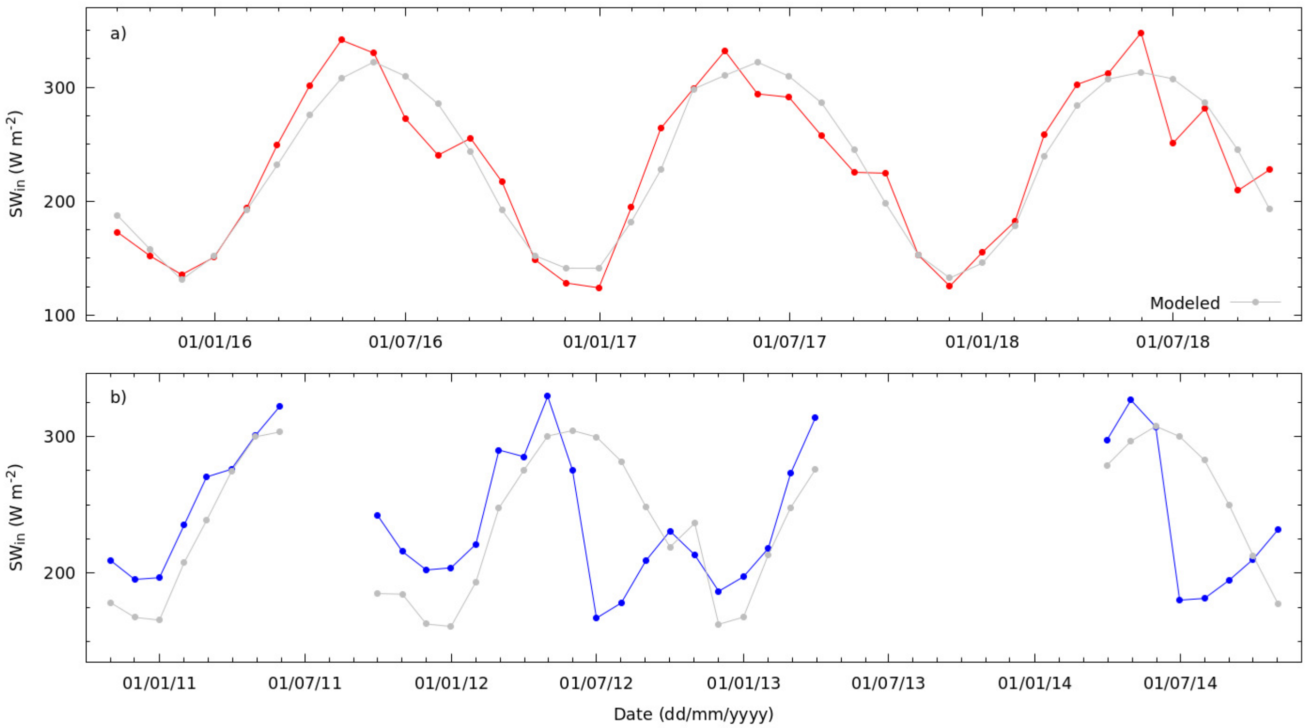

Figure S3. The incoming shortwave radiation (SW_{in}) estimated by VIC model was scaled so that it matched that observed at Himansh (Chandra catchment) and Changri Nup (upper Dudhkoshi catchment). In this plot, monthly modelled SW_{in} (gray lines + symbols) were shown for (a) Chandra, and (b) upper Dudhkoshi catchment, respectively. The corresponding monthly observed SW_{in} for Chandra (upper Dudhkoshi) catchment was shown by red lines + symbols (blue lines + symbols). In Chandra (upper Dudhkoshi) catchment the correction factor used was 2.1 (0.71).

Table S2. The values of the model parameters used in simulations.

Parameter	Range	Value used here
VIC model parameters (https://vic.readthedocs.io/en/master/)		
Ds	0.1–0.5	0.35
Ds_{max} (mm day^{-1})	10–20	15
Ws	0.4–1.0	0.7
b_{inf}	0.001–0.100	0.050
T_{th} ($^{\circ}$C)	-1.0–1.0	0.0
Glacier runoff (Hannah and Gurnell, 2001)		
K_{fast} (hr)	1–24	12
K_{slow} (hr)	500–2000	1200
Routing model (Lohmann et al., 1998)		
UH^{F}_{max} (hr)	0.5–4.0	2
UH^{F}_{pow} (hr)	2–6	4
Bf (hr)	1000–3000	2000
Ks (hr)	100–1000	550

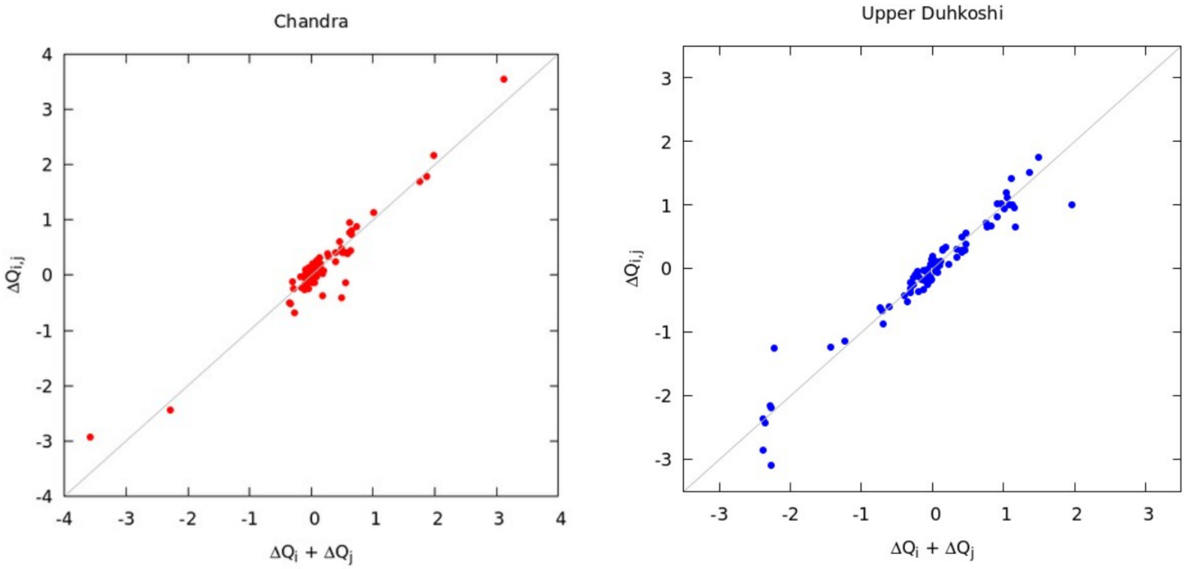

Figure S4. Percentage changes in runoff ($\Delta Q_{i,j}$) in 80 model runs, where two randomly chosen parameters out of the 11 VIC model parameters were perturbed simultaneously, are plotted against the sum of the runoff changes ($\Delta Q_i + \Delta Q_j$) from two corresponding experiments where only one of the two parameters were perturbed.

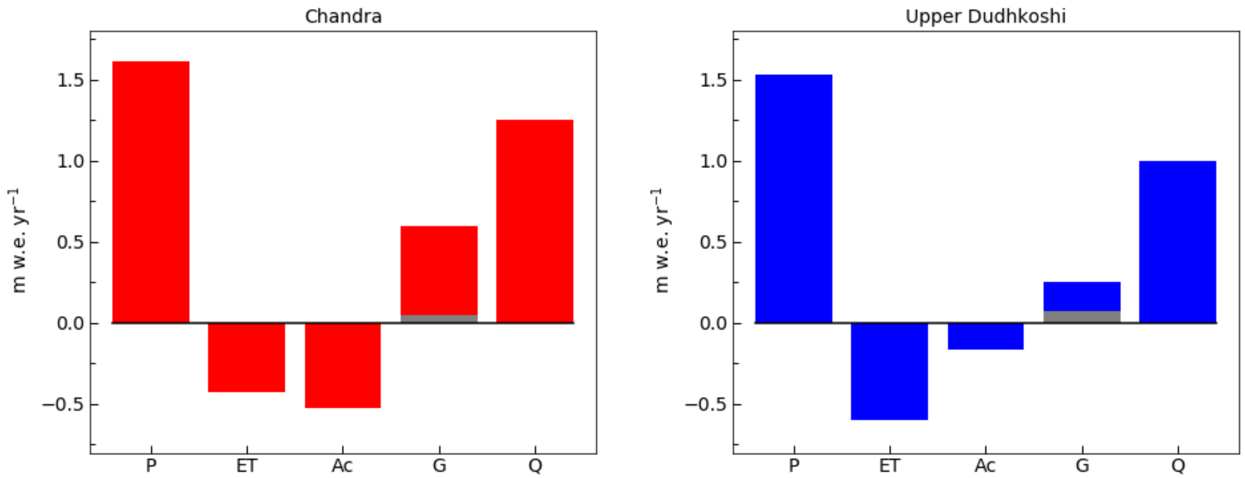

Figure S5. The components of annual hydrological balance equation $P - ET - Ac + G = Q$ are shown for the two catchments. All the components are normalised by the total catchment area. P, ET, Ac, G, and Q are the annual precipitation, evapotranspiration, glacier accumulation, the runoff from glacerised area, specific runoff from whole catchments, respectively. The imbalance contributions of the glaciers are also shown with grey bars.

Table S3. A comparison of modelled glacier mass balance with the available regional geodetic mass balance for both the catchments. For the modelled mass balance values marked with *, the modelled mean were computed starting from the year 1980.

Period	Mean modelled mass balance (m w.e yr^{-1})	Geodetic mass balance (reference) (m w.e yr^{-1})
	Chandra catchment	
1980–2018	−0.18±0.10	
1980–1992	0.29±0.18	
1993–2018	−0.42±0.14	
1975–2000	−0.05±0.11*	−0.13±0.14 (Maurer et al., 2019)
2001–2016	−0.32±0.12	−0.48±0.15 (Maurer et al., 2019)
2000–2012	−0.40±0.19	−0.52±0.32 (Vijay and Braun, 2016)
2000–2015	−0.41±0.16	−0.30±0.10 (Mukherjee et al., 2018)
2000–2016	−0.41±0.16	−0.37±0.09 (Brun et al., 2017)
		−0.31±0.08 (Shean et al., 2020)
1999–2011	−0.49±0.20	−0.45±0.13 (Gardelle et al., 2012)
		−0.44±0.09 (Vincent et al., 2013)
	Upper Dudhkoshi catchment	
1980–2018	−0.37±0.04	
1980–1992	−0.19±0.07	
1993–2018	−0.46±0.05	
1975–2000	−0.29±0.06*	−0.29±0.05 (Maurer et al., 2019)
1970–2007	−0.31±0.05*	−0.31±0.08 (Bolch et al., 2011)
2001–2016	−0.44±0.05	−0.39±0.06 (Maurer et al., 2019)
2000–2016	−0.44±0.05	−0.33±0.32 (Brun et al., 2017)
		−0.52±0.22 (King et al., 2017)
		−0.43± 0.25 (Shean et al., 2020)
1999–2011	−0.41±0.06	−0.26±0.13 (Gardelle et al., 2012)
1992–2008	−0.43±0.06	−0.42±0.30 (Nuimura et al., 2012)

Table S4. A comparison between the estimated glacier ice melt contribution to annual runoff from this study and that of from the available literature.

Study area	Glacerised fraction	Reference	% of glacier ice melt contribution to annual runoff
Chandra catchment	0.25	This study	31 ± 11
Sutri Dhakha glacier	0.50	Singh et al. (2019)	65 ± 14
Chhota Shigri glacier	0.50	Azam et al. (2019)	18 ± 3
		Engelhardt et al. (2017)	33 ± 4
Upper Dudhkoshi catchment	0.20	This study	32 ± 9
Dudhkoshi catchment	0.13	Nepal (2016)	5
		Andermann et al. (2012)	4
		Racoviteanu et al. (2013)	7
		Savèan et al. (2015)	29
Periche catchment	0.43	Mimeau et al. (2018)	45

Table S5. A comparison of glacier mass balance sensitivities to temperature and precipitation from this study with those available in the literature.

	References	Glacier mass balance sensitivity to	
		Temperature (mm yr^{-1} °C)	Precipitation (mm yr^{-1}, relative to 10% change in precipitation)
Regional values			
Chandra catchment	This study	-475 ± 93	200 ± 42
Upper Dudhkoshi catchment	This study	-274 ± 46	49 ± 20
High mountain Asia (HMA)	Wang et al. (2019)	-200 to -1490	-20 to 160
Indus basin	Shea and Immerzeel (2016)	-300 ± 100 to -800 $\pm$ 300	–
Ganga basin	Shea and Immerzeel (2016)	-300 ± 200 to -800 $\pm$ 400	–
Glacier specific values			
Chhota Shigri glacier	Azam et al. (2014)	-520	160
Zhadang glacier	Mölg et al. (2012)	-470	140
Dokriani glacier	Azam and Srivastava (2020)	-1110	240

Table S6. A comparison of catchment wide runoff sensitivities to temperature and precipitation from this study, with those reported in the available literature.

References	Study area	s_T (mm yr^{-1} °C)	s_P (mm yr^{-1} mm^{-1})
this study	Chandra catchment	117 ± 8	0.39 ± 0.03
	Upper Dudhkoshi catchment	116 ± 34	0.47 ± 0.06
Azam and Srivastava (2020)	Dokriani catchment	620	0.98
Pokhrel et al. (2014)	Dudhkoshi basin	5.7 ± 0.3	0.6 ± 0.02

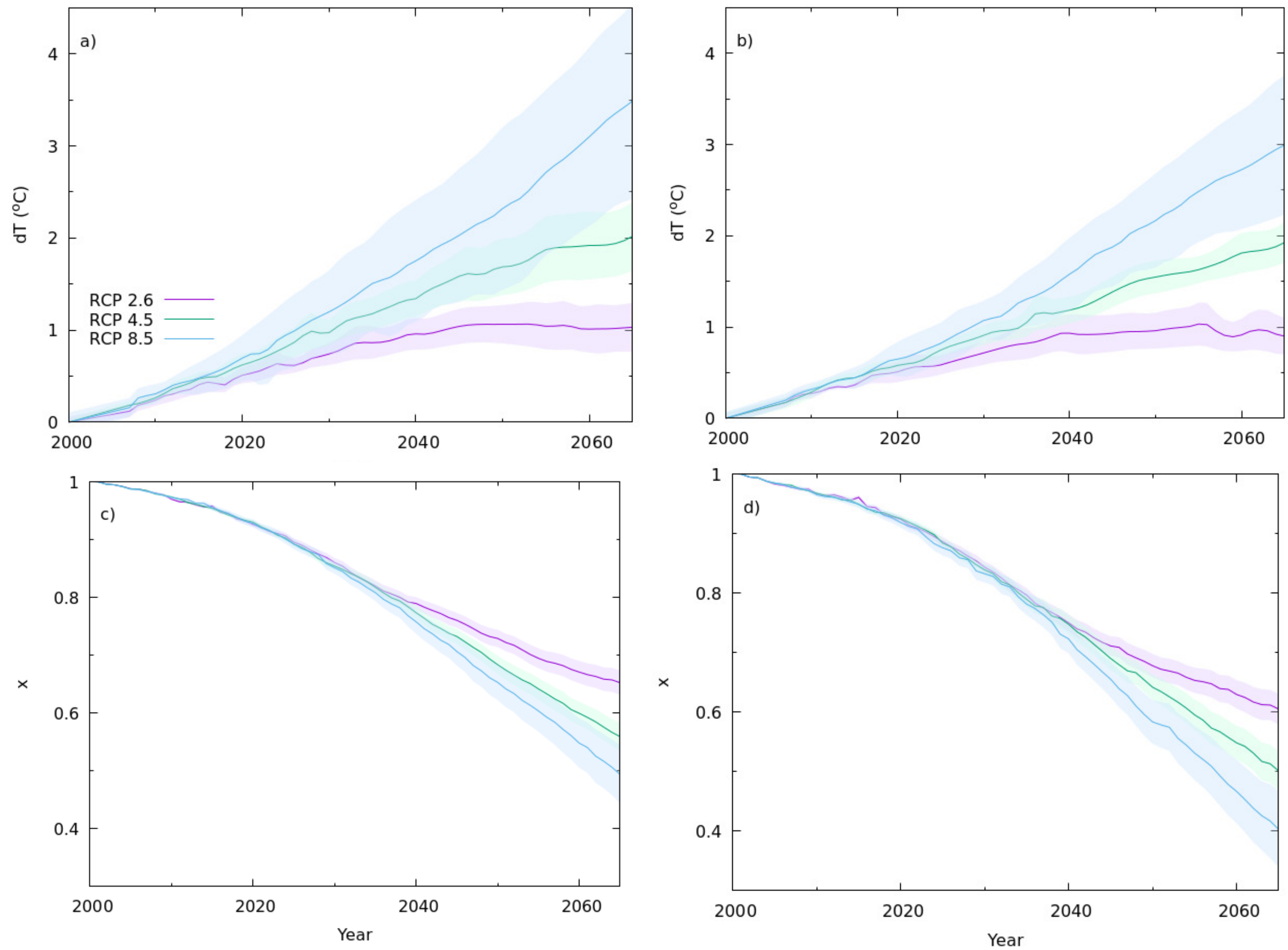

Figure S6. Projected temperature changes over the (a) western, and (b) eastern Himalaya predicted for three different climate scenarios (Kraaijenbrink et al., 2017). Kraaijenbrink et al. (2017) provided temperature change data from 2005 onward. Here we extrapolated the data between 2000–2005 using the trend between 2005–2010. Fractional changes in glacier area for (a) Indus, and (b) Ganga basins predicted using three RCP scenarios (Huss and Hock, 2018). In all the four plots, the band is showing the corresponding uncertainties associated with the future projection.

Table S7. A comparison of the 'peak water' timing of the specific glacier runoff and the corresponding runoff increase for three climate scenarios from this study with the existing values.

Climate scenario	Year of peak water (this study)	% runoff increase till peak water (this study)	Year of peak water (Huss and Hock, 2018)	% runoff increase till peak water (Huss and Hock, 2018)
		Chandra catchment		
RCP 2.6	2033±7	12±8	2028	15
RCP 4.5	2045±9	20±10	2033	23
RCP 8.5	2055±11	28±13	2040	30
		Upper Dudhkoshi catchment		
RCP 2.6	2022±5	10±7	2044	34
RCP 4.5	2031±6	13±9	2058	47
RCP 8.5	2034±9	17±12	2067	57

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