Hydrology and Earth System Sciences Discussions

Hydrol. Earth Syst. Sci. Discuss., author comment AC3
https://doi.org/10.5194/hess-2021-55-AC3, 2021
© Author(s) 2021. This work is distributed under
the Creative Commons Attribution 4.0 License.

Reply on RC3

Tessa Maurer et al.

Author comment on "Drivers of drought-induced shifts in the water balance through a Budyko approach" by Tessa Maurer et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-55-AC3, 2021

Dear Dr. Teuling,

Thank you very much for the thoughtful review of our paper. Please find below our point-by-point reply to comments, including our intended changes to the manuscript. Your comments are in italics, and our replies are in plain text.

Best,

Tessa Maurer on behalf of the co-authors

The manuscript by Maurer and co-workers addresses the issue of changes in water balance partitioning during drought. This is a relevant topic that fits well within the scope of HESS. The authors use a novel combination of methods and data, to arrive at the conclusion that not only the position along the Budyko curve changes during drought, but also the Budyko parameter reflecting the catchment functioning. The manuscript is generally well-written and nicely illustrated. However in contrast to reviewer #1, I unfortunately have some serious concerns about the robustness of the results, and the main motivation for the study, that I think need to be addressed. These are discussed in more detail below.

In the Introduction, the authors state that "A particular focus is the change or shift in the precipitation-runoff relationship during droughts, which usually results in less observed runoff per unit of precipitation than would be predicted using non-drought relationships" and that "it is not fully understood which hydrologic mechanisms trigger them". I disagree with this statement, and thereby unfortunately with the main motivation for the study. No hydrologist would claim that runoff response to a unit precipitation input should stay the same across different moisture regimes. In fact, it is well known that the runoff response is a strong and highly nonlinear function of catchment storage on short timescales (i.e. Kirchner, WRR, 2009), which is at least in part related to the nonlinear relation between soil moisture and unsaturated hydraulic conductivity (the main understanding of which dates back almost a 100 years). There is no reason why this would not work similar at longer timescales. The questions here is what we actually don't understand about drought *and water balance partitioning, and how the proposed method using a highly conceptual model can provide more insight into this. I believe the authors should do a better job here in formulating a research question that truly reflects, and builds on, the current state of knowledge.*

We thank the reviewer for bringing our attention to this important point on the framing of our work. We agree that we can better clarify how previous work on drought versus non-drought water balances has been presented. In particular, we agree that we can be more explicit in describing which processes and drivers are understood in this context versus those that are not. Specifically, we propose the following changes to the framing:

- (A) While we agree with the reviewer's statement that "No hydrologist would claim that runoff response to a unit precipitation input should stay the same across different moisture regimes. In fact, it is well known that the runoff response is a strong and highly nonlinear function of catchment storage on short timescales (i.e. Kirchner, WRR, 2009), which is at least in part related to the nonlinear relation between soil moisture and unsaturated hydraulic conductivity (the main understanding of which dates back almost a 100 years)", we note that some catchments do show a consistent response of runoff to precipitation or, in other words, a linear P-Q relationship with no significant shift during drought (Tian et al. 2020; Coron et al. 2012; Vaze et al. 2010; Saft et al. 2016; Avanzi et al. 2020). Thus, shifts in the water balance during droughts are not unexpected nor entirely inexplicable, but they are also not necessarily expected, either. This leaves open the broad motivating question of this as well as much prior work (e.g., Saft et al. 2016; Potter, Petheram, and Zhang 2011; Tian et al. 2020; Avanzi et al. 2020; Alvarez-Garreton et al. 2021): why do only some basins show a change in hydrologic functioning during droughts and what causes shifts in the places they are observed?
- (B) Furthermore, while the nonlinear relationship between runoff and storage is well-established, other drivers of runoff have also been identified as influencing drought versus non-drought water balances. For example, studies have shown the influence of catchment memory (Avanzi et al. 2020; Alvarez-Garreton et al. 2021), the role of vegetation water use (Saft et al. 2016; Avanzi et al. 2020), changes in precipitation seasonality (Van Dijk et al. 2013) and the influence of catchment topography and elevation (Saft et al. 2016; Tian et al. 2020). Thus, the causes of these water balance changes cannot be ascribed solely to variability with respect to storage, leaving open the question of what the other drivers and nonlinear relationships influencing this shift are. The locations that these other potential drivers are active and how they interact with each other and with storage is not fully understood. This, together with point (A) above, are the primary motivating questions of our work. In the revised manuscript, we will clarify that some well-understood processes such as storage certainly contribute to a shift in the water balance during droughts, but at the same time the evidence that some basins do not see these shifts leaves an overall incomplete picture of processes and relationships at play.
- (C) From a more technical standpoint, much previous literature (e.g. Saft et al. 2016; Avanzi et al. 2020; Tian et al. 2020; Alvarez-Garreton et al. 2021) has assumed a linear response between P and Q and handled deviations from this response as evidence of "shift". (Again, a linear response between P and Q does exist in some areas, so this is not an unreasonable assumption as a baseline). Thus, it is unclear if the "shift" is simply nonlinearity in the P-Q relationship across a variety of climatic conditions that the linearized approach used by these studies fails to capture, or if it is the signature of some catchment processes being more important during dry periods than during wet periods. Using a Budyko approach provides an opportunity here, in that it accounts for ET and thus allows one to explicitly consider the nonlinearity in the P-Q relationship across a variety of climatic conditions. We found that a certain proportion of what others call "shifts" is in fact explained by mere nonlinearity (what we call a regime shift), while there remains a fraction of the original shift that is less predictable

a priori (a partitioning shift). That portion of the shift is the signature of other processes being more important during dry periods than during wet periods. Thus, we believe the Budyko framework offers an important insight into characterizing shifts in the water balance during droughts and providing further context for previous literature on the subject. In the revised manuscript, we will explain the current ambiguity in the nature of water balance shifts during drought and explicitly address how the nonlinear nature of the Budyko conceptual model can help clarify it.

- (D) Finally, while there is scientific understanding of nonlinear relationships in the water balance, many operational tools do assume "that runoff response to a unit precipitation input should stay the same across different moisture regimes". For example, seasonal streamflow forecasting by the Department of Water Resources in California relies on a linear relationship between historical snowpack runoff and does not consider soil moisture or drought conditions (Harrison and Bales 2016). Thus, questions like clarifying the full range of processes that contribute to these shifts, in what areas they apply, and how they interact not only solicit more basic science, but also represent an urgent need for formulating more resilient water-resources policy in the current and future climate. Providing different or improved modeling options for these agencies could support more reliable water and economic security. We believe this is also important as a motivating factor for this work, and we will include a brief discussion of this in the revised introduction.

My second concern deals with the validity of the conclusions. This relates both to the quality of the datasets used and the consistency between them, and to the application of a modified Budyko framework.

The results rely heavily on the quality of the data used. Unfortunately, the selection of datasets used by the authors raises a number of questions. Firstly, the precipitation data is rescaled to force long-term average water balance closure (L113-114: "Finally, annual precipitation data were adjusted by the long-term average residual of P − ET − Q so total basin storage over the period of record was zero."). This is a highly unusual procedure, because normally P is the term with the smallest relative error. It is unclear how this procedure was implemented exactly, and how big the corrections were. In addition, it creates an inconsistency with the ET data used, which are calculated based on P which is now inconsistent with the P used in the water balance analysis. The authors should show clearly that this procedure is needed, and that its impact is limited. The rescaling might well mask larger errors in other terms, such as ET. While not much information is provided on ET, it seems to be based on statistical modeling of the relation between observed ET, NDVI, and P. The problem here is that observations of ET over forest ecosystems made by eddy covariance often are inconsistent with runoff observations (the "forest evapotranspiration paradox", see Teuling, Vadose Zone J. 17:170031. doi:10.2136/vzj2017.01.0031. I believe the authors should provide more evidence or arguments on why this ET dataset is useful in this context, and how non-forest and snow areas are dealt with.

Perhaps my biggest concern is with the runoff data. Little information is provided on these, so I did some searching on the web myself instead. Based on the following document: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/petitioners_exhibit/dwr/part2_rebuttal/dwr_1384.pdf, it seems that the unimpaired flows are subject to numerous calculations and assumptions that even differ between the individual basins. This raises the question if this data should be considered a model product or an observational product. My feeling after reading the document is more the former. This is particularly problematic, because any assumptions in the approach that may impact the runoff values differently in normal and drought years, will directly impact the results. The authors should show that the risk for such bias is small, otherwise their main findings might reflect an assumption made in a modeling chain, rather than an observation that tells us something new about how nature works.

We thank the reviewer for raising important points on the quality of the data used in this study. We agree that a more detailed discussion of uncertainty is important and useful for this work. We address the reviewer's comments for the precipitation, evapotranspiration, and runoff data below, and we will include these details in the supplementary information of the revised manuscript.

The PRISM precipitation dataset used in this study is the best-quality gridded data available for the Western U.S., with a monthly mean absolute error of 4.7 to 12.6 mm and a potential annual error of ±98.2 mm (Daly et al. 2008). Also, it is arguably the most used precipitation dataset for mountain hydrology in the Western U.S., and as such it represents a benchmark for hydrologic research in this region (see, e.g., Bolger et al. 2011; Abatzoglou, Redmond, and Edwards 2009; Ackerly et al. 2010; Raleigh and Lundquist 2012; Ishida et al. 2017). At the same time, it is well-established that precipitation uncertainty is high in steep, variable terrain with few ground-based measurements, which includes the montane regions of California. Point measurements that form the basis for interpolated gridded data can underestimate precipitation due to undercatch from wind, wetting loss, evaporation, and trace precipitation (Yang et al. 1999). The snow-dominated elevations of these regions are subject to further uncertainty in accurately measuring solid precipitation, particularly if precipitation gauges are not heated (Rasmussen et al. 2012). PRISM precipitation in the Sierra Nevada can undermeasure individual storms by up to 50% as compared to snow-water equivalent measurements from snow pillows (Lundquist et al. 2015). Adjusting for errors in gauge measurements on which PRISM is based is common practice (Allerup, Madsen, and Vejen 2000; Bales et al. 2009; Ma et al. 2015; Mernild et al. 2015), and such correction procedures are a necessary choice in other mountain regions as well, regardless of the specific precipitation product used (Avanzi et al. 2021). As a result, the precipitation data likely represent one of the least, not most, certain components of the water balance for this region, which justifies the adjustment procedure to reduce uncertainty in the dataset.

The adjustment procedure allows for reduction of systemic bias in the precipitation data without assuming that all data uncertainty rests in a specific water-balance component. The procedure was predicated on the assumption that long-term storage in the basin is stable. The procedure was as follows: using the annual, basin-wide values for precipitation, evapotranspiration, and full natural flow, we calculated the residual of P–ET–Q. This value represents the annual change in subsurface and deep groundwater storage in the basin (note that this value is not the same as ΔS calculated for this study using the *abcd* method, which represents only plant-accessible subsurface water). Next, we calculated the average of these annual residuals, which represents the adjustment factor. This value was subtracted from the annual precipitation, yielding the precipitation values used in this study. Note that by performing this adjustment, the average of the annual residuals of Padj – ET – Q is zero. As noted in the response to Reviewer #1, the highest adjustment factor was in the Shasta basin and represented 7.6% of the long-term average precipitation, a value that is fully in line with expected accuracy of this dataset and at the same time a minor fraction of both precipitation and all other water-budget terms. We will clarify the description of this procedure in Section 2.2 and, also as noted in the response to Reviewer #1, include the full set of adjustment factors, in depth and as a percentage of precipitation, in the supplement.

The ET data used in this study were from previously published methods (Roche et al. 2020). While our adjustment to precipitation does mean that it relies on different precipitation values, the calibration is distinct from our water balance application. Roche et al. 2020 used the data to perform a spatially distributed calibration rather than calculate the basin-scale water balance. We rely on the authors of the ET dataset to have made the most appropriate decisions for the calibration, and further note that assuming a long-term average storage change of zero for these mountain basins with little exploitation of subsurface water resources is appropriate. Thus, our assessment was that the adjustments of the precipitation data do not make them incompatible with use alongside the gridded ET products, any more than they would if an entirely different gridded precipitation dataset had been used as the index to calibrate the ET products.

The major value of the ET dataset in this context is the opportunity to assess water balance changes without determining any inputs residually, since doing so relegate all uncertainties in the data to a single water balance component (see Reviewer #1's comments on line 107). As with precipitation, uncertainties in the ET dataset are related to both the underlying ground-based data as well as the interpolation method, and uncertainties in the tower-based eddy-covariance data plus satellite data used for scaling are estimated to give a modeling uncertainty of between 10-20% for a given pixel (Roche et al. 2020). Absent a systematic bias in the data, the aggregate basin-scale ET estimate should be lower. This gridded ET product was also based on substantial prior work that provides the theoretical grounding for the regression (see, in particular, Goulden et al. 2012, for an important discussion of why statistical approaches to ET are best suited to the Sierra Nevada region). In addition, while we understand the reviewer's valid concern about the inconsistencies between ET from eddy covariance measurements and runoff, this has been shown to be less of a concern in the Sierra Nevada (see Figure 10 in Roche et al. 2020). Further, the linear P-Q relation provided a good match to P-ET for basins with measured streamflow in the Sierra headwaters (see Figure 1 in the Supplement to this comment). Prior work in regions with similar climates and topography have cited eddy covariance as an accurate method for measuring evapotranspiration (Rana and Katerji 2000; Wilson and Baldocchi 2000; Wang et al. 2015). Variations in land cover and vegetation type are accounted for by use of NDVI in the regression, which has been shown to have a strong relationship with ET in semi-arid landscapes (Roche et al. 2020; Groeneveld et al. 2007). Since the ET maps were developed on an annual basis and there is no permanent snow cover in these regions, precipitation phase (rain versus snow) was not considered in the regression. We will include these details about the regression methods and associated uncertainty in the revised manuscript.

Finally, we agree that full-natural flows (FNF) are an imperfect substitute for true runoff values. At the same time, we note that estimating runoff using FNF is virtually the only way runoff can be included in hydrologic research in California due to the prevalence of human intervention (e.g. dams and diversions) on the majority of major rivers in the state. While we agree that greater consideration should be given to the implications of substituting FNF for runoff, much research exists that leverages FNF in place of runoff (e.g. Guan et al. 2016; Ejeta 2013; Brown and Bauer 2010; He, Russo, and Anderson 2017; Dettinger and Cayan 2003; Zeff et al. 2021). Since performing a comprehensive assessment of the implications of this substitution would amount to a full separate research project, it is outside the scope of the present study. However, we agree with the reviewer that a more in-depth discussion of the sources of uncertainty in the FNF calculations and the implications of a FNF-for-runoff substitution is merited for this study, and we will include this in the discussion section of the revised manuscript. For the current study, we simply note that FNF matches P-ET at the basin scale (see Figure 2 in the Supplement to this comment).

Regarding uncertainty, the Department of Water Resources report cited by the reviewer (Huang and Kadir 2016) mentions that most of the uncertainty in FNF values is related to evapotranspiration from overfull banks and natural wetlands (page 9), which we expect to more heavily impact flows through the Central Valley floor and outflows through the Sacramento-San Joaquin Delta, downstream of outlets of the headwater basins used in this study. The report states in Section 5 (page 79): "Upper rim watersheds, located in the foothill and mountain regions of the Sierra Nevada and California Coast Ranges, are relatively undeveloped. Precipitation-runoff processes are assumed to be assumed unchanged from natural condition for a given climate. Therefore, simulated natural outflows from these watersheds should be similar to estimates of unimpaired flows"

(Huang and Kadir 2016). This assumption has been validated in prior studies for certain headwater basins in California comparing FNF to P-ET; see, for example, Figure 5 in Bales et al. 2018 and Figure 10 in Roche et al. 2020.

With respect to the assumptions in the calculations of FNF, the California Department of Water Resources calculates unimpaired runoff starting with measured impaired streamflow or estimated change in reservoir storage. Reservoir evaporation, basin water exports, and irrigation diversions are added, while basin imports and irrigation return flows are subtracted. Differences in the specific adjustments in each basin exist because the type of human intervention, quality measured data on the impact of interventions, and information on historical flow regimes vary across basins (Ejeta et al. 2007).

My second main concern deals with the modified Budyko approach. I share the concern expressed by referee #2 that the modified framework has not been sufficiently tested or proven for the current application. Even in case the framework is valid, there is a fundamental difference between the plots with P, and P−ΔS. In the traditional Budyko framework, the aridity index PET/P reflects an external climate forcing that is decoupled from the catchment itself. Here, the Budyko parameter reflects how the catchment partitions precipitation between ET and Q, at a given atmospheric forcing. In the modified formulation, this interpretation is no longer possible because PET/(P−ΔS) on the x-axis now becomes dependent on catchment properties (through ΔS which is affected by optimization that is different for drought and non-drought years). This means that changes along the Budyko curve can no longer be considered as only induced by climate variation, and changes in the Budyko parameter no longer reflect changes in catchment functioning only. This potentially creates a flaw in the interpretation of the drivers of drought-induced shifts in water balance partitioning. The authors should provide convincing evidence or arguments on why the modified Budyko framework can be interpreted in the same way as the traditional framework. I also suggest to use a symbol for the Budyko parameter that is distinctively different from the "w" used in most papers, stressing the fact that they are not the same parameters.

We thank the reviewer for raising this question about the modified Budyko approach. We used a modified approach in acknowledgement that the traditional Budyko framework is not intended for the annual timestep (Budyko 1974), but in practice, the change in storage values are small compared to the precipitation values, so changes along the x-axis will largely reflect climate outputs. Across the basins, average annual ΔS values for a given year ranged between 1.5 and 11.6% of the annual precipitation; we will include these values in the supplemental information of the revised manuscript. The method we use in this paper was developed by Du et al. 2016 and validated in arid, headwater montane regions similar to those examined in this study.

Regarding the reviewer's comment "ΔS which is affected by optimization that is different for drought and non-drought years," we wish to further clarify that ΔS is not optimized differently for drought and non-drought years, since the *abcd* model by which those yearly values were determined was run continuously for all years. Only the relationship between all water balance components (available water, P-ΔS; available energy, PET; and water demand, ET) is optimized differently for different periods. Thus, no procedure should create systemic bias in the water balance values based on the year type (drought vs non-drought). We apologize for the confusion on this point and will revise section 2.3 in the Methods section to ensure the distinction is clear.

Regarding parameter symbols for the modified Budyko framework, we are happy to use a different option in the revised manuscript. However, we note that ω was also used by Du et al. 2016 when they introduced this modified approach, and we believe it is preferable not to introduce more variation and potentially unnecessary confusion in the already fragmented landscape of scientific literature.

References:

Abatzoglou, John T., Kelly T. Redmond, and Laura M. Edwards. 2009. "Classification of Regional Climate Variability in the State of California." *Journal of Applied Meteorology and Climatology* 48 (8): 1527–41. https://doi.org/10.1175/2009JAMC2062.1.

Ackerly, D. D., S. R. Loarie, W. K. Cornwell, S. B. Weiss, H. Hamilton, R. Branciforte, and N. J.B. Kraft. 2010. "The Geography of Climate Change: Implications for Conservation Biogeography." *Diversity and Distributions* 16 (3): 476–87. https://doi.org/10.1111/j.1472-4642.2010.00654.x.

Allerup, Peter, Henning Madsen, and Flemming Vejen. 2000. "Correction of Precipitation Based on Off-Site Weather Information." A*tmospheric Research* 53 (4): 231–50. https://doi.org/10.1016/S0169-8095(99)00051-4.

Alvarez-Garreton, Camila, Juan Pablo Boisier, René Garreaud, Jan Seibert, and Marc Vis. 2021. "Progressive Water Deficits during Multiyear Droughts in Basins with Long Hydrological Memory in Chile." *Hydrology and Earth System Sciences* 25 (1): 429–46. https://doi.org/10.5194/hess-25-429-2021.

Avanzi, Francesco, Giulia Ercolani, Simone Gabellani, Edoardo Cremonese, Paolo Pogliotti, Gianluca Filippa, Umberto Morra DI Cella, et al. 2021. "Learning about Precipitation Lapse Rates from Snow Course Data Improves Water Balance Modeling." *Hydrology and Earth System Sciences* 25 (4): 2109–31. https://doi.org/10.5194/hess-25-2109-2021.

Avanzi, Francesco, Joseph Rungee, Tessa Maurer, Roger Bales, Qin Ma, Steven Glaser, and Martha Conklin. 2020. "Climate Elasticity of Evapotranspiration Shifts the Water Balance of Mediterranean Climates during Multi-Year Droughts." *Hydrology and Earth Science Systems* 24: 4317–37. https://doi.org/10.5194/hess-24-4317-2020.

Bales, Roger C., Michael L. Goulden, Carolyn T. Hunsaker, Martha H. Conklin, Peter C. Hartsough, Anthony T. O'Geen, Jan W. Hopmans, and Mohammad Safeeq. 2018. "Mechanisms Controlling the Impact of Multi-Year Drought on Mountain Hydrology." *Scientific Reports* 8 (1): 1–8. https://doi.org/10.1038/s41598-017-19007-0.

Bales, Roger C., Qinghua Guo, Dayong Shen, Joseph R. McConnell, Guoming Du, John F. Burkhart, Vandy B. Spikes, Edward Hanna, and John Cappelen. 2009. "Annual Accumulation for Greenland Updated Using Ice Core Data Developed during 2000-2006 and Analysis of Daily Coastal Meteorological Data." *Journal of Geophysical Research Atmospheres* 114 (6). https://doi.org/10.1029/2008JD011208.

Bolger, Benjamin L., Young Jin Park, Andre J.A. Unger, and Edward A. Sudicky. 2011. "Simulating the Pre-Development Hydrologic Conditions in the San Joaquin Valley, California." *Journal of Hydrology* 411 (3–4): 322–30. https://doi.org/10.1016/j.jhydrol.2011.10.013.

Brown, Larry R., and Marissa L. Bauer. 2010. "Effects of Hydrologic Infrastructure on Flow Regimes of California's Central Valley Rivers: Implications for Fish Populations." *River Research and Applications* 26: 751–65. https://doi.org/10.1002/rra.1293.

Budyko, M.I. 1974. *Climate and Life*. Academic Press, Inc.

Coron, L., V. Andréassian, C. Perrin, J. Lerat, J. Vaze, M. Bourqui, and F. Hendrickx. 2012. "Crash Testing Hydrological Models in Contrasted Climate Conditions: An Experiment on

216 Australian Catchments." *Water Resources Research* 48 (5): 1–17. https://doi.org/10.1029/2011WR011721.

Daly, Christopher, Michael Halbleib, Joseph I. Smith, Wayne P. Gibson, Matthew K. Doggett, George H. Taylor, Jan Curtis, and Phillip P. Pasteris. 2008. "Physiographically Sensitive Mapping of Climatological Temperature and Precipitation across the Conterminous United States." *International Journal of Climatology March*. https://doi.org/10.1002/joc.1688.

Dettinger, Michael D., and Daniel R. Cayan. 2003. "Interseasonal Covariability of Sierra Nevada Streamflow and San Francisco Bay Salinity." *Journal of Hydrology* 277 (3–4): 164–81. https://doi.org/10.1016/S0022-1694(03)00078-7.

Dijk, Albert I.J.M. Van, Hylke E. Beck, Russell S. Crosbie, Richard A.M. De Jeu, Yi Y. Liu, Geoff M. Podger, Bertrand Timbal, and Neil R. Viney. 2013. "The Millennium Drought in Southeast Australia (2001-2009): Natural and Human Causes and Implications for Water Resources, Ecosystems, Economy, and Society." *Water Resources Research* 49 (2): 1040–57. https://doi.org/10.1002/wrcr.20123.

Du, C., F. Sun, J. Yu, X. Liu, and Y. Chen. 2016. "New Interpretation of the Role of Water Balance in an Extended Budyko Hypothesis in Arid Regions." *Hydrology and Earth System Sciences* 20 (1): 393–409. https://doi.org/10.5194/hess-20-393-2016.

Ejeta, Messele Z. 2013. "Validation of Predicted Meteorological Drought in California Using Analogous Orbital Geometries." *Hydrological Processes* 28: 3703–13.

Ejeta, Messele Z., Sushil K. Arora, Tariq Kadir, and Hongbing Yin. 2007. "California Central Valley Unimpaired Flow Data." Sacramento, CA. https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spprtinfo/dwr_2007a.pdf.

Goulden, M. L., R. G. Anderson, R. C. Bales, A. E. Kelly, M. Meadows, and G. C. Winston. 2012. "Evapotranspiration along an Elevation Gradient in California's Sierra Nevada." *Journal of Geophysical Research*: Biogeosciences 117 (3): 1–13. https://doi.org/10.1029/2012JG002027.

Groeneveld, David P., William M. Baugh, John S. Sanderson, and David J. Cooper. 2007. "Annual Groundwater Evapotranspiration Mapped from Single Satellite Scenes." *Journal of Hydrology* 344 (1–2): 146–56. https://doi.org/10.1016/j.jhydrol.2007.07.002.

Guan, Bin, Duane E Waliser, F Martin Ralph, Eric J Fetzer, and Paul J Neiman. 2016. "Hydrometeorological Characteristics of Rain-on-Snow Events Associated with Atmospheric Rivers." *Geophysical Research Letters* 43: 2964–73. https://doi.org/10.1002/2016GL067978.

Harrison, Brent, and Roger Bales. 2016. "Skill Assessment of Water Supply Forecasts for Western Sierra Nevada Watersheds." *Journal of Hydrologic Engineering* 21 (04016002). https://doi.org/10.1061/(ASCE)HE.1943-%0A5584.0001327.

He, Minxue, Mitchel Russo, and Michael Anderson. 2017. "Hydroclimatic Characteristics of the 2012-2015 California Drought from an Operational Perspective." *Climate* 5 (1): 1987–92. https://doi.org/10.3390/cli5010005.

Huang, Guobiao, and Tariq Kadir. 2016. "Estimates of Natural and Unimpaired Flows for the Central Valley of California: Water Years 1922-2014." Sacramento, CA. https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhib its/docs/petitioners_exhibit/dwr/part2_rebuttal/dwr_1384.pdf.

Ishida, K., M. Gorguner, A. Ercan, T. Trinh, and M. L. Kavvas. 2017. "Trend Analysis of Watershed-Scale Precipitation over Northern California by Means of Dynamically-Downscaled CMIP5 Future Climate Projections." *Science of the Total Environment* 592: 12–24. https://doi.org/10.1016/j.scitotenv.2017.03.086.

Lundquist, Jessica D., Mimi Hughes, Brian Henn, Ethan D. Gutmann, Ben Livneh, Jeff Dozier, and Paul Neiman. 2015. "High-Elevation Precipitation Patterns: Using Snow Measurements to Assess Daily Gridded Datasets across the Sierra Nevada, California." *Journal of Hydrometeorology* 16 (4): 1773–92. https://doi.org/10.1175/JHM-D-15-0019.1.

Ma, Yingzhao, Yinsheng Zhang, Daqing Yang, and Suhaib Bin Farhan. 2015. "Precipitation Bias Variability versus Various Gauges under Different Climatic Conditions over the Third Pole Environment (TPE) Region." *International Journal of Climatology* 35 (7): 1201–11. https://doi.org/https://doi.org/10.1002/joc.4045.

Mernild, Sebastian H, Edward Hanna, Joseph R McConnell, Michael Sigl, Andrew P Beckerman, Jacob C Yde, John Cappelen, Jeppe K Malmros, and Konrad Steffen. 2015. "Greenland Precipitation Trends in a Long-Term Instrumental Climate Context (1890–2012): Evaluation of Coastal and Ice Core Records." *International Journal of Climatology* 35 (2): 303–20. https://doi.org/https://doi.org/10.1002/joc.3986.

Potter, N. J., C. Petheram, and L. Zhang. 2011. "Sensitivity of Streamflow to Rainfall and Temperature in South-Eastern Australia during the Millennium Drought." In MODSIM 2011 - 19th International Congress on Modelling and Simulation - Sustaining Our Future: Understanding and Living with Uncertainty, 3636–42.

Raleigh, Mark S, and Jessica D Lundquist. 2012. "Comparing and Combining SWE Estimates from the SNOW-17 Model Using PRISM and SWE Reconstruction." *Water Resources Research* 48 (1): 1–16. https://doi.org/10.1029/2011WR010542.

Rana, G., and N. Katerji. 2000. "Measurement and Estimation of Actual Evapotranspiration in the Field under Mediterranean Climate: A Review." In *European Journal of Agronomy*, 13:125–53. Elsevier. https://doi.org/10.1016/S1161-0301(00)00070-8.

Rasmussen, Roy, Bruce Baker, John Kochendorfer, Tilden Meyers, Scott Landolt, Alexandre P. Fischer, Jenny Black, et al. 2012. "How Well Are We Measuring Snow: The NOAA/FAA/NCAR Winter Precipitation Test Bed." *Bulletin of the American Meteorological Society* 93 (6): 811–29. https://doi.org/10.1175/BAMS-D-11-00052.1.

Roche, James W., Qin Ma, Joseph Rungee, and Roger C. Bales. 2020. "Evapotranspiration Mapping for Forest Management in California's Sierra Nevada." *Frontiers for Global Change*. https://doi.org/10.3389/ffgc.2020.00069.

Saft, Margarita, Andrew W. Western, Lu Zhang, Murray C. Peel, and Nick J. Potter. 2016. "The Influence of Multiyear Drought on the Annual Rainfall-Runoff Relationship: An Australian Perspective." *Water Resources Research* 51: 2444–63. https://doi.org/:10.1002/ 2014WR015348.

Tian, Wei, Peng Bai, Kaiwen Wang, Kang Liang, and Changming Liu. 2020. "Simulating the Change of Precipitation-Runoff Relationship during Drought Years in the Eastern Monsoon Region of China." *Science of the Total Environment* 723: 138172. https://doi.org/10.1016/j.scitotenv.2020.138172.

Vaze, J, D A Post, F H S Chiew, J.-M. Perraud, N R Viney, and J Teng. 2010. "Climate Non-Stationarity – Validity of Calibrated Rainfall–Runoff Models for Use in Climate Change Studies." *Journal of Hydrology* 394 (3): 447–57. https://doi.org/10.1016/j.jhydrol.2010.09.018.

Wang, Shusen, Ming Pan, Qiaozhen Mu, Xiaoying Shi, Jiafu Mao, Christian Brümmer, Rachhpal S. Jassal, Praveena Krishnan, Junhua Li, and T. Andrew Black. 2015. "Comparing Evapotranspiration from Eddy Covariance Measurements, Water Budgets, Remote Sensing, and Land Surface Models over Canada." *Journal of Hydrometeorology* 16 (4): 1540–60. https://doi.org/10.1175/JHM-D-14-0189.1.

Wilson, Kell B., and Dennis D. Baldocchi. 2000. "Seasonal and Interannual Variability of Energy Fluxes over a Broadleaved Temperate Deciduous Forest in North America." *Agricultural and Forest Meteorology* 100 (1): 1–18. https://doi.org/10.1016/S0168-1923(99)00088-X.

Yang, Daqing, Shig Ishida, Barry E. Goodison, and Thilo Gunther. 1999. "Bias Correction of Daily Precipitation Measurements for Greenland." *Journal of Geophysical Research* 104 (D6): 6171–81. https://doi.org/10.1029/1998JD200110.

Zeff, Harrison B., Andrew L. Hamilton, Keyvan Malek, Jonathan D. Herman, Jonathan S. Cohen, Josue Medellin-Azuara, Patrick M. Reed, and Gregory W. Characklis. 2021. "California's Food-Energy-Water System: An Open Source Simulation Model of Adaptive Surface and Groundwater Management in the Central Valley." *Environmental Modelling and Software* 141 (March): 105052. https://doi.org/10.1016/j.envsoft.2021.105052.

Please also note the supplement to this comment:
https://hess.copernicus.org/preprints/hess-2021-55/hess-2021-55-AC3-supplement.pdf