# The effect of plant-physiological responses to rising $CO_2$ on global streamflow

By

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**River flow statistics are expected to change as a result of increasing atmospheric $CO_2$, but uncertainty in Earth System Models (ESM) projections is high. While this is partly driven by changing precipitation, with well-known ESM uncertainties, here we show the influence of plant stomatal conductance feedbacks can cause equally large changes in regional flood extremes and even act as the main control on future low latitude streamflow. Over most tropical land masses, modern climate predictions suggest plant-physiological effects will boost streamflow, overwhelming opposing effects of soil drying driven by $CO_2$'s effects on atmospheric radiation, warming and rainfall redistribution. The relatively unknown uncertainties in representing eco-physiological processes must therefore be better constrained in land-surface models. To this end, we identify a distinct plant-physiological fingerprint on annual peak, low, and mean discharge throughout the tropics and identify river basins where physiological responses dominate radiative responses to rising $CO_2$ in modern climate projections.**

The effects of climate change on the hydrologic cycle will likely alter river networks and floodplains globally. Improving our understanding of the drivers behind these changes is critical for increasing confidence in projections of future flow extremes. If, for example, the main driver of basin-wide hydrologic change is a result of atmospheric responses to $CO_2$ increases, then model development efforts should focus on improving the representation of precipitation in ESMs, which is frequently noted as a critical component of flood projection uncertainty[1–4]. The ability of plant-physiological changes (i.e. stomatal closure at high $CO_2$) to modify extreme runoff, however, has only recently received attention[5]. We posit that such ecosystem effects could be just as important as precipitation for streamflow extremes, consistent with known first-order impacts on mean runoff and discharge[6–9], thus also requiring significant model improvement efforts to reduce uncertainty.

The atmospheric (radiative) effects of rising $CO_2$ have been widely studied. Global mean precipitation is expected to increase, with the most extreme rates projected to intensify even more than the Clausius-Clapeyron rate[10–12]. Regionally, more frequent/intense precipitation can contribute to more soil saturation, leading to higher streamflow or more frequent flooding. This is of particular concern in the tropics, where a multi-model ensemble suggests an increase in the frequency and intensity of heavy precipitation despite mean decreases[13].

However, atmospheric processes may not be the sole driver of streamflow changes in some regions. As the concentration of $CO_2$ rises, many plants respond by closing their stomata, which can lower the amount of water lost through transpiration[7,14,15]. While this effect may be offset at mid-latitudes by increased leaf area, the physiological response of stomata is an important mechanism regulating changes in evapotranspiration in densely forested tropical regions[16]. Decreases in transpiration and increases in water use efficiency can lead to higher antecedent soil moisture, and as a consequence, streamflow may increase even without a shift in precipitation statistics.

The relative roles of future radiative vs. plant-physiological responses in regulating flooding and seasonal streamflow changes have not been previously quantified. In part, this is due to the highly uncertain magnitude of the physiological response in observations, related to the difficulty of directly observing such changes over sufficiently long periods of time[17] and across a large range of sites[18]. Incorporating sparse observations into global-scale ESMs has led to wide variance in representation[19], with subsequent effects on river discharge further hampered by the lack of sophisticated river routing models in most ESMs. The goals of this study are thus two-fold: first, to assess the extent to which plant-physiological effects modulate global flood frequency and seasonal streamflow relative to radiatively driven changes; and second, to identify river basins where plant responses are dominant and thus where efforts to constrain the strength of the net physiological effects in nature (i.e., through carbon enrichment experiments[20,21] or regional simulations attempting to match observed streamflow changes) may prove most fruitful.

## Physiological and radiative effects on extreme flooding

To separate the atmospheric and plant responses to elevated $CO_2$, we conduct a series of four fully-coupled ESM experiments using the Community Earth System Model with biogeochemistry enabled (CESM1-BGC)[22,23], which are validated against flood and streamflow estimates from established CMIP5 RCP8.5 multi-model means by Hirabayashi et al.[4] (hereafter *H13*) and Koirala et al.[24] (hereafter *K14*). Leaf area in the Community Land Model (CLM4[25]) increases with enhanced $CO_2$ but no dynamic vegetation is represented (consistent with most CMIP5/6 models), which could limit a potential buffering effect from changes in forest area and associated evapotranspiration. The transpiration reduction in CLM4 may also be overestimated relative to observations[19,26,27], though the large spread among observational sites and comparison to other ESMs suggest that the model is not an extreme outlier[14].

In three sensitivity experiments, $CO_2$ was increased to quadruple its pre-industrial value (*CTRL*; 285 ppm) at a rate of 1% $yr^{-1}$. This increasing concentration was applied to the atmosphere and land in *FULL*, only the atmosphere in *RAD*, and only the land in *PHYS*, following the C4MIP experimental protocol[28,29] (where *PHYS* and *RAD* refer to the simulations' forcing rather than a specific mechanism in the complex regional responses). These experiments were extended for 50 years at constant 1140 ppm $CO_2$. We used daily runoff from the last 30 years of each (*CTRL, FULL, PHYS,* and *RAD*) to hydrodynamically downscale river discharge using the Catchment-Based Macroscale Floodplain model (CaMa)[30]. This choice allows consistency with *H13*, but our main findings are insensitive to expanding to 50 years (*Supplementary Fig. S1*). Though human management of rivers is not included in our analysis, we have confirmed that CaMa captures the geographic diversity of annual average streamflow (*Methods and Supplementary Figure S2*) and that *PHYS*-induced ecosystem responses are consistent with previous studies (*Supplementary Note* and *Supplementary Fig. S3*).

To estimate flood frequency, we fit the 30-year time series of annual maximum discharge at every location to an extreme value distribution (here, the Generalized

Extreme Value; GEV) to compute the return period of a flood magnitude equivalent to the 100-year flood in pre-industrial conditions (hereafter the $CTRL_{100}$ flood), following *H13*. We consider flood changes relative to this baseline return period of 100 years; regions with increased (decreased) flooding thus have future return periods less (greater) than 100 years. We limit our analysis to signals that are significant at 95% as measured across a large bootstrap ensemble (see *Methods*).

To confirm that our use of a single ESM produces flood shift patterns comparable to an established multi-model ensemble, we compared the resulting return period in *FULL* (*Fig. 1a*) with the CMIP5 analysis of *H13 (Fig. 1b*). Though the magnitude of return period varies between the two, and in fact varies based on how the extreme value distribution itself is defined (see *Methods*), the sign is reassuringly consistent -- 78.3% of locations in *FULL* show flood changes in the same direction as *H13*. In both cases, the $CTRL_{100}$ flood occurs at least twice as frequently over much of the tropics (dark blue shading in *Fig. 1*). Flood frequency decreases instead throughout Western Europe, the northeast and east coasts of South America, and parts of North America (red shading in *Fig. 1*), where reduced mean precipitation (over eastern South America) or less spring snow melt (high latitudes) tends to reduce runoff extremes.

***Fig 1: Frequency of the pre-industrial 100-year flood under elevated $CO_2$ and its drivers.*** *(a) Return period of the historical 100-year flood in FULL vs. (b) the results of H13 for a multi-model average under RCP8.5 forcing (H13 Figure 1; dry regions masked). (c) PHYS and (d) RAD as individual drivers of flood responses in FULL. (e)*

*Regional categorization of flood increases as primarily PHYS-driven (green), RAD-driven (orange), or a combination of both (blue) based on their contributions to the return period of the* $CTRL_{100}$ *flood in FULL. Results omitted in (a, c-e) where insignificant at 95% confidence based on a large bootstrap ensemble (see Methods).*

Flood shifts in *FULL* are shown to be a result of both physiologically- (*Fig. 1c*) and radiatively- (*Fig. 1d*) driven changes in return period, while changes of similar magnitude are induced by either mechanism alone. Over the Western Amazon, for example, increased flooding is primarily plant-driven, where dynamical mountain-forest interactions result in basin-wide precipitation rearrangement[16]. Increased flooding over much of South Asia is a result of radiatively-forced changes, potentially due to intensification of the Indian summer monsoon rain[31]. A third class of region can be defined by concurrent changes in both *PHYS* and *RAD*, thus dividing the globe into three flood-driving regimes: *PHYS*-driven, *RAD*-driven, and multiply stressed (*Fig. 1e*).

Eight regions with broadly consistent drivers are defined by rectangles in *Figure 1e* and analyzed further to determine the cause of increased flooding (*Supplementary Note* and *Supplementary Tables S1-S3*). For multiply stressed regions (blue rectangles in *Fig. 1e*), *PHYS* leads to more frequent flooding through increased soil moisture, which we interpret as a direct effect of $CO_2$-induced transpiration decline (*Supplementary Fig. S3*) since it occurs despite increases in plant productivity, leaf area and surface shortwave radiation; all of those changes, with varying degrees of statistical significance, would tend to dry the soil (*Supplementary Table S1 and Fig. S3*). When only the atmosphere responds to rising $CO_2$ (*RAD*), increased precipitation is likely the most important driver given the inability of other variables such as snowmelt, which is already near zero in these regions during the flood season, to explain the increased flooding. Other possible causative drivers, like increases in soil moisture and ET, are difficult to disentangle from precipitation changes (*Supplementary Table S1*). Control by precipitation also dominates radiatively-driven regions (orange rectangles in *Fig. 1e; Supplementary Table S2*), consistent with the expectation that warmer temperatures can promote higher mean precipitation and/or more frequent extremes, which can increase the likelihood of flooding.

Regions with plant-driven flood changes (green rectangles in *Fig. 1e*) experience more frequent flooding not only as a result of increased soil moisture via *direct* stomatal closure, but also through *indirect* precipitation effects, including mean precipitation increases over the Western Amazon (*Supplementary Note* and *Table S3*) – in turn a result of complex interactions between surface energy partitioning, vertical vapor transport by planetary boundary layer turbulence, and lateral vapor advection by regional orographic flow[16,32–34].

## Plant-physiological effects on annual streamflow metrics

Although CESM produces a striking physiological effect on floods, uncertainties in stomatal responses to $CO_2$ are large. Beyond a handful of regional ecosystems that have been subjected to Free Air $CO_2$ Enrichment experiments[17,35], data are sparse, notably in the tropics; extending direct measurements to span a sufficient range of climates to constrain the magnitude of the stomatal response in ESMs is untenable. This motivates the need for indirect observable proxies of the plant-physiological effect on streamflow in nature, as originally suggested by Gedney et al.[8]. If the same processes that produce large changes in extreme floods also modulate annual streamflow statistics, these -- being more readily observable -- could provide a useful metric for constraining net ecosystem responses to rising $CO_2$.

We thus investigate the seasonal cycle of streamflow, identifying broad regions and specific river basins where the *PHYS* effect rivals *RAD* contributions to *FULL*. Following *K14*, we compute annual mean ($Q_{mean}$), peak ($Q_{peak}$), and low flows ($Q_{low}$) for each river gridcell based on daily discharge, where seasonal extrema are defined as the 5th and 95th percentile flow rates annually, averaged to climatology.

***Fig. 2: Changes in seasonal streamflow.*** *Percent change from CTRL in* $Q_{mean}$ *(a),* $Q_{low}$ *(b) and* $Q_{peak}$ *(c). Regions with CTRL* $Q_{low}$ *discharge less than 50 or* $Q_{peak}$ *less than* $500\ m^3\ s^{-1}$ *masked (Supplementary Fig. S4). Latitudinal decompositions are smoothed with a 5° running mean; shading denotes zonal variability as the interquartile range.*

We confirm the validity of CESM by comparing our results with CMIP5 mean changes from *Figure 1* of *K14*, as discussed in the *Supplementary Note* and *Supplementary Figure S5*. In brief, *FULL* agrees well with the pattern of that multi-model average –

79.2%, 80.5%, and 68.0% of river gridcells in our experiment agree on the sign of $Q_{mean}$, $Q_{peak}$, and $Q_{low}$ changes respectively. The datasets generally agree in terms of large-scale spatial trends, showing increased $Q_{peak}$ over much of the globe and concentrating the largest $Q_{low}$ increases over northern latitudes (*Supplementary Fig. S4*).

The key result here, however, is that plant physiological changes are the *main* control of these streamflow statistics (mean, seasonal peak, and especially seasonal low flow) equatorward of 35˚. *PHYS* plays a major role in driving dramatic $Q_{low}$ increases throughout low latitude regions (*Fig. 2a*), which is linked primarily to higher soil moisture as a result of reduced stomatal conductance (*Fig. 3b*); rainwater simply becomes more prone to running off as increased plant water efficiency maintains a higher subsurface moisture reservoir that limits infiltration. Radiatively driven changes in $Q_{low}$ actually tend to oppose this increase throughout the tropics due to increases in evaporative demand (*Supplementary Fig.* S6), but this is vastly overwhelmed by physiological effects in the zonal mean. Systematic increases in $Q_{peak}$ and $Q_{mean}$ equatorward of 45˚N are again mostly controlled by plant responses, though radiatively driven changes in both cases are nearly neutral in the zonal mean (*Fig. 2b*). In the tropics and parts of the subtropics then, *PHYS* is almost solely responsible for increasing annual streamflow cycles across large portions of land.

***Fig. 3: Changes in environmental conditions**. Changes in 1m soil moisture (top; a-c) and the fraction of precipitation that reaches the surface as rain instead of snow*

*(bottom; d-f) relative to their values in CTRL for FULL (left; a,d), PHYS (center; b,e), and RAD (right; c,f). Mean differences are taken over the full 30-year period.*

At higher latitudes, the importance of atmospherically-driven changes in *RAD* increases relative to plant-driven effects. Increases in all three streamflow metrics over much of high-latitude western Europe and North America can be linked to strong polar-amplified warming in *RAD*, which tends to reduce peak snowmelt rates (contributing to earlier and lower peak discharge in spring) and shift the ratio of falling precipitation towards rainfall at the expense of snow (*Supplementary Fig. S6; Fig. 3f*). This change raises winter low flow by increasing runoff rather than allowing water to be stored in seasonal snowpack. The geographic disparity between tropical and higher latitude regions is summarized by pattern correlations in *Supplementary Table S4*.

Interestingly*, PHYS* also plays a non-negligible role in increasing $Q_{low}$ and $Q_{mean}$ across high-latitude continental interiors *(Supplementary Fig. S4)*, with a signal that is strongest towards the southern edge of the boreal forest, i.e. decreasing with latitude, opposite to the polar-amplified warming effect of *RAD* and associated snow-rain transitions (*Fig. 3*). This might suggest the potential for an identifiable fingerprint of the physiological effect in unmanaged high latitude river basins, with the caveat that radiative controls tend to dominate the *FULL* response poleward of 45˚N. In the transition zone between *PHYS*- and *RAD*-dominated $Q_{low}$ regimes, the influence of rising $CO_2$ on ecosystem processes allows for increasing vegetation cover in *PHYS*, yet transpiration reductions overwhelm these changes causing soil moisture to increase with a sharp boundary at the southern edge of the boreal forest region (*Fig. 3*).

### Radiative and physiological effects on basin-level discharge

Our analysis allows us to separate the relative contributions of *PHYS* and *RAD* to changes in discharge for large river basins. We limit our attention to 18 of the 32 basins assessed (*Supplementary Fig. S7*) in which the relative effects of *PHYS* and *RAD* on *FULL* are additive for mean, peak, or low flow. In these basins, the residual of the following decomposition is small relative to the sum of *PHYS* and *RAD*, suggesting the response of *FULL* can be well explained by a linear combination of individual drivers,

$$\frac{\Delta FULL}{CTRL} = \frac{\Delta PHYS}{CTRL} + \frac{\Delta RAD}{CTRL} + \varepsilon \qquad (1)$$

Where $\Delta FULL$, $\Delta PHYS$, and $\Delta RAD$ are the basin-averaged differences in streamflow from *CTRL,* and $\varepsilon$ is the residual, computed as the root mean square error between $\Delta FULL$ and the sum of Δ*PHYS* and Δ*RAD* across the 30-year ensemble (*Supplementary Fig. S8* and *Tables S5*-*S7*). The results of the decomposition are included below (*Fig. 3*).

***Fig. 4: Basin-level streamflow changes.*** *FULL changes in (a)* $Q_{mean}$*, (b)* $Q_{peak}$*, and (c)* $Q_{low}$ *relative to CTRL. (d-f) The contributions of* $\Delta PHYS$ *and* $\Delta RAD$ *to ΔFULL flow changes. Black stars represent the FULL percent change from CTRL (as shown by shaded circles in a-c), and black circles represent the sum of* $\Delta PHYS$ *and* $\Delta RAD$*.*

*Colored bars indicate the ΔPHYS* (green) + Δ*RAD (blue) percent changes that support the total.*

The primary driver of streamflow change can be identified by the dominant color of the basin's bar in the bottom row of *Figure 3*, with the magnitude of *FULL* indicated by the overall size of the circles in the top row. Again, basin responses are driven by *PHYS*, *RAD*, or a combination of both: Mekong $Q_{mean}$ and $Q_{low}$ increases are primarily plant-driven, while the Yukon is almost exclusively radiatively-driven. In general, the zonal pattern indicated in *Figure 2* is seen here at the basin level as well, where tropical regions tend to be more strongly controlled by *PHYS* while high latitudes are more heavily impacted by *RAD*.

Four basins stand out in particular as nearly exclusively plant-driven – the Amazon, Parana, Congo, and Yangtze. Annual streamflow cycles in those basins reveal a systematic effect of *PHYS* to raise streamflow, which controls changes in *FULL* despite opposing changes in *RAD* (*Fig. 5*).

***Fig. 5: Average annual streamflow cycles at river outlets in PHYS-dominated basins.*** *Area-weighted average streamflow annual cycles near the outlets of each river. Dashed black lines represent nearby GRDC station data (all available years in the period 1970-2005) while colored lines show modeled streamflow, where all grid cells*

*within a quarter degree of the GRDC station have been averaged together. Error bars correspond to twice the standard error of discharge over the 30-year period.*

Details on these streamflow cycles and their comparison to observations are included in the *Supplementary Note*. In brief, despite a series of varying bias patterns in each basin – expected given ESM precipitation biases (*Supplementary Fig. S10*) and the exclusion of human water management in CaMa -- the effect of reduced stomatal conductance is a systematic increase in streamflow across all months that is common to all four basins. This consistency adds confidence that the streamflow response to *PHYS* is a robustly simulated signal, in line with the observational findings of Gedney et al.[8] despite the fact that they did not allow for leaf area changes[36].

## Discussion

Improved understanding of the physical mechanisms behind streamflow and flood frequency changes is critical for future ecosystem planning and management. Here, for the first time, we have linked ESM experiments that isolate the plant-physiological from radiative effects of $CO_2$ on runoff to a hydrodynamic model that predicts their consequences for streamflow globally. Flood frequency analysis shows that plant-physiological effects on the terrestrial water cycle are a first order control on future shifts of the 100-year flood.

Despite the major role of plants in the evolution of hydrological extremes under $CO_2$ forcing in CESM demonstrated here, the coupling between water and carbon cycles in modern land-surface models remains poorly constrained. To help address this source of uncertainty and complement sparse observational constraints, we use the model to identify fingerprints of plant-physiological effects in observable metrics of annual streamflow. For low flows, the results show a competition in which the radiative effect tends to reduce but the physiological effect tends to increase seasonal flow minimums throughout low latitudes. At high latitudes, the relatively smaller net plant effect on mean and low flow expresses itself with an opposing meridional gradient to the polar-amplifying radiative effect across boreal forest watersheds. For peak flows, the plant response is the main driver of future changes throughout most low latitudes. Given this, we encourage more investigation of such fingerprints across multiple independent hydrodynamically downscaled ESMs, towards the hope of using observed streamflow to constrain the magnitude of buffered ecosystem responses to $CO_2$ in nature. The effect of the plant-physiological response on hydrologic extremes across timescales is often overlooked in future climate projections, but this work highlights the need to assess these effects more explicitly moving forward.

## Methods

### *CESM experiments*

The four CESM1-BGC simulations include fully active atmosphere (CAM4)[37], land (CLM4)[25], ocean (POP2)[38], and sea ice (CICE4)[39] components, as described in

Koopermen et al.[5]. *CTRL* was initialized from spun-up pre-industrial conditions with a fixed $CO_2$ concentration of 285 ppm, which was maintained for 50 years. Three additional experiments (i.e., *FULL, RAD,* and *PHYS*) were then initialized from the end of *CTRL* to test the flood response to quadruple the amount of $CO_2$. In these simulations the $CO_2$ concentration increased at 1%/year over a 140-year period and was then held fixed for an additional 50 years. In *RAD* and *PHYS*, the land and atmosphere, respectively, experience the original 285 ppm of $CO_2$ rather than the increased value of 1140 ppm when they are not the targeted response pathway, while in *FULL* both the land and atmosphere experienced the increased value. Global runoff from these 1˚ resolution simulations are interpolated to 0.5˚ via a bi-linear cubic spline before being used in the CaMa model.

### ***Hydrodynamic downscaling and extreme value curve fitting***

For downscaling coarse resolution ESM output, we use the CaMa-Flood model (version 3.6.2), which uses daily runoff to generate high resolution streamflow by solving a hydrodynamic flow equation[30]. This method of downscaling is well established in recent literature[3,4,24,40,41] and produces a reasonably accurate global river flow pattern[4,30]. Using runoff instead of precipitation as the driving boundary condition accounts for $CO_2$ impacts on both precipitation and evapotranspiration, while our experiment design allows us to separate the radiative (*RAD*) and plant-physiological (*PHYS*) contributions to runoff changes. To ensure that CESM1-generated runoff is able to produce reasonable streamflow estimates when paired with CaMa, we compare *CTRL* river discharge with observations from 30 large river basins, as reported by the Global Runoff

Data Centre (GRDC). We take the same approach as in H13, choosing 30 river basins that meet spatial (areas larger than 150,000 km$^2$) and temporal requirements (at least 20 years of data in the modern period of 1970-2000). Computing the correlation between the two datasets provides an estimate of how well the model can simulate streamflow (*Supplementary Fig. S2*). The reasonably good agreement provides some confidence that CESM is a useful tool for exploring future changes in streamflow originating from radiative and physiological impacts of rising $CO_2$.

We consider two extreme value distributions to fit annual maximum discharge to, the Gumbel and the Generalized Extreme Value (GEV). The pattern of flood frequency shifts created from this fitting is found to be insensitive to the choice of distribution, though the magnitude of the changes can vary significantly between the two (*Supplementary Fig. S1*). As a result, we focus here only on the regional distribution of changes and the relative contributions of *PHYS* and *RAD* to that pattern. These metrics are insensitive to the choice of curve fit.

We choose the GEV here based on its simulation of less extreme frequency shifts and a reasonable value of the global average probability plot correlation coefficient (0.90). The GEV was then used to find the shape ($\xi$), location ($\mu$), and scale ($\sigma$) parameters to estimate river discharge, *F(x)*:

$$F(x) = \exp\left(-\left(1+\xi\frac{(x-\mu)}{\sigma}\right)^{-\frac{1}{\xi}}\right) \qquad (2)$$

The statistical fit to this distribution is carried out independently at each location and for each of the four experiments. The curve itself can thus be shifted based on the location parameter or stretched/shrunk based on the scale parameter, while additional characteristics like its skewness can be altered by changes in the shape parameter at every location. The magnitude of a given flood ($U_T$) can then be determined based on return period ($T$) by inverting the CDF of the GEV above:

$$U_T = \mu + \frac{\sigma}{\xi}\left(-\ln\left(1-\frac{1}{T}\right)^{-\xi} - 1\right) \tag{3}$$

This is used to estimate the magnitude of the $CTRL_{100}$ flood. *Equation 3* is then solved for $T$ to determine the frequency of a flood with the $CTRL_{100}$ magnitude in each of the enhanced $CO_2$ experiments. Statistical confidence is built by limiting our analysis to signals that are significant at the 95% level, measured by a large bootstrap that is produced by randomly sampling with replacement the actual 30-year annual maxima time series at each location and repeating the GEV fit 1,000 times.

### *Defining grid cells as RAD-driven, PHYS-driven, or multiply stressed*

To better isolate regions with flood increases that are driven by the atmospheric response (*RAD*-driven), the plant response (*PHYS*-driven), or by a combination of the two (multiply stressed), each grid cell is sorted based on agreement between the three experiments. *RAD* and *PHYS* flood frequency increases must both be at least 20% of the increase in *FULL* for a region to qualify as multiply stressed. Otherwise, the location is assigned to the driver with the larger change between the two. This practice is first carried out at the 0.25˚ CaMa-Flood resolution but is then scaled to the 1˚ CESM grid by identifying the mode of drivers within each larger CESM grid cell. Note that although the Nile region is particularly noticeable as a multiply stressed region (shown in blue in *Fig. 1e*), it is not selected for detailed analysis due to the high aridity of the region.

## Methods References

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## Code availability

All scripts that replicate the results of this study are accessible at https://github.com/megandevlan/Physiology-Streamflow. Data associated with these scripts are included in the repository, with a few exceptions. Relevant CESM and CaMa output are not included due to their size but are available at http://portal.nersc.gov/archive/home/m/mdfowler/www/. Data obtained from Y. Hirabayashi, S. Koirala, and from the GRDC are not included and should be requested from the sources independently. The CaMa model itself can be obtained by emailing the developer, D. Yamazaki, while CESM is publicly available through a Subversion code repository – see http://www.cesm.ucar.edu/models/cesm1.0/ for more details.

## Data Availability

The relevant datasets generated during this analysis are available at http://portal.nersc.gov/archive/home/m/mdfowler/www/. The full CESM output record is archived and available upon request. Data used to create *Figure 1b* was received via personal correspondence with Y. Hirabayashi, and requests should be directed to her. Similarly, CMIP5 multi-model mean streamflow data used for comparison between *FULL* and *K14* was received via personal communication with the lead author, and should be requested from S. Koirala. Full CESM output is archived at the National Center for Atmospheric Research. Global Runoff Data Base observations in *Figure 5* are freely available from GRDC, but cannot be redistributed by the author; requests should be sent directly to GRDC.

## Competing Interests

The authors declare no competing interests.

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## Author contributions

All authors contributed to the design of the experiment, interpretation of results, and manuscript editing. G.J.K. performed the CESM simulations and M.D.F. performed the CaMa downscaling, carried out the analysis, and drafted the initial manuscript with advice from M.S.P.

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