Using precipitation sensitivity to temperature to adjust projected global runoff

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Abstract
Climate change affects the water cycle. Despite the improved accuracy of simulations of historical temperature, precipitation and runoff in the latest Coupled Model Intercomparison Project Phase 6 (CMIP6), the uncertainty of the future sensitivity of global runoff to temperature remains large. Here, we identify a statistical relationship at the global scale between the sensitivity of precipitation to temperature change (1979–2014) and the sensitivity of runoff to temperature change (2015–2100). We use this relation to constrain future runoff sensitivity estimates. Our statistical relationship only slightly reduces the uncertainty range of future runoff sensitivities (order 10% reduction). However, more importantly, it raises the expected global runoff sensitivity to background global warming by 36%–104% compared to estimates taken directly from the CMIP6 model ensemble. The constrained sensitivities also indicate a shift towards globally more wet conditions and less dry conditions.

1. Introduction
Land surface runoff is changing with the global climate warming (Labat et al 2004, Chai et al 2020). These runoff changes can affect water availability for irrigation, hydropower generation, vegetation growth, industry and drinking water, especially in arid and semi-arid regions (Sorg et al 2012). Thus, it is important to provide an accurate estimate of the feedback of future global runoff to rising temperatures. Such knowledge would not only help to better understand the effects of climate change on the terrestrial-water cycle, but could also assist in creating effective decision-making tools for water resources management and environmental protection (Rothausen et al 2011).

There are however large uncertainties in the future effects of climate on global runoff, largely caused by poor simulation of rainfall and the inaccurate representations of the soil-plant-atmosphere system and human impacts (e.g. dams’ operation and irrigation) in current earth system models (ESMs) (Du et al 2016). Such uncertainties are sometimes to the extent that even the sign of the runoff change is unknown (Gedney et al 2006, Piao et al 2007, Shi et al 2011). Considering the models included in the 5th generation Climate Model Intercomparison Project (CMIP5) (Taylor et al 2012), the spread of global runoff across these models was rather large, as described in reports of the International Panel on Climate Change and several other studies (Alkama et al 2013, IPCC 2014, Zhang et al 2014, Yang et al 2019). Compared to CMIP 5, the latest generation of ESMs (Coupled Model Intercomparison Project Phase 6 (CMIP6)) have a higher vertical and horizontal spatial and include more comprehensive numerical experimental designs and more detailed processes descriptions. (Meehl et al 2014, Hall et al 2019). Yet, the latest generation of ESMs (CMIP6) is still expected to have significant
uncertainty in projecting the response of global runoff to a warming climate (Tokarska et al. 2020, Wang et al. 2020), largely caused by oversimplified land-vegetation-atmosphere interactions.

Bias correction methods have been developed to downscale the predicted future climate changes (e.g. future runoff changes) based on correction factors that are obtained from statistical differences between historical simulations and observations (Chen et al. 2011, Johnson et al. 2011). The values of these correction factors are assumed to persist into the future, and thereby can be applied to correct future projections (González-Zeas et al. 2012). This correction procedure has some shortcomings as, for example, a statistical bias correction can lead to physical inconsistencies of climate variables. For instance, after application of bias corrections the temperature might be sub-zero, whereas rainfall is not converted into snowfall (Hempel et al. 2013).

In this study, we try to build a statistical relationship between current climate (variable X) and the projected future changes [i.e. future runoff sensitivities (ΔR/ΔT)] across a range of CMIP6/CMIP5 models, which may enable us to narrow the large spread of ΔR/ΔT derived from CMIP6 and CMIP5 simulations (Zhang et al. 2014). A key challenge in introducing the relationship is the identification of a factor (i.e. variable X) that dominates the uncertainties in the target variable, in our case global ΔR/ΔT, and thereby constraining projections of the future climate. In addition, this empirical relationship would need to be grounded in a physical mechanism we understand, which is more physically-based than bias correction methods that apply a simple transformation to the data. However, finding such a climate factor can be difficult, because runoff changes in response to warming are affected by many interrelated processes, including atmosphere, soil, and vegetation dynamics (Piao et al. 2007).

First, we evaluate the performance of the 21 CMIP6 models’ simulations of the historical climate by comparing them with both observations and CMIP5 simulations of temperature, precipitation and runoff for the period 1979–2014 (see details in SI 1 (available online at stacks.iop.org/ERL/16/124032/mmedia)). Subsequently, we assess the uncertainties in future ΔR/ΔT during 2015–2100 both for CMIP6 models (under climate scenarios SSP126, SSP245, SSP370 and SSP585 (O’Neill et al. 2016)) and for CMIP5 models (under climate scenarios RCP26, RCP45, RCP60 and RCP85 (Taylor et al. 2012)). We use the simulations of precipitation, evaporation, snow melt and soil water content from these ESM ensembles to infer a main cause of the trends in future ΔR/ΔT. Identifying such a climate factor would enable to introduce a constrained relationship reduces the uncertainties of estimated ΔR/ΔT, under the condition that we find a strong relationship between historical climate changes of the identified variable and future ΔR/ΔT. The analysis concerns annual runoff and is performed at the global level.

2. Performance of CMIP6 models

2.1. Temperature simulations

The latest generation of CMIP6 models reproduce historical temperatures at both the regional and the global scale better compared to the CMIP5 models (figures 1(a), (b) and S1). CMIP6’s performance is relatively low in some mountainous regions (e.g. the Himalayas and Andes) and high latitude regions such as eastern Greenland and eastern Siberia (figure 1(b)). However, also in these regions the performance of the CMIP6 models is higher compared to the CMIP5 models (figure S1). Similar to the previous-generations of ESM ensembles (Rogelj et al. 2012, Keenan et al. 2018), the CMIP6 simulations project widespread warming under various emission scenarios whereby temperatures are rising throughout the 21st century (figures 1(a) and S2).

The highest rates of surface warming are expected at high latitudes, due to polar amplification (Stuecker et al. 2018, Biskaborn et al. 2019). Up to the year 2050, the global warming trends are largely similar across the four emission scenarios (SSP126, SSP245, SSP370 and SSP585), while after 2050 the projected temperatures diverge more clearly between the emission scenarios (figure 1(a)). This divergence is caused by substantially lower CO₂ emissions after 2050 under SSP126 and SSP245 compared to SSP370 and SSP585 (Gidden et al. 2019). Between the periods 2015–2024 and 2091–2100, the global land surface temperature is estimated to increase by 1.11 ± 0.52 °C (i.e. mean ± standard deviation) under SSP126, up to 5.61 ± 1.08 °C under SSP585 (figure 1(a)). These reported temperature increases are comparable with those in other studies that also use CMIP6 but with slightly different ensembles (Cook et al. 2020, Fan et al. 2020, Tokarska et al. 2020).

2.2. Precipitation simulations

Besides surface temperatures, the CMIP6 models also show higher performance in simulating historical precipitation, compared to the CMIP5 models. Noticeable improvements include the reduced underestimation of precipitation in southeastern China, India and South America (figures 1(c), (d) and S3). However, most CMIP6 models still considerably overestimate global precipitation, whereby overestimations appear especially strong in mountainous regions (e.g. the Himalayas and Andes), but to a lesser extent than the CMIP5 projections (figures 1(d) and S3). Future global precipitation is predicted to increase, especially in mountainous regions, in major monsoon regions, and at high latitudes (figure S4). Both these regional and global increases in precipitation are consistent with projections of CMIP5 models (IPCC 2014). The CMIP6
models project that precipitation will decline mainly in large parts of South America, the Mediterranean, Southern Africa and Oceania, which is also largely consistent with CMIP5. By the end of the 21st century (2091–2100), global precipitation is projected to increase by 0.063 ± 0.023 mm d\(^{-1}\) (SSP126) up to 0.197 ± 0.065 mm d\(^{-1}\) (SSP585) compared to 2015–2024.

### 2.3. Land surface runoff simulations

The CMIP6 historical runoff simulations (figure 1(f)) are significantly lower compared to the observation-based Global Composite Runoff Fields from the Global Runoff Data Centre (figure S5) (Fekete et al 2002), but the underestimation of the global runoff is smaller than for CMIP5 (figure S6). Models that are unable to reproduce past climate variations may have biases in their future climate predictions (Klein et al 2015). Therefore, the underestimation of historical runoff is likely to lead to an underestimation of projections of future runoff. Underestimations of historical runoff are mainly found in humid regions, including eastern North America, Europe, Southeast Asia, Central Africa, and Indonesia. Such biases in modeled global runoff have also been reported in CMIP5 and are likely largely the result of poor descriptions of precipitation, the soil-plant-atmosphere system and human impacts (e.g. dams’ operation and irrigation) (Du et al 2016, Lehner et al 2019). Global runoff is generally projected to increase marginally, but consistently over the 21st century (figure 1(e)). The estimated increase in global runoff for the period of 2091–2100 compared to 2015–2024 ranges from 0.009 ± 0.009 mm d\(^{-1}\) (SSP126) up to 0.035 ± 0.032 mm d\(^{-1}\) (SSP370), which equates to roughly a 2.25 ± 1.88% to 10.24 ± 10.91% increase. Especially East Asia, Central Africa and high northern latitudes show strong increases in surface runoff over the 21st century (figure S7), which is consistent with the projected precipitation increases in these same regions (figure S4). Highly consistent spatial distributions between future changes in precipitation...
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Estimates of global $\Delta P/\Delta T$ (mm d$^{-1}$ °C$^{-1}$) and global $\Delta R/\Delta T$ (mm d$^{-1}$ °C$^{-1}$). Panel (a) shows the linear regression relations between annual average daily precipitation and annual average temperature based on CMIP6 outputs for the historical period of 1979–2014 ($P = 0.0482$ T, $r = 0.93$, p value < 0.001), and for the future period of 2015–2100 under SSP126 ($P = 0.0528$ T, $r = 0.88$, p value < 0.001), SSP245 ($P = 0.0393$ T, $r = 0.96$, p value < 0.001), SSP370 ($P = 0.0343$ T, $r = 0.99$, p value < 0.001), and SSP585 ($P = 0.0343$ T, $r = 0.99$, p value < 0.001). Panel (b) shows the trends in the observed precipitation and temperature during 1979–2014 using HadCRUT5 data set and CRU TS Version 4.04 data set, respectively. Panel (c) shows the observed $\Delta P/\Delta T$ during 1979–2014 using HadCRUT5—CRU TS Version 4.04 data sets ($P = 0.0557$ T, $r = 0.51$, p value < 0.001), HadCRUT5—GPCC data sets ($P = 0.0612$ T, $r = 0.55$, p value < 0.001) and GISS—GPCC data sets ($P = 0.0609$ T, $r = 0.56$, p value < 0.001). Panel (d) shows the linear regression relations between runoff and temperature based on CMIP6 outputs for the historical period of 1979–2014 ($R = 0.0142$ T, $r = 0.85$, p value < 0.001), and for the future period of 2015–2100 under SSP126 ($R = 0.0085$ T, $r = 0.64$, p value < 0.001), SSP245 ($R = 0.0072$ T, $r = 0.88$, p value < 0.001), SSP370 ($R = 0.0084$ T, $r = 0.95$, p value < 0.001) and SSP585 ($R = 0.0060$ T, $r = 0.95$, p value < 0.001). Panels (e) and (f) show the spread of $\Delta R/\Delta T$ across CMIP6 models and across CMIP5 models, respectively.

and runoff may imply a strong constraint of precipitation on runoff. Future land surface runoff is projected to decrease across large parts of Europe, central North America, Southern Africa, and the Amazon basin. Nevertheless, there is a wide range in these predictions, comparable in magnitude to the mean.

3. Climate sensitivities

3.1. Global precipitation sensitivity to temperature

CMIP6 models indicate that Earth’s warming climate increases global precipitation (figures 1(a) and (c)). The atmosphere can be expected to reduce its radiative energy under climate warming, which would result in increased longwave emission due to higher temperatures (Previdi et al 2010). To obey the conservation of energy, atmospheric latent heating would increase as an important compensating process, which in turn would increase global precipitation (Liepert et al 2009). Because of these basic physical mechanisms, we hypothesize that a strong relationship between global precipitation and global land surface temperature will exist. We indeed find a strong linear relationship between precipitation and land surface temperature anomalies ($\Delta P/\Delta T$, mm d$^{-1}$ °C$^{-1}$), both for the historical simulations ($r = 0.95$, p value < 0.001) as well as the future projections ($r \geq 0.98$, p value < 0.001) (figures 2(a) and S8). The historical observations also have trends in global precipitation and temperature that are synchronously rising (figure 2(b)). Linear estimates of $\Delta P/\Delta T$ using CMIP6, whether derived from the historical simulations (0.0482 mm d$^{-1}$ °C$^{-1}$, figure 2(a)) or derived from the future projections (0.0343–0.0528 mm d$^{-1}$ °C$^{-1}$) are considerably lower.
than to the linear estimates of \( \Delta P/\Delta T \) derived from the three observational data sets (0.0557–0.0612 mm d\(^{-1}\) °C\(^{-1}\), figure 2(c)). These results suggest that the \( \Delta P/\Delta T \) is underestimated in both the historical and future projections of the CMIP6 models. Precipitation increases are expected to contribute to the increase of land surface runoff (e.g. Labat et al. 2004). Therefore, the likely underestimation of \( \Delta P/\Delta T \) in the CMIP6 simulations may also result in the underestimation of \( \Delta R/\Delta T \). This potential underestimation of \( \Delta R/\Delta T \) is also expected to be present in CMIP5 models, because these previous generation models yield even lower \( \Delta P/\Delta T \) estimates (0.0312–0.0550 mm d\(^{-1}\) °C\(^{-1}\), figure S8) compared to CMIP6.

### 3.2. Global runoff sensitivities and their uncertainties

Similar to the above-reported sensitivities of precipitation to temperature changes, we also find a clear sensitivity of global runoff to temperature (\( \Delta R/\Delta T \), mm d\(^{-1}\) °C\(^{-1}\)). This relation is expected as runoff tends to vary systematically with precipitation amounts. CMIP6 outputs exhibit a significant linear relationship between runoff and temperature (figure 2(d)), both in the historical simulations (\( r = 0.85, p \text{ value } < 0.001 \)) as well as in the future projections (\( r = 0.65–0.95, p \text{ values } < 0.001 \)), which corroborates the existence of a distinct global \( \Delta R/\Delta T \). Positive relationships between runoff and temperature also exist in CMIP5 models (\( r = 0.29–0.92, p \text{ values } < 0.001 \); figure S9). Using a similar approach as for the CMIP6 multi-model mean in figure 2(d), we derived an estimate of future global \( \Delta R/\Delta T \) for each individual model (figure 2(e)). As expected, estimated \( \Delta R/\Delta T \) relationships show considerable variation across the CMIP6 models, to the extent that both positive and negative sensitivities are estimated for a single emission scenario (figure 2(e)). A wide range of \( \Delta R/\Delta T \) relationships are also visible in all RCP scenarios for the 5th generation of CMIP models (figure 2(f)), but with narrower ranges than CMIP6 (possibly due to smaller climate sensitivity (\( \Delta T/\Delta CO_2 \)) in CMIP5 than in CMIP6). It should be noted that across all four emission scenarios the means of estimated \( \Delta R/\Delta T \) in CMIP6 (0.005–0.011 mm d\(^{-1}\) °C\(^{-1}\)) are higher than those of CMIP5 (–0.001 to 0.004 mm d\(^{-1}\) °C\(^{-1}\)). This again suggests that in general, the CMIP6 generation models show a smaller underestimation of runoff sensitivity to temperature compared to CMIP5.

### 4. Constrained relationships

#### 4.1. Physical mechanisms

Identifying a dominant climatic factor that drives future runoff changes and its uncertainties is key for increasing the confidence and understanding of the constrained relationships. Once this climatic factor is identified, we can use observations of this climate factor to reduce the uncertainties in estimated \( \Delta R/\Delta T \). This is done by combing the empirical relationship between current variability in this climatic factor and the future \( \Delta R/\Delta T \) (see SI 2.1 and 2.2 for details). The water balance dictates that long-term changes in runoff depend on changes in precipitation, snow melt, soil water storage and total evaporation (Lutz et al. 2014, Schoener et al. 2019). The last term, evaporation, is not only driven by near-surface atmospheric conditions, but is also strongly modulated by physiological and structural components of the vegetation (Gedney et al. 2006, Piao et al. 2007). Such complex interacting mechanisms that can affect land surface runoff, might make it difficult to distinguish a single main driving factor.

Through examining the runoff–precipitation relations, we found a strong linear relationship between them in almost all the models under all the four Shared Socio-economic Pathways (SSPs) (SI 3.1 for details). This tight relationship across most of the global land surface indicates a strong constraint of precipitation on runoff changes. By using the multiple regression technique (see method in SI 2.5 for details), we explored the relative contributions of the potential driving factors (i.e. precipitation, soil water, total evaporation and snow melting runoff) on the future global runoff changes. The results (see SI 3.2 for details) indicate that precipitation dominates the future global runoff changes (contributing by 54.0%–79.4%), while soil water content (5.2%–16.05%), total evaporation (3.65%–38.8%) and snow melting runoff (0.11%–10.14%) only contribute marginally. This is consistent with previous studies that also highlight a dominant role of precipitation in affecting runoff changes (Labat et al. 2004, Gerten et al. 2008, Li et al. 2020).

Through a simple linear regression analysis method, we further explored the factors contributing to inter-model spread in estimated \( \Delta R/\Delta T \) values. Such an approach has been earlier applied to investigate the main drivers behind the changes in seasonal sea-ice albedo feedback (Thackeray et al. 2019). The correlation coefficients of the linear relationships between future global runoff changes and its potential main driving variables (figures S14 and S15(a)) show that both precipitation and total evaporation exhibit a strong positive relationship with future runoff changes (0.64 ≤ \( r \) ≤ 0.9, \( p \) values < 0.001). On the contrary, changes in snow melt and soil water storage appear less important as they show much weaker relationships with changes in global runoff (0.04 ≤ \( r \) ≤ 0.34, \( p \) values > 0.1) (figure S15(a)). Spatially and temporally varying land surface conditions can make the drivers of regional runoff changes more complex, but on global scale, the effects of precipitation and total evaporation change appear far greater than the other factors. We note that increasing surface air temperatures can be expected to result in a
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\[ Y_{\text{Chai}} \leq \theta - (\text{SSP370}) \text{ or SSP126 are 0.005 mm d}^{-1} \text{ across SSP126 up to 0.0075 mm d}^{-1} \text{ before and after constraint} \]

\[ \text{Mean} (\text{gray shading) and r} \Delta T \text{ during 1979–2014 (see bottom \( \Delta \) and p increases for 0.0082 mm d}^{-1} \text{ 3 \pm 0.0016 mm d}^{-1} \text{ C}^{-1}) \text{. The green shading is the 90\% prediction error of the linear fitting; the black line and blue line are the probability density functions (PDFs, see top x-axis and left y-axis) for the future global } \Delta R/\Delta T \text{ before and after constraint (see SI 2.3 for more details); The horizontal gray shading and the blue shading are the future global } \Delta R/\Delta T \text{ before and after constraint [Mean \pm one standard deviation (SD)]}. \]

\[ \text{Note: the uncontrained and constrained } \Delta R/\Delta T \text{ under SSP126 are } 0.005 \pm 0.0082 \text{ mm d}^{-1} \text{ C}^{-1} \text{ (gray shading) and 0.0012 \pm 0.0075 \text{ mm d}^{-1} \text{ C}^{-1} \text{ (blue shading), respectively.} \]

Figure 3. Constraint on the future global } \Delta R/\Delta T \text{. This figure shows the constrained relationship for the outputs from CMIP6 models under SSP126. Note: red line is the linear relationship between ‘the future global } \Delta R/\Delta T \text{ during 2015–2100 (see left y-axis)’ and ‘the historical global } \Delta P/\Delta T \text{ during 1979–2014 (see bottom x-axis)’; yellow shading is the observational } \Delta P/\Delta T \text{ from the HadCRUT3–CRU TS Version 4.04 data sets (0.005 \pm 0.016 mm d}^{-1} \text{ C}^{-1}). \]

\[ \text{The green shading is the 90\% prediction interval; the black line and blue line are the probability density functions (PDFs, see top x-axis and left y-axis) for the future global } \Delta R/\Delta T \text{ before and after constraint (see SI 2.3 for more details); The horizontal gray shading and the blue shading are the future global } \Delta R/\Delta T \text{ before and after constraint [Mean \pm one standard deviation (SD)]. Note: the uncontrained and constrained } \Delta R/\Delta T \text{ under SSP126 are } 0.005 \pm 0.0082 \text{ mm d}^{-1} \text{ C}^{-1} \text{ (gray shading) and 0.0012 \pm 0.0075 \text{ mm d}^{-1} \text{ C}^{-1} \text{ (blue shading), respectively.} \]

widespread increase in evaporation, which should logically result in a decline of global runoff. However, the future global runoff is predicted to increase in both the CMIP6 and the CMIP5 models. Therefore, we identify precipitation as the dominant climatic factor affecting changes in runoff that can be used for constraining future } \Delta R/\Delta T \text{. This constrained relation still holds in the observations of 120 larger rivers as there are significant relations between the observed precipitation and runoff } (r > 0.5 \text{ at 68}\% \text{ of the rivers, figure S15(b)), even though these rivers are strongly affected by damming and other human influences (Nilsson et al 2005). Strong linear relationships between } \Delta P/\Delta T \text{ and } \Delta R/\Delta T \text{ (figure S16) further indicate that the higher the } \Delta P/\Delta T \text{ projected by a CMIP6 model, the higher the } \Delta R/\Delta T \text{ that is derived from the same model, leading to a wide range of runoff sensitivities across models (See SI 3.3 for details). Because changes in precipitation drive runoff changes, and are therefore similar in spatial and temporal character, we expect that we can constrain the uncertainties in future } \Delta R/\Delta T \text{ using the historical } \Delta P/\Delta T \text{ that we defined above (figure 2(a)).} \]

4.2. Constrained runoff sensitivity

Despite the relatively large variations in estimates of historical } \Delta P/\Delta T \text{ and future } \Delta R/\Delta T \text{ across CMIP6 models (figure 2(e)), we still identify strong linear relationships between them across all emission scenarios } (0.67 \leq r \leq 0.71, p \text{ values } < 0.001, \text{ figure 3 for SSP126, and figure S17 for SSP245, SSP370 and SSP585}). \text{ Even after excluding regions with negative correlation coefficients between runoff and precipitation, we find that the constrained relationships remained, for almost all four SSPs (see SI 3.4 for details), proving that the influence of such regions on the area-averaged constrained relationship is relatively small. By using the observational } \Delta P/\Delta T \text{ from the HadCRUT3 dataset (yellow shading in figure 3), we find that most of the CMIP6 climate models lie outside the nominal uncertainty bounds of the observational estimates. This may seem unexpected, but it has been shown that most models do indeed show a systematic bias in their predictions (Klein and Hall 2015). This indicates that combining the empirical relationships of historical } \Delta P/\Delta T \text{ and future } \Delta R/\Delta T \text{, we can constrain future } \Delta R/\Delta T \text{ by projecting the observed } \Delta P/\Delta T \text{ onto the vertical axis (figure 3).} \]

The constrained future } \Delta R/\Delta T \text{ increases for all emission scenarios (blue line in figures 3 and S17) compared to the original CMIP6 outputs (black line). The original } \Delta R/\Delta T \text{ ranges from 0.005 \pm 0.0082 mm d}^{-1} \text{ C}^{-1} \text{ (SSP126) up to 0.009 \pm 0.0092 mm d}^{-1} \text{ C}^{-1} \text{ (SSP370) (table S9), whereas the constrained estimates range from 0.0102 \pm 0.0075 mm d}^{-1} \text{ C}^{-1} \text{ (SSP126) up to 0.0122 \pm 0.0081 mm d}^{-1} \text{ C}^{-1} \text{ (SSP370). This increase indicates that the future } \Delta R/\Delta T \text{ has been underestimated in the multi-model means by 36\%–104\% (0.0032–0.052 mm d}^{-1} \text{ C}^{-1}). \text{ Such a significant range in underestimation by the CMIP6 original outputs is also present when using the constrained relationship with the other two observational data sets, where } \Delta R/\Delta T \text{ is}
underestimated by 0.0043–0.0065 mm d\(^{-1}\) °C\(^{-1}\) (figure S19 and table S9). Furthermore, the constrained probability density function (PDF) of runoff sensitivity narrows compared to the unconstrained PDFs for all the emission scenarios, which indicates that the inter-model spread in the future \(\Delta R/\Delta T\) successfully reduced after the constraint. The percentages of the reduced uncertainties are 8.5%, 7.2%, 12.0% and 10.0% for the emission scenarios from SSP126 to SSP585 respectively. Similar strong empirical relationships between historical \(\Delta P/\Delta T\) and future \(\Delta R/\Delta T\) also exist among CMIP5 models under RCP26, RCP45, RCP60 and RCP85 (0.34 \(< r \leq 0.71, p\) value < 0.05, figure S20), which again increases the estimates of future \(\Delta R/\Delta T\) after applying the constraint. These results consistently show that our introduced constrained relationship is valid and can be applied to constrain the models.

By multiplying the future increased multi-model mean temperature (\(\Delta T\)) by the constrained future \(\Delta R/\Delta T\), we estimate the constrained future runoff changes in 2091–2100 relative to 2015–2024. Future runoff increases estimated using the constrain range from 0.0111 ± 0.0088 mm d\(^{-1}\) (SSP126) up to 0.0656 ± 0.0504 mm d\(^{-1}\) (SSP585), which is much larger than those of the original future runoff from CMIP6 models which range from 0.009 ± 0.009 mm d\(^{-1}\) (SSP126) up to 0.032 ± 0.039 mm d\(^{-1}\) (SSP585) (table S9).

4.3. Implications of the shift in runoff sensitivity to temperature

The shift in PDFs of runoff sensitivity indicate that the probabilities of very low runoff sensitivities are smaller than in the original CMIP6 outputs (figures 3, S17 and table S10). The constrained sensitivities indicate that it is likely that runoff sensitivities are higher than is presently observed in the CMIP6 model outputs. This suggests that globally, a higher runoff can be expected with increasing surface temperatures in the future. In addition, the future annual \(\Delta P/\Delta T\) exhibit a strong positive linear relationship with the future \(\Delta R/\Delta T\) for each emissions scenario (figure S21). This positive relationship, combined with the constrained future \(\Delta R/\Delta T\), will shift the \(\Delta P/\Delta T\) to a higher value compared to the unconstrained future \(\Delta R/\Delta T\). Both results suggest that there may be an underestimation of \(\Delta P/\Delta T\) in the CMIP6 model projections. This again suggests that the Earth’s land surface may experience more extreme wet conditions in the future compared to what can be expected from the original CMIP6 projections. In fact, the constrained sensitivities suggest that a change to a wetter Earth, with more precipitation and runoff globally, is more likely that previously thought.

The expectation of more extreme wet conditions but fewer dry conditions is supported by investigating the relationships between the future \(\Delta P/\Delta T\) and the future yearly changes in both global average annual light and heavy rain days (see SI 2.4). We find negative relations which indicate that a model with a higher \(\Delta P/\Delta T\) has a fewer global average annual light rainfall days (figure S22). Thus, a potential underestimated \(\Delta P/\Delta T\) (figure S21) is shown by an overestimated frequency in future global average light rain days. In contrast, future yearly increases in global average annual heavy days exhibit a positive relationship with \(\Delta P/\Delta T\) (figure S23). An underestimated \(\Delta P/\Delta T\) moves the future yearly increases in global average annual heavy days to a larger value by combining this positive relationship. Using the constrained future \(\Delta R/\Delta T\) from the two other observed data sets (table S9), we still reach the conclusion that the future increases in global average light rainfall frequency has been overestimated by the CMIP6 models outputs, while that for the global average heavy rainfall frequency has been underestimated.

5. Conclusions

In this study, we find a strong physically-explainable empirical linear relationship between the inter-model spread in the historical global \(\Delta P/\Delta T\) and the inter-model spread in the future global \(\Delta R/\Delta T\), both for CMIP6 and CMIP5 model ensembles. This relationship suggests that most of the current ESMs underestimate \(\Delta P/\Delta T\) in comparison with the observations, indicating that the processes included in the ESMs related to this underestimated sensitivity require careful examination and further development. This may not necessarily be focused towards improving land surface schemes to improve runoff estimates. Instead, further work on ESMs could improve how precipitation responds to warming. Our analysis has not allowed us to narrow substantially the spread in future runoff sensitivities estimates from models. However, of particular importance is that although we only lower slightly the range of uncertainty, our constraint analysis does place the range of values to be higher than those estimated directly from both the original CMIP6 and CMIP5 outputs. This implies that the land water cycle may be accelerating faster than suggested by the models’ initial projections. The constrained estimates also suggest that future global climate will be more wet, with higher precipitation and runoff, compared with the original CMIP6 projections, which agrees with a recent study (Cui et al 2021). These implications for climates extremes are also supported by the CMIP6’s overestimated future increases in global average annual light rainfall days and CMIP6’s underestimated future increases in global average annual heavy rainfall days. We note that this result applies at the averaged global scale and is not necessarily opposed to the ‘dry regions get drier; wet regions get wetter’ paradigm that applies to the changes in the regional water cycle. Regional or continental scale feedbacks may still enhance the dryness in dry parts.
of the globe. However, at the global scale the increased moisture holding capacity of the atmosphere leads to an accelerated hydrological cycle in which the Earth system overall is shifting towards a wetter state of the climate.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://esgf-node.llnl.gov/projects/cmip6/.

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References

Alkama R, Marchand L, Ribes A and Decharme B 2013 Detection of global runoff changes: results from observations and CMIP5 experiments Hydrolog. Earth Syst. Sci. 17 2967
Biskaborn B K et al 2019 Permafrost is warming at a global scale Nat. Commun. 10 1–11
Chai Y, Yue Y, Zhang L, Miao C, Borthwick A G L, Zhu B, Li Y and Dolman A J 2020 Homogenization and polarization of the seasonal water discharge of global rivers in response to climatic and anthropogenic effects Sci. Total Environ. 709 136062
Chen J, Brissette F P and Leconte R 2011 Uncertainty of downsampling method in quantifying the impact of climate change on hydrology J. Hydrool. 401 190–202
Cook B L, Mankin J S, Marvel K, Williams A P, Smerdon J E and Anchukaitis K J 2020 Twenty-first century drought projections in the CMIP6 forcing scenarios Earth’s Future 8 e2019EF001461
Cui J, Yang H, Huntingford C, Kooperman G J, Lian X, He M and Piao S 2021 Vegetation response to rising CO2 amplifies contrasts in water resources between global wet and dry land areas Geophys. Res. Lett. 48 e2021GL094293
Du E, Di Vittorio A and Collins W D 2016 Evaluation of hydrologic components of community land model 4 and bias identification Int. J. Appl. Earth Obs. Geoinf. 48 5–16
Fan X, Duan Q, Shen C, Wu Y and Xing C 2020 Global surface air temperatures in CMIP6: historical performance and future changes Environ. Res. Lett. 15 104056
Fekete B M, Vörösmarty C J and Grabs W 2002 High-resolution fields of global runoff combining observed river discharge and simulated water balances Glob. Biogeochem. Cycle 16 1–15
Gedney N, Cox P M, Betts R A, Boucher O, Huntingford C and Stott P A 2006 Detection of a direct carbon dioxide effect in continental river runoff records Nature 439 835–8
Gerten D, Rost S, Von Bloh W and Lucht W 2008 Causes of change in 20th century global river discharge Geophys. Res. Lett. 35 L20405
Gidden M J et al 2019 Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century Geosci. Model Dev. 12 1443–75
González-Zeas D, Garrote L, Iglesias A and Sordo-Ward A 2012 Improving runoff estimates from regional climate models: a performance analysis in Spain Hydrolog. Earth Syst. Sci. 16 1709–23
Hall A, Cox P, Huntingford C and Klein S 2019 Progressing emergent constraints on future climate change Nat. Clim. Change 9 269–78
Hempel S, Frieler K, Warszawski L, Schewe J and Piontek F 2013 A trend-preserving bias correction-the ISI-MIP approach Earth Syst. Dyn. 4 219–36
IPCC 2014 Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed Core Writing Team, R K Pachauri and L A Meyer (Geneva: IPCC)
Johnson F and Sharma A 2011 Accounting for interannual variability: a comparison of options for water resources climate change impact assessments Water. Resour. Res. 47 W104508
Koenan T F and Riley W J 2018 Greening of the land surface in the world’s cold regions consistent with recent warming Nat. Clim. Change 8 825–8
Klein S A and Hall A 2015 Emergent constraints for cloud feedbacks Carr. Clim. Change Rep. 1 276–87
Labat D, Goddérès Y, Probst J L and Guyot J L 2004 Evidence for global runoff increase related to climate warming Adv. Water Resour. 27 631–42
Lehner F, Wood A W, Vano J A, Lawrence D M, Clark M P and Mankin J S 2019 The potential to reduce uncertainty in regional runoff projections from climate models Nat. Clim. Change 9 926–33
Li L et al 2020 Global trends in water and sediment fluxes of the world’s large rivers Sci. Bull. 65 62–69
Liepert B G and Previdi M 2009 Do models and observations disagree on the rainfall response to global warming? J. Clim. 22 3156–66
Lutz A F, Immerzeel W W, Shrestha A B and Bierkens M F P 2008 Consistent increase in High Asia’s runoff due to increasing glacier melt and precipitation Nat. Clim. Change 4 587–92
Meehl G A, Moss K, Taylor K E, Eyring V, Stouffer R J, Bony S and Stevens B 2014 Climate model intercomparisons: preparing for the next phase EOS Trans. Am. Geophys. Union 95 77–78
Nilsson C, Reidy C A, Dynesius M and Revenga C 2005 Fragmentation and flow regulation of the world’s large river systems Science 308 405–8
O’Neill B C et al 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 Geosci. Model Dev. 9 3461–82
Piao S, Friedlingstein P, Ciais P, de Noblet-ducoudré N, Labat D and Zaehe S 2007 Changes in climate and land use have a
larger direct impact than rising CO$_2$ on global river runoff trends Proc. Natl Acad. Sci. USA 104 15242–7
Previdi M 2010 Radiative feedbacks on global precipitation Environ. Res. Lett. 5 025211
Rogelj J, Meinshausen M and Knutti R 2012 Global warming under old and new scenarios using IPCC climate sensitivity range estimates Nat. Clim. Change 2 248–53
Rothausen S G and Conway D 2011 Greenhouse-gas emissions from energy use in the water sector Nat. Clim. Change 1 210–9
Schoener G and Stone M C 2019 Impact of antecedent soil moisture on runoff from a semiarid catchment J. Hydrol. 569 627–36
Shi X, Mao J, Thornton P E, Hoffman F M and Post W M 2011 The impact of climate, CO$_2$, nitrogen deposition and land use change on simulated contemporary global river flow Geophys. Res. Lett. 38 108704
Sorg A, Bolch T, Stoffel M, Solomina O and Beniston M 2012 Climate change impacts on glaciers and runoff in Tien Shan (Central Asia) Nat. Clim. Change 2 725–31
Stuecker M F et al 2018 Polar amplification dominated by local forcing and feedbacks Nat. Clim. Change 8 1076–81
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98
Thackeray C W and Hall A 2019 An emergent constraint on future Arctic sea-ice albedo feedback Nat. Clim. Change 9 972–8
Tokarska K B, Stolpe M B, Sippel S, Fischer E M, Smith C J, Lehner F and Knutti R 2020 Past warming trend constrains future warming in CMIP6 models Sci. Adv. 6 eaa9549
Wang Z, Zhan C, Ning L and Guo H 2020 Evaluation of global terrestrial evapotranspiration in CMIP6 models Theor. Appl. Climatol. 143 521–31
Yang Y, Roderick M L, Zhang S, McVicar T R and Donohue R J 2019 Hydrologic implications of vegetation response to elevated CO$_2$ in climate projections Nat. Clim. Change 9 44–48
Zhang X, Tang Q, Zhang X and Lettenmaier D P 2014 Runoff sensitivity to global mean temperature change in the CMIP5 models Geophys. Res. Lett. 41 5492–8