

# The 2018 Kerala floods: a climate change perspective

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### The 2018 Kerala floods: a climate change perspective

Kieran M. R. Hunt · Arathy Menon

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Abstract In August 2018, the Indian state of Kerala
received an extended period of very heavy rainfall as a
result of a low-pressure system near the beginning of the
month being followed several days later by a monsoon
depression. The resulting floods killed over 400 people
and displaced a million more.

Here, a high resolution setup (4 km) of the Weather 7 Research and Forecasting (WRF) model is used in con-8 junction with a hydrological model (WRF-Hydro, run 9 at 125 m resolution) to explore the circumstances that 10 caused the floods. In addition to a control experiment, 11 two additional experiments are performed by perturb-12 ing the boundary conditions to simulate the event in 13 pre-industrial and RCP8.5 background climates. 14

Modelled rainfall closely matched observations over the study period, and it is found that this would this would have been about 18% heavier in the preindustrial due to recent weakening of monsoon lowpressure systems, but would be 36% heavier in an RCP8.5 climate due to moistening of the tropical troposphere.

Modelled river streamflow responds accordingly: it is shown the six major reservoirs that serve the state would have needed to have 34% more capacity to handle the heavy rainfall, and 43% had the deluge been amplified by an RCP8.5 climate. It is further shown that this future climate would have significantly extended

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Arathy Menon Department of Meteorology University of Reading United Kingdom the southern boundary of the flooding. Thus it is concluded that while climate change to date may well have mitigated the impacts of the flooding, future climate change would likely exacerbate them.

Keywords floods  $\cdot$  modelling  $\cdot$  depression  $\cdot$  India

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#### 1 Introduction

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About 80% of the annual rainfall in India falls dur-48 ing the monsoon season (Parthasarathy et al, 1994) 49 and the Indian population depends on this water for 50 agriculture, hydration, and industry. Any variability in 51 timing, duration and intensity of the monsoon rains 52 have a significant impact on the lives of the people 53 in India. In recent years, several parts of India have 54 experienced devastating flooding events. For example, 55 on 26 July 2005, Mumbai experienced the worst flood-56 ing in recorded history when the city received 942 mm 57 of rainfall on a single day (Prasad and Singh, 2005). 58 Similarly, on 17 June 2013, the state of Uttarakhand 59

received more than 340 mm of rainfall resulting in dis-60 astrous flood and landslides that lead to unparalleled 61 damage to life and property (Dube et al, 2014; Martha 62 et al, 2015). The November 2015 Chennai floods, which 63 resulted in over 500 deaths when Chennai experienced 64 three times the usual rainfall, is another such example 65 (Rav et al, 2019). Each year, flooding in India from ex-66 treme rains results in a loss of around \$3 billion, which 67 constitutes about 10% of global economic losses (Roxy 68 et al, 2017). 69

In August 2018, the state of Kerala experienced 70 worst flooding since 1924. The devastating flood 71 its and associated landslides affected 5.4 million people 72 and claimed over 400 lives. The post-disaster assess-73 ment commissioned by the Government of Kerala es-74 timated the economic loss to be more than \$3.8 mil-75  $lion^1$ . These floods, as well as many like the ones listed 76 earlier, occurred during the passage of a monsoon de-77 pression. Though depressions are not directly responsi-78 ble for more than a few percent of the monsoon rain-79 fall over Kerala (Hunt and Fletcher, 2019), could their 80 broad scale modulate the westerly moisture flux that is 81 responsible? 82

Kerala is bounded by Arabian Sea to its west and 83 the Western Ghat mountain range to its east. Around 84 44 rivers flow through Kerala and there are about 85 50 major dams distributed mostly across the Western 86 Ghats (Ramasamy et al, 2019) which provide water for 87 agriculture and hydroelectric power generation. Second 88 to the northeastern states, Kerala receives the most 89 monsoon rainfall in India: the average annual rainfall 90 is around 300 cm spread over 6 months, the highest 91 amounts being received in June and July. Between 1 92 and 19 August 2018, Kerala received 164% more rain-93 fall than normal, most of which fell during the two tor-94 rential rainfall episodes of 8-10 August (contempora-95 neous with a low-pressure area, see Fig. 1) and 14-19 96 August (contemporaneous with a monsoon depression). 97 During 14-19 August, the Keralan district of Idukki re-98 ceived the most rainfall ( $\sim 700 \text{ mm}$ ) - about twice the 99 normal amount. According to Mishra et al (2018a), the 100 one- and two-day extreme precipitation values that oc-101 curred in Kerala on 15-16 August had return periods of 102 75 and 200 years respectively when compared to a long 103 term record from 1901-2017. Perivar basin, one of the 104 most affected areas, received a 145-year return period 105 rainfall (Sudheer et al, 2019). 106

The first of these two episodes of rain resulted in flooding along the banks of some of the rivers and water was released from only a few dams as the rain fell mostly

over their catchment areas. After the first episode of 110 heavy rain, most of the reservoirs in the state were near 111 their Full Reservoir Level (FRL) and most of the soil 112 in the region became saturated. Thus, when the sec-113 ond episode started several days later, the authorities 114 had to open the shutters of almost all the major dams 115 in Kerala. A combination of these torrential rains and 116 opening of the dam shutters resulted in severe flooding 117 in 13 out of the 14 districts in Kerala (Mishra et al, 118 2018b; CWC, 2018). Given the volume of precipitation 119 that fell during this period, could the dams possibly 120 have prevented the floods that followed? 121

Sudheer et al (2019) used a hydrological model to 122 explore the role of dams in the Perivar river basin in the 123 2018 floods. They suggested that emptying the reser-124 voirs in advance would not have avoided the flood as a 125 large bulk of the surface runoff was caused by interme-126 diate catchments which do not have controlled reservoir 127 operations. They found that in the Perivar river basin, 128 improved reservoir management would have only at-129 tenuated the flood by 16-21%. Furthermore, they high-130 lighted that the probability of getting extreme rainfall 131 events in the Perivar river basin in August is only 0.6%132 and hence a reliable extreme rainfall event forecast cou-133 pled with a reservoir inflow forecast is needed to plan 134 mitigation. Mishra et al (2018b) found that the extreme 135 precipitation and subsequent flooding of the 2018 event 136 was unprecedented over a 66-year record. They sug-137 gested that while mean monsoon precipitation has de-138 creased and mean temperature has increased over that 139 period, one- and two-day extreme precipitation and ex-140 treme runoff conditions in in August 2018 exceeded the 141 95th percentile of the long-term mean from 1951-2017. 142

According to the recent Intergovernmental Panel for 143 Climate Change (IPCC) report (Solomon et al, 2007), 144 wet extremes are projected to become more severe in 145 many areas where mean precipitation is projected to in-146 crease, as is flooding in the Asian monsoon region and 147 other tropical areas. Several studies suggest that rain-148 fall extreme events will increase in India under global 149 warming (Goswami et al, 2006a; Rajeevan et al, 2008; 150 Guhathakurta et al, 2011a; Menon et al, 2013; Roxy 151 et al, 2017). Most extreme events over central India are 152 associated with monsoon depressions (Dhar and Nan-153 dargi, 1995), hence intensification of extreme rainfall 154 events could be related to the change in dynamics of 155 the monsoon depressions (Pfahl et al, 2017). However, 156 due to the coarse resolution of global climate models, 157 it is unknown if the extreme rainfall events in these 158 models are caused by monsoon depressions (Turner and 159 Annamalai, 2012). Several observational studies, how-160 ever suggest that the frequency of monsoon depressions 161 has decreased and the frequency of low-pressure sys-162

https://www.undp.org/content/dam/undp/library/ Climate%20and%20Disaster%20Resilience/PDNA/PDNA\_ Kerala\_India.pdf

tems has increased in the recent past (Dash et al, 2004;
Ajayamohan et al, 2010), implying a weakening trend in
monsoon synoptic activity. So, how did climate change
affect the 2018 floods, and to what extent would they
differ under future climate change?

In this study, we will use high-resolution WRF and 168 the WRF-Hydro simulations to explore the major fac-169 tors behind the Kerala floods of August 2018. We also 170 simulate the floods under pre-industrial and RCP8.5 171 background states to determine the effects of past and 172 future climate change. Section 2 explains the model 173 setup, data and methods used in this study. Section 174 3 deals with the major results from the precipitation 175 and hydrology analysis. Results are concluded and dis-176 cussed in Section 4.

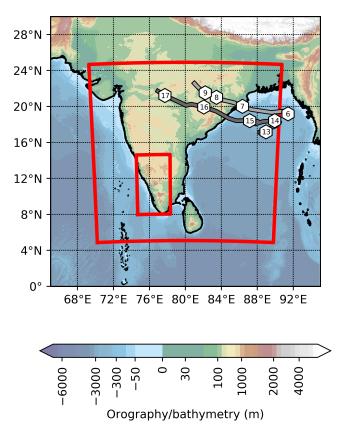


Fig. 1: Coverage of the two WRF domains (red), overlaid on an topographic map of India. The tracks of the monsoon low pressure area and monsoon depression occurring during August 2018 are marked in grey, with markers showing their 00UTC positions for each day.

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#### 2 Data and methodology

#### 2.1 ERA-Interim

For the initial and lateral boundary conditions in our 180 regional model setup, we use the European Centre for 181 Medium-Range Weather Forecasts Interim reanalysis 182 (ERA-I; Dee et al, 2011). The surface fields, as well 183 as soil temperature and moisture at selected depths are 184 used only for initial conditions; atmospheric variables, 185 which include wind, temperature and moisture defined 186 over pressure levels are used to construct both initial 187 and boundary conditions. All fields are available at six-188 hourly intervals with a horizontal resolution of T255 189 ( $\sim 78$  km at the equator), with the three-dimensional 190 fields further distributed over 37 vertical levels span-191 ning from the surface to 1 hPa. Data are assimilated 192 into the forecasting system from a variety of sources, 193 including satellites, ships, buoys, radiosondes, aircraft, 194 and scatterometers. Fields deriving purely from the 195 model (i.e. not analysed), for example precipitation and 196 cloud cover, are not used in this study. 197

#### 2.2 Precipitation data

We need a relatively high-resolution observational rain-199 fall dataset with which to compare our model output. 200 Arguably the most suitable such dataset is the NCM-201 RWF merged product (Mitra et al, 2009, 2013), which 202 combines automatic gauge data from the India Me-203 teorological Department with satellite data from the 204 TRMM multisatellite precipitation analysis (Huffman 205 et al, 2007). This provides a rainfall dataset covering 206 India and surrounding oceans at daily frequency and 207  $0.25^{\circ}$  horizontal resolution. 208

#### 2.3 CMIP5

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For this study, we use the 32 freely-accessible CMIP5 210 models (Taylor et al, 2012) for which monthly pressure 211 level data were available. Where possible, the r1p1i1 en-212 semble member was chosen as the representative of each 213 model, so as not to unfairly weight the results towards 214 any particular model. The exception was EC-EARTH, 215 for which, due to data availability reasons, member 216 r9p1i1 was used. In this study, we use data from three 217 of the CMIP5 experiments: historical, pre-industrial, 218 and RCP8.5. The historical experiments of all mod-219 els used here are forced with observed natural and an-220 thropogenic contributions, usually from over the period 221 1850-2005, from which we take a representative period 222

of 1980-2005, against which all perturbations are com-223 puted. The pre-industrial experiment comprises longer 224 simulations with no anthropogenic forcings; these have 225 varying baseline periods depending on the model, so we 226 take the representative period as being the last 25 years 227 of the run. The future scenario used here, RCP8.5, cor-228 responds to an effective net change in radiative forcing 229 in 2100 of 8.5 W m<sup>-2</sup>, equivalent to roughly 1370 ppm 230  $CO_2$  (Van Vuuren et al, 2011). We again choose the 231 final 25 years (2075-2100) as the representative period 232 for the experiment. 233

#### 234 2.4 WRF

Throughout this study we will make use of version 4.0 235 of the Advanced Research Weather Research and Fore-236 casting (WRF) model (Skamarock et al, 2008). Two 237 domains (see Fig. 1) were employed for this study: the 238  $61 \times 61$  outer domain had a resolution of 36 km, whereas 239 the  $100 \times 181$  inner domain had a resolution of 4 km. We 240 note that though this nesting ratio seems high, previ-241 ous authors (e.g. Liu et al, 2012; Mohan and Sati, 2016) 242 have found that results are insignificant to the ratio, so 243 long as it is an odd number. The inner domain was cho-244 sen to encapsulate the entire state of Kerala, as well as 245 the Western Ghats and an area of the Arabian Sea to 246 the west, allowing us to capture offshore convective de-247 velopment as well as the orographic features that play 248 an important role in monsoon rainfall in the state. The 249 larger domain, which covers most of India, was chosen 250 to include the monsoon depression that was contempo-251 raneous with the flooding. 252

Convection was parameterised in the outer domain, 253 but explicit in the inner - this and the other physics 254 schemes used are outlined in Tab. 1. Here, we use the 255 combination recommended by NCAR and specified in 256 the WRF User's Guide for convection-permitting sim-257 ulations of tropical cyclones; it is very similar to that 258 used by previous authors simulating orographic rain-259 fall in South Asia (e.g. Patil and Kumar, 2016; Norris 260 et al, 2017), as well as monsoons in general (e.g. Srini-261 vas et al, 2013; Dominguez et al, 2016). We use 35 eta 262 levels in the vertical with a model lid at 50 hPa. Lateral 263 boundary conditions were supplied at every six hourly 264 timestep from ERA-Interim reanalysis data, as were ini-265 tial conditions for the first timestep. 266

#### 267 2.5 WRF-Hydro

In this study, we use the WRF-Hydro hydrological
model (Gochis et al, 2014), coupled to the Noah-MP
land surface model (LSM; Gochis and Chen, 2003; Niu

et al, 2011; Yang et al, 2011). In our configuration, both 271 overland (steepest descent) and channel routing (differ-272 ential wave gridded) were activated, with the hydrolog-273 ical model running at a resolution of 125 m (timestep: 274 10 s) and the land surface model running at 4 km 275 (timestep: 1 hr). The LSM takes as input hourly output 276 from the WRF model, distributing surface precipitation 277 among its four soil layers (set at 7, 28, 100, and 289 cm 278 to match ERA-Interim) and the surface; WRF-Hydro 279 then channels this moisture accordingly at the higher 280 resolution. The high-resolution input files, containing 281 important geospatial information (e.g. slope direction, 282 river channel mask) were created using the WRF-Hydro 283 GIS preprocessing toolkit and the satellite-derived Hy-284 droSHEDS hydrographic dataset (Lehner et al, 2008; 285 Lehner and Grill, 2013). These modelled rivers and 286 their basins are shown in Fig. 2. 287

Because of a lack of relevant reservoir and lake data 288 for the state of Kerala, these features were not imple-289 mented in the hydrological model; one major implica-290 tion of this was that the surface water output from 291 WRF-Hydro was inaccurate (while the natural lakes 292 were correctly represented, the artificial reservoirs were 293 not). Given that some of the reservoirs are substan-294 tial (the largest, created by the Idukki dam, is about 295  $60 \text{ km}^2$ ), we chose to run the LSM and WRF-Hydro 296 offline (i.e. coupled to each other but not to WRF) in 297 order to mitigate incorrect feedbacks caused by mislo-298 cated surface water. 299

Furthermore, the long spin-up time necessary for the hydrological model meant that a cold start in the summer of 2018 would have been inappropriate. As such, we ran WRF with the control experiment parameters from 1 June 2017 to 1 July 2018 (the start date of all experiments), using the output to force WRF-Hydro so that warm restart files were available for the study period. 306

#### 2.6 Climate perturbation and experimental setup

One of the key foci of this study will be to explore how 308 the 2018 floods would have differed in the absence of an-309 thropogenic climate change and how it would differ in a 310 projected future climate. To this end we use a technique 311 commonly referred to as pseudo-global warming (PGW, 312 e.g. Kimura and Kitoh, 2007; Prein et al, 2017; Hunt 313 et al, 2019). Taking an example of modifying 01-08-2018 314 00Z boundary conditions to reflect RCP8.5 conditions, 315 we describe the methodology below: 316

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1. For a given prognostic variable, say, temperature, compute the CMIP5 multi-model August mean for the historical experiment over the period 1980-2005.  $_{319}$ Call this  $T_0$ .  $_{320}$ 

Parameterisation	Scheme	Citation
cloud microphysics	WRF Single-moment 6-class	Hong and Lim (2006)
planetary boundary layer	Yonsei University	Hong et al $(2006)$
cumulus (outer domain only)	Kain-Fritsch	Kain (2004)
radiation (LW & SW)	RRTMG	Iacono et al $(2008)$
land surface	Unified Noah LSM	Tewari et al $(2004)$
surface layer	Revised MM5	Jiménez et al $(2012)$

Table 1: Physics schemes used in the WRF setup.

- 221 2. Compute the multi-model August mean for the RCP8.5 experiment over the period 2075-2100. Call 223 this  $T_p$ .
- 3. Take the difference field,  $T_d = T_p T_0$ , then slice and interpolate it to match the dimensions of the boundary condition. Add  $T_d$  to the boundary condition, and repeat for all boundaries for T at this time step.
- 4. Repeat for all variables (and all time steps) on both
  lateral and lower boundaries.

In this way, we can keep the important highmagnitude, high-frequency weather information, but see how the impacts adjust when perturbed by a lowmagnitude, low-frequency climate signal.

#### 335 2.7 Storage calibration

Much of this study focuses on reservoirs, and since the hydrological model used can only compute the river discharge (or reservoir inflow) for a given point, we need to be able to convert this to storage, so that it can be compared appropriately with observations. To this end, we propose a simple model to compute the storage, S, at some time  $t_1$ , given its value at  $t_0$ , the inflow rate as a function of time,  $\phi(t)$ , the evacuation rate,  $\eta$ , and some shape parameter,  $\alpha$ :

$$S(t_1) = S(t_0) + \alpha \int_{t_0}^{t_1} \left[\phi(t) - \eta\right] dt \,. \tag{1}$$

The evacuation rate represents the sum of all contribu-336 tions to drainage from the reservoir - comprising arti-337 ficial sinks (sluices, spillways) and natural sinks (seep-338 age, evaporation). Strictly speaking, this should be a 339 function of time; however, that information is not freely 340 available for the dams studied in this work and fitting a 341 time dependent variable using model output would be a 342 highly underconstrained problem. Therefore, we make 343 a simplification - separating the contributions into a 344 constant (following the notion that reservoir output is 345 generally intended to be kept constant),  $\eta$  and a factor 346 proportional to the accumulated storage as a function 347 of time (assuming that, e.g., groundwater seepage is 348

proportional to storage<sup>2</sup>),  $\beta$ . For readability, we define  $\alpha = 1 - \beta$  and call that the shape factor because it also includes the effects of having a more complex, partitioned reservoir system. 352

#### 3 Results

#### 3.1 Precipitation

We start our analysis by looking at the primary cause of 355 all floods: precipitation. Fig. 3 shows different aspects 356 of the rainfall occurring during and immediately be-357 fore the floods, covering the period August 6 to August 358 18 inclusive. The leftmost panel shows the mean rain-359 fall for this period according to the NCMRWF merged 360 precipitation product (see Sec. 2.2). Rainfall is concen-361 trated mostly along the peaks of the Western Ghats, 362 thus the hydrological stress that triggered the flood-363 ing came about from an (approximate) amplification of 364 the mean monsoon pattern rather than through rainfall 365 falling in unusual locations. This pattern is in agree-366 ment with the assessment of Mishra and Shah (2018) 367 who investigated IMD rainfall data<sup>3</sup> for the period. 368 Most of the rainfall falls over land as opposed to ocean 369 indicating the extended presence of a so-called coastal 370 convective phase, as described by Fletcher et al (2018). 371 Coastal phases stand in contrast to offshore phases, and 372 usually develop under conditions of anomalously strong 373 and moist westerlies - in this case provided by the low 374 pressure systems passing over the peninsula. 375

Second from left in Fig. 3 is the mean rainfall for our WRF control experiment for the same period (06/08-18/08), showing a broad structure very similar to observations for the period shown in the first panel<sup>4</sup>. Again, the rainfall is predominantly onshore, concentrated over 380

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 $<sup>^2</sup>$  This is only strictly true if reservoir cross-sectional area is constant with height. Of course it isn't; but for the sake of simplicity, we make this approximation.

 $<sup>^3</sup>$  Note that the NCMRWF dataset used here is in part derived from IMD rainfall data, so a high pattern correlation is expected.

<sup>&</sup>lt;sup>4</sup> For a fairer comparison, the model output should be regridded to the resolution of the NCMRWF dataset. However we intend this particular comparison to be qualitative, not quantitative - and have thus retained the higher resolution.

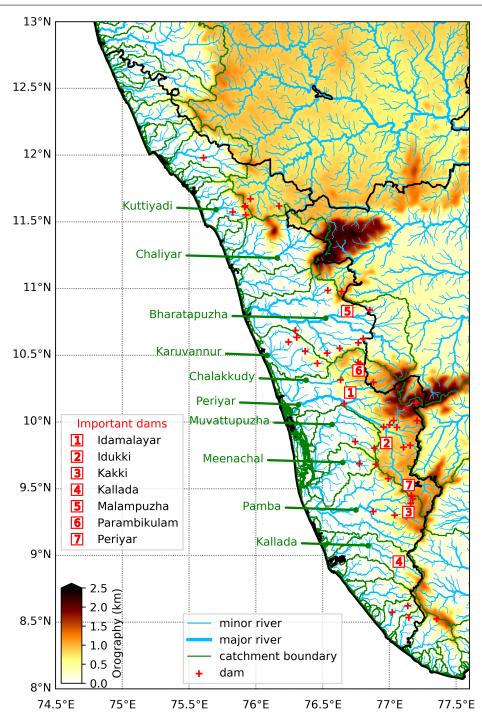


Fig. 2: Locations of important hydrological features in the state of Kerala, with state boundaries given in black. Major river catchment boundaries are given in green, with selected rivers labelled accordingly. Plotted river width is a function of Strahler stream order.

the orography. At this resolution, though it was suggested by the observational data, we can see that the mean rainfall for this period is heaviest over - or slightly upstream of - the major dams. Upstream of Idamalayar and Parambikulam the mean rate for some areas reached more than 15 mm  $hr^{-1}$ , amounting to an accumulation exceeding 4.5 m for period. This is in accordance with data released by the Central Water Commission<sup>5</sup>, as is the spatial distribution.

<sup>5</sup> summarised in https://reliefweb.int/sites/ reliefweb.int/files/resources/Rev-0.pdf

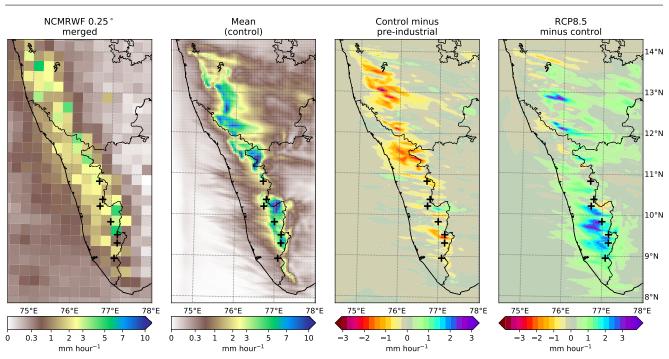


Fig. 3: Mean precipitation  $[mm hour^{-1}]$  over the inner domain for the period August 6 to August 18 inclusive. From left: the NCMRWF merged product; the control experiment; the difference between the control and pre-industrial experiments; and the difference between the RCP8.5 and control experiments. State boundaries are marked in black, with black crosses representing the major dams shown in Fig. 2

The remaining two panels, on the right hand side of 390 Fig. 3, compare the control experiment mean rainfall 391 with that of the two perturbation experiments. We re-392 call from the methodology that these experiments are 393 - like the control - hindcasts, with their boundary con-394 ditions adjusted to simulate how the events leading to 395 the flood may differ if occurring under pre-industrial or 396 RCP8.5 climates. The first of these (second from right) 397 shows the difference in mean rainfall for the period be-398 tween the control and pre-industrial experiments. It is 399 almost universally drier in the pre-industrial experi-400 ment - averaging a mean reduction over the inner do-401 main of about 18% compared to the control. Let us 402 start to unpick this by noting that historical rainfall 403 trends show that the monsoon is drying and that that 404 pattern is amplified over Kerala and the Western Ghats 405 due to weakening monsoon westerlies (Krishnan et al, 406 2016). This picture is complicated somewhat by previ-407 ous studies showing that extreme rainfall events embed-408 ded within the monsoon have seemingly worsened (e.g. 409 Goswami et al, 2006b), though spatial maps of such 410 trends (Guhathakurta et al, 2011b) suggest that they 411 are very slight along the southwest coast. We will re-412 solve this in the next section by looking at the changes 413 from a moisture flux perspective. Finally, we compare 414 the control and RCP8.5 experiments, as shown in the 415

rightmost panel of Fig. 3. The RCP8.5 perturbed sce-416 nario is almost universally wetter than the control over 417 the inner domain (by about 36%), particularly over the 418 southern Keralan Ghats, where the control rainfall is 419 highest and where the major dams are situated. This 420 is in contrast to the pre-industrial experiment which 421 exhibited the most drying over the north of the state 422 with a more mixed signal around the major dams. This 423 non-linearity could indicate that different processes are 424 responsible for the respective changes. 425

The moisture flux that impinges upon the Western Ghats is responsible for the vast majority of the monsoon rainfall that falls over Kerala, subject to localised dynamics dependent also on the land-sea contrast (Fletcher et al, 2018). To first order, changes in this moisture flux can be thought of as a sum of contributions from changes to humidity and changes to the wind field, i.e.:

$$q\mathbf{u} = (q\mathbf{u})' + \overline{(q\mathbf{u})} = \bar{q}\bar{\mathbf{u}} + q'\bar{\mathbf{u}} + \bar{q}\mathbf{u}' + q'\mathbf{u}', \qquad (2)$$

where q and  $\mathbf{u}$  are the quantities in the perturbation 426 experiment,  $\bar{q}$  and  $\bar{\mathbf{u}}$  are the values in the control experiment, and q' and  $\mathbf{u}'$  are the differences between them. 428

Considering the period when the monsoon depression was most active: Aug 15 to Aug 18 inclusive, we compare these terms between the control experiment 431

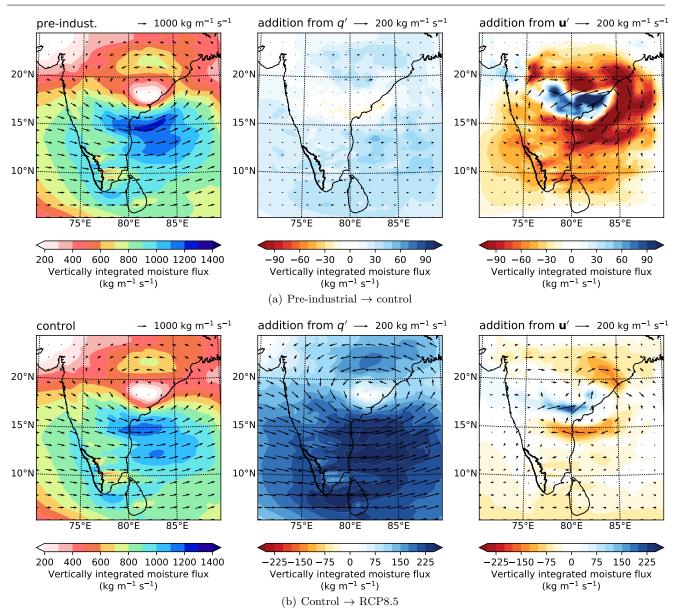


Fig. 4: Vertically-integrated moisture flux for the period 2018-08-15 00Z to 2018-08-19 00Z over the outer domain (with Kerala indicated in black). The left panels shows the mean vector field and its magnitude for the preindustrial and control experiments respectively. The middle panels show the changes to those fields in the control and RCP8.5 experiments respectively considering only changes to specific humidity. The right panels are as the middle panels but for changes to the wind field. The right and middle panels are coloured by the effect their presence has on the total magnitude, note that the colours scales differ between the two pairs of experiments.

and two perturbation experiments in Fig. 4. The first 432 of the two groups, Fig. 4(a) treats the pre-industrial ex-433 periment as the base, with the control experiment act-434 ing as the perturbation. The leftmost panel, indicating 435 mean moisture flux for the period, shows clearly the im-436 pact of the depression. It dominates the organisation of 437 moisture over the peninsula, with high values of verti-438 cally integrated flux and flux convergence both slightly 439 to the south of its centre and over Kerala. The mid-440

dle panel shows how this pattern would change in the 441 present day considering differences to humidity alone. 442 As the tropical atmosphere has not moistened drasti-443 cally since the pre-industrial, these changes are slight 444 when compared to the absolute values, adding only a 445 very small positive contribution - amounting to a few 446 percent - to the flux magnitude over Kerala. The right-447 hand panel is as the middle panel, but instead looking 448 at the contribution from the wind field alone. Imme-449

diately, one can see that the depression is surrounded 450 by a significantly weaker circulation causing a reduc-451 tion in moisture flux over almost all of India, except 452 for a small region near the depression centre caused 453 by track translation. This is expected: previous stud-454 ies have shown that monsoon low-pressure systems be-455 come weaker and less numerous as the climate warms 456 (Prajeesh et al, 2013; Cohen and Boos, 2014; Sandeep 457 et al, 2018) as low-level vorticity associated with the 458 monsoon decreases. Despite this, the reduction in flux 459 over Kerala is comparatively weak, though easily more 460 than enough to override the contribution from q'. This 461 is largely in agreement with Sørland et al (2016) who 462 found that, for an ensemble of ten individual storms, 463 uniform atmospheric temperature increases of 2 K and 464 4 K yielded mean precipitation increases of 22% and 465 53% respectively. 466

The second set of panels, Fig. 4(b), shows the con-467 tributions to the difference in moisture flux between 468 the control and RCP8.5 experiments. The mean ver-469 tically integrated moisture flux for the control experi-470 ment appears quite similar to that of the pre-industrial 471 experiment, which we expect from the preceding anal-472 ysis. The humidity change (middle panel) increases the 473 moisture flux incident on Kerala by over 20% from the 474 control experiment to the RCP8.5 experiment, as well 475 as a universally positive contribution over the whole 476 subcontinent. The expected further weakening of the 477 depression (right-hand panel) is much weaker than in 478 the pre-industrial to control case before, and nowhere 479 near strong enough to counter the large moisture-drive 480 contribution. 481

In summary, in the control (present-day) exper-482 iment, there was marginally less moisture flux over 483 Kerala than in the pre-industrial experiment due to a 484 marked weakening of the monsoon depression; in con-485 trast, there is significantly increased flux over Kerala 486 in the RCP8.5 experiment in spite of slight weakening 487 of the depression, due to a large rise in tropospheric 488 humidity. 489

#### 490 3.2 Hydrology

Precipitation is only one part of the complex hydrological cascade that leads to flooding. To work towards a
more complete picture, we now use the WRF hydrological model (see Sec. 2.5) to explore the response of
rivers to the heavy precipitation analysed in the previous section.

Fig. 5 shows the mean modelled discharge over from 13-08-2018 00Z to 19-08-2018 00Z for the control experiment and how it compares to the two perturbation experiments. The control mean (Fig. 5(a)) splits the

discharge into decades, with green hues representing 501 the largest rivers (flow rates exceeding  $100 \text{ m}^3 \text{ s}^{-1}$ ), 502 red hues representing the smallest rivers (flow rates be-503 low 10 m<sup>3</sup> s<sup>-1</sup>), and yellow covering those in between. 504 All seven of the important dams (and their epony-505 mous reservoirs) lie on major rivers or significant trib-506 utaries thereof. Given the complicated partitioning of 507 river basins over Kerala (Fig. 2), these maps provide a 508 useful overview of their response to heavy rainfall dur-509 ing August 2018 and how that response changes when 510 the rainfall responds to the different climates of the 511 pre-industrial and RCP8.5 perturbation experiments. 512

Fig. 5(b) shows the difference between the mean 513 control discharge and that of the pre-industrial experi-514 ment. As the rainfall is generally less in the latter dur-515 ing this period, we see the expected pattern of almost 516 completely reduced streamflow over the domain; the ex-517 act reduction varies considerably depending on location 518 (and is indeed an increase in some areas) but averages 519 16% over the domain. In contrast, Fig. 5(c) shows that 520 streamflow almost universally increases over the do-521 main in the RCP8.5 experiment when compared to the 522 control. In some places, the change is quite drastic: the 523 mean increase over the domain is 33%, the upper guar-524 tile is 77%, and the ninetieth percentile is 97%. In other 525 words, one in ten river points in the domain would have 526 experienced twice the discharge were this event to have 527 happened in an RCP8.5 climate. The domain-averaged 528 changes of -16% and 33% for pre-industrial and RCP8.5 529 are in strong agreement with the domain-averaged rain-530 fall changes of -18% and 36% respectively. 531

The story would be incomplete without some focus 532 on the reservoir/dam system that failed in the lead up 533 to the floods. While a complete treatment of that topic 534 is beyond the scope of this work, we will endeavour to 535 give a thorough analysis with the available data. We 536 start by using the largest reservoir in the state, Idukki, 537 as a case study. Fig. 6 shows the modelled inflow and 538 storage for all three experiments, as well as the observed 539 storage from India-WRIS and the nominal capacity of 540 the reservoir. As discussed in Sec. 2.7, to convert mod-541 elled inflow to a representative storage we must inte-542 grate it over time and include both a sluicing rate and 543 a shape factor. These are reservoir-specific unknowns 544 that we need to fit for using a standard least-squares 545 method. Leveraging part of the long spin up period 546 required by the hydrological model, we calibrated us-547 ing observational and (control experiment) model data 548 from January to June 2018 inclusive; the low rainfall 549 during the pre-monsoon being particularly useful to es-550 tablish the correct sluicing rate. 551

The inflow rates from all three experiments are in 552 line with what we expect from Fig. 5: overall the con-553

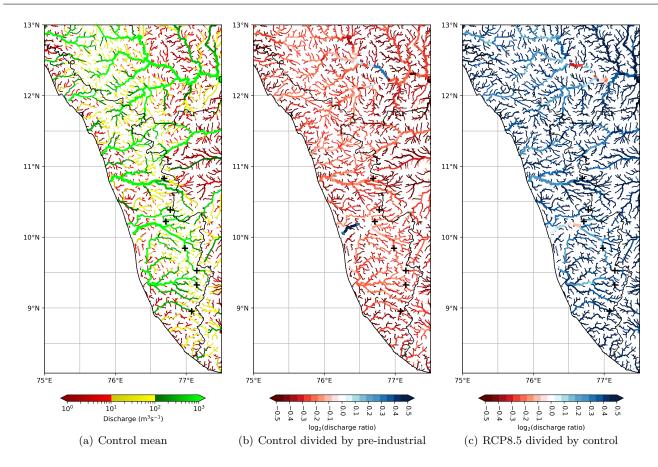


Fig. 5: Modelled river discharge  $(m^3 s^{-1})$  for 13-18 August 2018 inclusively as: (a) the control experiment mean; (b) the ratio of the control experiment and pre-industrial experiment means; and (c) the ratio of the RCP8.5 experiment and control experiment means. The seven major dams shown in Fig. 2 are given here by black crosses.

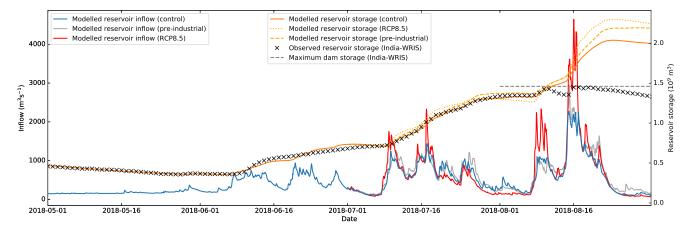


Fig. 6: Idukki reservoir: modelled inflow (blue, grey, red lines for control, pre-industrial, RCP8.5 experiments respectively), modelled storage (orange solid, dotted, dashed lines respectively), and observed storage (black crosses). Nominal reservoir maximum capacity is marked by the dashed grey line towards the right of the figure.

trol experiment is the driest, with slightly more inflow
in the pre-industrial experiment and significantly more
in the RCP8.5 experiment. The control experiment inflow very closely matches that given in the CWC report

(see their Fig. 4). These project accordingly onto the modelled storages, all three of which closely follow the observations until the first LPS (Aug 6 to Aug 10). At that point, the reservoir hit capacity - denoted in Fig. 6 561

by the dashed horizontal grey line, and the floodgates 562 had to be opened. Our model is not party to that infor-563 mation and continues to assume the constant sluicing 564 rate from the pre- and early monsoon periods, result-565 ing in a divergence between the three model storages 566 and observations. The control experiment provides a 567 useful estimate of how much additional storage would 568 have been required: the nominal maximum capacity is 569  $1.45 \times 10^9$  m<sup>3</sup>, the control experiment modelled stor-570 age peaked at  $2.04 \times 10^9$  m<sup>3</sup> (41% higher), and the 571 RCP8.5 experiment reached a storage of  $2.30 \times 10^9$  m<sup>3</sup> 572 (59% higher than maximum capacity, 13% higher than 573 the control). Making the naïve assumption that when 574 modelled storage values exceed the maximum capacity, 575 the difference is converted into floodwater, the control 576 experiment yields a total excess of  $5.89 \times 10^8 \text{ m}^3$  be-577 tween breaching on August 11th and remission ten days 578 later; the RCP8.5 experiment (breaching one day ear-579 lier) yields  $8.52 \times 10^8$  m<sup>3</sup>, an increase of 45%. It is clear, 580 therefore, that using the dams to mitigate downstream 581 flooding would have been largely impossible; further-582 more, were such an event to happen again in an end-of-583 century RCP8.5 climate, it would be significantly more 584 catastrophic. 585

We now generalise this analysis to the major Ker-586 alan reservoirs. This is only possible for the six whose 587 storage data are released by India-WRIS, without 588 which we cannot calibrate using Eq. 1. Observed and 589 modelled storages, along with climatological informa-590 tion, are given for these six (Idamalayar, Idukki, Kakki, 591 Kallada, Malampuzha, and  $Periyar^6$ ) in Fig. 7. There 592 are two brief caveats to make before we move into the 593 analysis. Firstly, we have assumed that the reservoir 594 outflow is the sum of a constant sluicing rate and some 595 additional contribution proportional to the inflow; this 596 is a very good approximation for the larger reservoirs 597 (which the reader is invited to verify by inspection of 598 the CWC report) but can be poor in smaller reser-599 voirs where the supply and demand is comparably much 600 more variable. Secondly, as discussed in the previous 601 section, our model has no information on floodgates, so 602 continues to add to the storage of a reservoir even af-603 ter the maximum capacity (FRL) has been passed. In 604 each case this manifests as a large divergence between 605 modelled and observed storage starting in mid August. 606

Fig. 7 compares these storages for the reservoirs in question. In all cases except Periyar (and to a lesser extent, Kallada), the modelled storage from the control experiment closely follows the observed storage; in all but Kallada, the 2018 observed storage reached its FRL; and in all cases, at some point in July or Au-

gust, the storage reaches its highest value since records 613 began in 2001. Two reservoirs, Idamalayar and Malam-614 puzha, exhibit seemingly counter-intuitive behaviour: 615 by the end of August, the largest storage values come 616 from the pre-industrial experiment and the smallest 617 from RCP8.5. Inspection of Fig. 3 reveals that although 618 nearly everywhere in the domain receives more rain-619 fall in the RCP8.5 experiment (compared to the con-620 trol), both these dams are situated downstream of small 621 regions where the reverse is true, seemingly in part 622 due to the absence of some rainfall-triggering event in 623 mid July. Thus, in these unusual cases, it is possible 624 that future climate may mitigate hydrological stress 625 on these reservoirs. The remaining four have storage 626 patterns that more closely reflect the general results 627 presented earlier in this study: the highest storage val-628 ues are reached in RCP8.5, followed by pre-industrial, 629 with control at the bottom. Averaged over these four 630 reservoirs, the peak storage in the control experiment 631 is 34% higher than the nominal maximum capacity, 632 rising to 43% in pre-industrial conditions and 54% in 633 RCP8.5 conditions. Including the two anomalous reser-634 voirs, these become 37%, 50% and 44% respectively. 635

Finally, we look at the general impact on the 62 636 dams/reservoirs shown in Fig. 2, whose inflows are 637 grouped by river basin in Fig. 8; for each basin, the 638 inflow is computed as the sum of inflow to all reservoirs 639 therein. Noting that the basins are arranged by lati-640 tude, several important contrasts emerge. Firstly, the 641 relative impact of the first LPS (triggering the peaks 642 between Aug 8 and Aug 10) is less among the more 643 southerly basins; likely because as a weaker system, it 644 would have a smaller region of influence, and thus less 645 impact on the bulk monsoon flow. Secondly, the im-646 pact of switching to an RCP8.5 climate becomes dras-647 tically more significant in basins situated further south. 648 Over the period Aug 14 to Aug 19 inclusive, the three 649 smaller basins towards the north (Kuttiyadi, Bharata-650 puzha, and Karuvannur) have mean control inflow of 651  $26.2 \text{ m}^3 \text{ s}^{-1}$ , rising 25% to  $32.7 \text{ m}^3 \text{ s}^{-1}$  in the RCP8.5 652 experiment. For the middle three basins (Chalakkudy, 653 Periyar, and Muvattupuzha), the mean inflow increases 654 32% from 563  $\rm m^3~s^{-1}$  in the control to 745  $\rm m^3~s^{-1}$ 655 in RCP8.5. For the southernmost three (Meenachal, 656 Pamba, and Kallada), this changes drastically: rising 657 98% from 152 m<sup>3</sup> s<sup>-1</sup> to 302 m<sup>3</sup> s<sup>-1</sup>. Revisiting Figs. 3 658 and 4(b), we can see why: this area has the largest frac-659 tional increase of rainfall in the RCP8.5 experiment 660 (this can be confirmed directly by looking at a ratio 661 map, which we do not show here). This in turn is at 662 least partially caused by a significant increase in mois-663 ture flux and moisture flux convergence over the south-664 ernmost part of the peninsula, a pattern that is echoed 665

<sup>&</sup>lt;sup>6</sup> Note that in some literature, this is referred to Mullaperiyar.

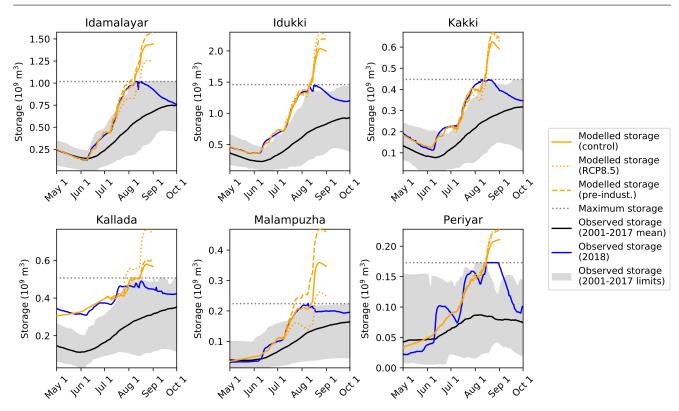


Fig. 7: Comparison of modelled (orange) and observed storage rates for 2018 with the 2001-2017 climatology (mean in black, with grey swath denoting extrema) for six major reservoirs. Storage at maximum capacity for each is given by the dotted grey line. The three modelled storage values are given by solid, dashed, and dotted lines for the control, pre-industrial, and RCP8.5 experiments respectively.

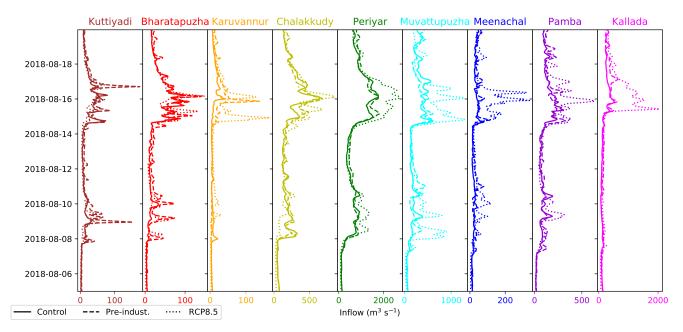


Fig. 8: Sum of model inflow to all reservoirs (see Fig. 2) separated by river basin. Basins are organised by latitude, with the northernmost being shown at the left hand side. Solid, dashed, and dotted lines represent the control, pre-industrial, and RCP8.5 experiments respectively.

in CMIP5 projections (Sharmila et al, 2015). This has a
profound implication: the southern part of Kerala did
not flood in 2018 (Mishra and Shah, 2018), but the
results here suggest that it almost certainly would do
were such an event to happen again in an end-of-century
RCP8.5 climate.

#### 672 4 Discussion

2018,During mid-August unprecedented and 673 widespread flooding resulted in the deaths of over 674 400 people and the displacement of over a million more 675 in the Indian state of Kerala. The flooding was pre-676 ceded by several weeks of heavy rainfall over the state, 677 caused mostly due a monsoon depression (13-17 Aug) 678 that immediately followed a monsoon low-pressure 679 system (6-9 Aug). In this manuscript, we explored the 680 underlying causes and hydrological responses, as well 681 as how they would differ under alternative climate 682 scenarios. To achieve this, we used a two-domain 683 setup in the Weather Research and Forecasting Model 684 (WRF) with the outer domain (20 km resolution) 685 covering most of the Indian peninsula and the nested 686 inner domain (4 km resolution, explicit convection) 687 covering its southwest, including the entire state of 688 Kerala and a significant portion of the Arabian Sea. 689 Alongside this, we used the companion hydrological 690 model (WRF-Hydro) at 125 m resolution to simulate 691 river channel response to the varying precipitation 692 forcings. The 'alternative' climates (pre-industrial and 693 RCP8.5) were simulated by perturbing the model 694 initial and lateral boundary conditions by their pro-695 jected difference from the present day, computed using 696 CMIP5 multi-model output. 697

We found that the simulated rainfall from the con-698 trol experiment, concentrated over the Western Ghats, 699 closely matched observations for that period. The rain-700 fall over this period was higher in both the perturbation 701 experiments: by about 36% over the inner domain in 702 the RCP8.5 experiment and by about 18% in the pre-703 industrial. We attributed these changes to two trends 704 that previous studies have established as effects of cli-705 mate change: the weakening of synoptic activity within 706 the Indian monsoon and the moistening of the trop-707 ical troposphere. We found that the former was the 708 dominant driver of moisture flux change between the 709 pre-industrial and the present day (hence lower rainfall 710 in the control than in the pre-industrial experiment), 711 whereas the latter was the strongest driver of change be-712 tween the present-day and RCP8.5. Given this trade-off 713 714 between competing factors, we cannot safely infer how the rainfall associated with this event would change in 715

other future climates (e.g. RCP4.5, RCP6.0), and so we leave this task for future work. 717

Using a high-resolution setup of WRF-Hydro, we 718 showed that the change in domain mean rainfall pro-719 jected onto approximately equivalent changes in mean 720 river streamflow, though as expected there was sub-721 stantial spatial and temporal variance: for example, the 722 90th percentile streamflow over the domain increased 723 by 97% in the RCP8.5 experiment compared to the 724 control. Because the India Water Resource Information 725 Service (India-WRIS) only make certain data publically 726 available (only storage data, and only for six of the 727 largest reservoirs), we used a simple model to convert 728 modelled inflow into reservoir storage to verify our hy-729 drological model. For four of the six reservoirs, before 730 reaching their full reservoir level (FRL), the Pearson 731 correlation coefficient between the observed and mod-732 elled storage exceeded 0.99 with the remaining two both 733 exceeding 0.9. Furthermore, inflow values for several 734 reservoirs in the days preceding the flood published in 735 a report by the Central Water Commission agree closely 736 with the model output, confirming the efficacy of the 737 hydrological model. 738

By comparing the modelled storage, which is not 739 affected by FRL, with the observed storage, which is, 740 we were able to calculate the surplus water for each of 741 the six main reservoirs. On average, over the four reser-742 voirs that most closely represented the rainfall trends, 743 34% more capacity would have been required to han-744 dle all the excess precipitation that fell during August 745 2018; rising to 43% in the pre-industrial and 54% in 746 RCP8.5. It is clear, therefore, that no matter what ap-747 proach was taken to opening the dams, the catastrophe 748 was inevitable; furthermore the results presented here 749 suggest that they would be significantly more devas-750 tating in an end-of-century RCP8.5 climate. Analysis 751 of river streamflow at all 62 dams in the state showed 752 that climate change would have the strongest impact in 753 the south of the state: mean inflow for Aug 14 to Aug 754 19 increased 25% between the control and RCP8.5 ex-755 periments in the three northernmost river basins, rising 756 to 98% in the three southernmost basins. 757

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