Evaluating an Earth system model from a water manager perspective

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Abstract. The large spatial scale of global Earth system models (ESM) is often cited as an obstacle to using the output by water resource managers in localized decisions. Recent advances in computing have improved the fidelity of hydrological responses in ESMs through increased connectivity between model components. However, the models are seldom evaluated for their ability to reproduce metrics that are important for and resonate with practitioners, or that allow practitioners to situate higher-resolution model outputs within a cascade of uncertainty stemming from different models and scenarios. We draw on the combined experience of the author team and water manager workshop participants to identify salient water management metrics and evaluate whether they are credibly reproduced over the conterminous U.S. by the Community Earth System Model v2 Large Ensemble (CESM2). We find that while the exact values may not match observations, aspects such as interannual variability can be reproduced by CESM2 for the mean wet day precipitation and length of dry spells. CESM2 also captures the proportion of annual total precipitation that derives from the heaviest rain days in watersheds that are not snow-dominated. Aggregating the 7-day mean daily runoff to HUC2 watersheds also shows rain-dominated regions capture the timing and interannual variability in annual maximum and minimum flows. We conclude there is potential for far greater use of large ensemble ESMs, such as CESM2, in long-range water management decisions to supplement high resolution regional projections.

1 Introduction

Water availability and water quality for human consumption, ecosystems, and agriculture are fundamental requirements, making pertinent assessments of future change crucial for adaptation planning (IPCC, 2022). Climate related changes in the hydrologic cycle will affect substantial portions of the world population, most directly through changes in water availability at or near the surface (Mankin et al., 2020; Sedláček and Knutti, 2014). The information required by water managers for decision making is not readily available in a relevant format, or at sufficient spatial or temporal resolutions from global Earth system models (ESM; e.g., Ekström et al., 2018). We explore how the Community Earth System Model (CESM) represents the climatology of water availability, focusing on metrics that are familiar to decision makers in planning investment-scale decisions. The inability of ESMs to explicitly resolve sub-grid scale (~100 km) processes is often cited as the limitation preventing direct model use in decision making. Literature from large organizations making infrastructure decisions (e.g., Brekke, 2011; Brekke et al., 2009; Reclamation, 2016, 2014) emphasize downscaling climate model data closer to the scale of the watersheds they manage. These additional modeling steps add complexity and may increase statistical errors (Clark et al., 2015; Ekström et al., 2018). Extracting useful and robust information directly from ESMs would reduce such errors if metrics most important to decision makers, such as the timing of peak flow, were known to be robustly represented.

There are many comprehensive examples of metrics used to evaluate climate and hydrological models (e.g., Ekström et al., 2018; Mizukami et al., 2019; Wagener et al., 2022), and communicate the impacts of climate change (e.g., Reed et al., 2022), or to identify decision-relevant metrics (e.g., Bremer et al., 2020; Mach et al., 2020; Underwood et al., 2018; Vano et al., 2014). However, very few have examined whether user defined metrics can be reliably reproduced by ESMs (Mankin et al., 2020), and if further model development and scale reduction is warranted instead of improved communication (Pacchetti et al., 2021). Better communication may also reduce the temptation of some users to calculate "standard hydroclimate metrics" that are not supported by the climate model data (Ekström et al., 2018).

In contrast, climate model output can be rejected unnecessarily when simulated annual minima from freely running simulations do not "match" the sequence of observed low flows (Ekström et al., 2018; Moise et al., 2015). Similarly, the benefits of a range of projected outcomes from different climate models are not widely appreciated beyond the climate model community (Tebaldi and Knutti, 2007). Large ensembles from a single climate model initialized with a range of atmospheric and ocean conditions, such as the CESM2 Large Ensemble (LENS2; Rodgers et al., 2021), help to bound the uncertainty that derives from a naturally chaotic system. Averaged over the full ensemble, they give a better estimate of the model's response to internal and external forcing (Deser et al., 2012) and enable assessments of the rarity of projected extremes. The additional analysis to identify structural (i.e. model formulation) and internal variability within regional climate models means that there are fewer large ensembles at a high resolution (Deser et al., 2020).

Since different decision makers have different priorities and time-scales of interest, Shepherd et al. (2018) recommended the development of climate storylines to communicate with those using climate data to make decisions. Informed by prior surveys of water managers (e.g., Brekke, 2011; Brekke et al., 2009; Cantor et al., 2018; Raff et al., 2013; Wood et al., 2021), Fig. 1 aims to map the different types of water decisions (e.g., Raff et al., 2013 Fig. 3) to the different scales of model resolution (Meehl et al., 2009 Fig. 2). Water managers make daily operational decisions (e.g., to control instantaneous river flow) with the aid of fine-scale weather and flood models (<4 km) that reliably represent convective and local weather scale processes even though their predictability is relatively short lived (Yuan et al., 2019; far left side of Fig. 1). Larger watershed operations (such as reservoir management or groundwater recharge; e.g., Regional Water Authority, 2019) depend on seasonal outlooks (middle left of Fig. 1). Smaller adaptation and mitigation projects take place at the typical policy or decadal prediction scale (i.e., 4-10 years; middle right of Fig. 1). Finally, major public investments and inter-basin agreements occur at the same time scales as climate projections (30-100 years; far right of Fig. 1) where persistent and relatively predictable synoptic and planetary scale processes are well represented in lower resolution (~100 km) climate models (Phillips et al., 2020). While forecasts (seasonal or decadal) are re-initialized from specific atmosphere, ocean or land states at regular time intervals, climate projections are run freely from a variety of atmospheric and oceanic conditions that take several decades to converge to a mean climatology. In considering the utility and useability of information directly from ESMs we focus on decisions made over decadal to climate scales at larger spatial scales.

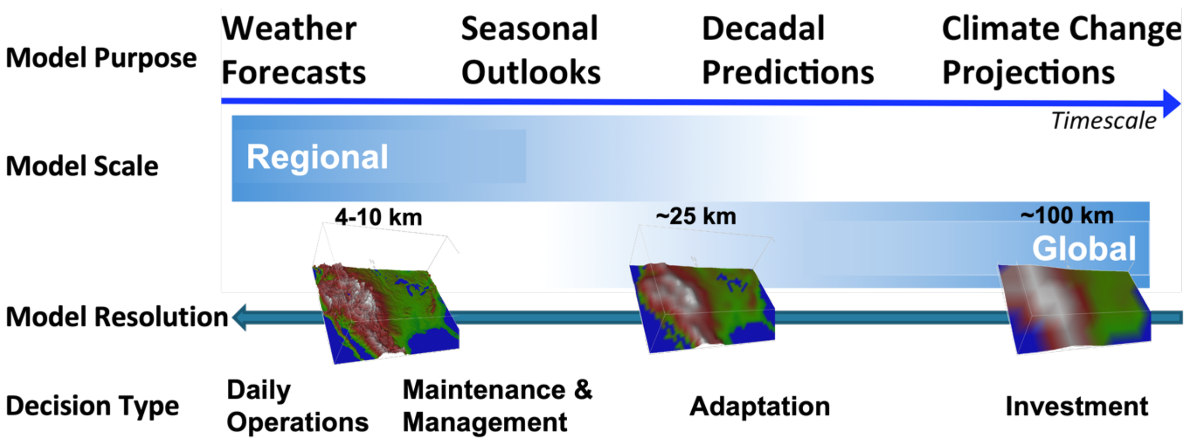


Figure 1: Mapping the temporal and spatial scales of models to the timeframes for water management decisions.

Given that ESMs have advanced immeasurably in the recent decade, it is time to re-evaluate whether their direct output can support decision makers. Such an evaluation needs to focus on how well the models can reproduce metrics used by decision makers, and whether the results are credible (Briley et al., 2020; Jagannathan et al., 2021). Here we evaluate the credibility of one ESM in generating metrics known to be salient for water management decisions; specifically, decisions for water management infrastructure project investments.

The motivation for this paper is to identify:

- a set of water availability metrics that resonates with decision makers and supports their investment-scale decisions;
- how well CESM2 represents the climatology and recent observed behaviors of those metrics; and
- the range of CESM2 structural uncertainty and internal variability for these metrics.

This paper builds off a decade of collaboration between scientists at the National Center for Atmospheric Research (NCAR) and US water agencies that led to a virtual workshop (Tye, 2023), and presents a test case for improved communication with water management decision makers. The focus is on the Conterminous United States (CONUS) to match the interest of workshop participants.

2 Climate Information Needs from Prior Research

Information needs vary greatly, from 5-minute rainfall totals at a point (ASCE, 2006), to basin-wide measures of annual minimum and maximum total runoff. Water management decision metrics can be grouped into similar types such as timing, frequency, magnitude, extreme values, variability, and duration of events (Ekström et al., 2018). While some aspects of timing, magnitude, or variability can be reliably reproduced by ESMs (e.g., Deser et al., 2020; Tebaldi and Knutti, 2007), others such as short duration extremes are less reliable.

Methods of evaluation and data use also differ. For instance, Clifford et al. (2020) reported that predicting general changes in the frequency of extreme precipitation events is more useful for future planning than the precise prediction of mean values evaluated by model developers. Lehner et al. (2019) emphasized that models need to be evaluated for their ability to reproduce sensitivities (e.g., streamflow changes in response to temperature and precipitation changes) in addition to mean states. However, metrics that are meaningful for evaluating a model's capabilities (e.g., the ratio of precipitation to runoff) are less valuable for management decisions (Lehner et al., 2019; McMillan, 2021; Mizukami et al., 2019). When reporting results, water managers are more familiar with the 'water year', rather than the calendar year, to capture the full annual hydrological cycle (Ekström et al., 2018). While the use of water years is a nuance that does not add substantial value to climate model assessments, communication with decision makers is improved by presenting data in a familiar format (Briley et al., 2020).

There is a need for information at the local scale that is unlikely to be met directly by raw outputs from the current generation of ESM. But better communication of the variability in future daily precipitation and associated runoff can add value to the detailed models by bringing in the added statistical context and perspective of the large ensembles. Thus, we believe that ESMs can produce useful information about hydro-meteorological extremes when presented at different spatial or temporal scales, and offer the benefits of large climate model ensembles to constrain future impact uncertainty.

Appendix A summarizes potential hydrological metrics used in water management decisions (Jagannathan et al., 2021) or statistical assessments of extremes (Zhang et al., 2011), and model evaluations (Phillips et al., 2020). Metrics in bold are presented in this paper. We only considered a simplistic measure of meteorological drought (absence of rain) in the current work, as drought is sensitive to the definition (Bachmair et al., 2016) and local conditions (Mukherjee et al., 2018), and so not suited to a generalized assessment. Similarly, snow measures are not included in this assessment in part due to limited availability of high-quality, long-duration, quality-controlled, observational data (McCrary et al., 2017); and partly due to the biases in snow distribution arising from the smoothed topography in GCMs (McCrary et al., 2022).

3 Data and Methods

3.1 Climate Model Data

CESM2 (Danabasoglu et al., 2020) is a fully coupled global model that simulates the Earth's climate system through interactive models for atmosphere, ocean, land, sea-ice, river runoff, and land-ice. Variables considered in this project are taken from the Community Atmosphere Model version 6 (CAM6) and the Community Land Model version 5.0 (CLM5; Lawrence et al., 2019) and are part of the default model outputs. A schematic of the model components is included in Appendix B. This project uses daily values scaled up to annual (e.g., annual maximum daily precipitation) on a ~1 degree resolution grid. Data were extracted over the CONUS from 10 ensemble members of LENS2 (Rodgers et al., 2021) for model validation in the current era (1981-2010).

3.2 Observations

Gridded daily observations of precipitation at 1/16° horizontal resolution (~6 km) were obtained from the Livneh et al. (2013) dataset covering CONUS and southern Canada for the control period (1981-2010), hereafter referred to as "Livneh". Pierce et al. (2021) provided an update to the Livneh data set to address time adjustments that result in an underestimation of the most extreme daily precipitation totals and resultant runoff and flood potential (Pierce et al. 2021). However, as we are also interested other measures of precipitation and in runoff minima, we did not employ the updated gridded observations.

Livneh daily temperature maxima and minima, and precipitation were used to force the Variable Infiltration Capacity Model (VIC; Liang et al., 1994) version 4.1.2 to obtain runoff estimates for years 1980-2005 as evaluated in Livneh et al. (2013). Hereafter referred to as "Livneh-VIC".

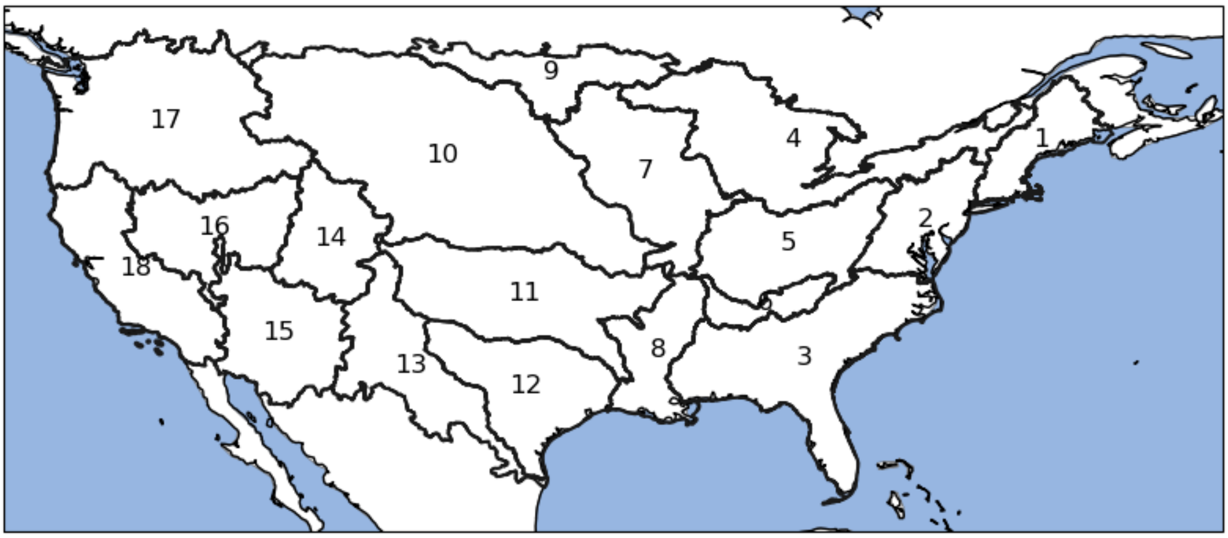


Figure 2: HUC 2 regions used in data validation and analysis. Regions defined by USGS (2013): Region 01 New England (NE); Region 02 Mid-Atlantic (MA); Region 03 South Atlantic-Gulf (SA); Region 04 Great Lakes (GL); Region 05 Ohio (OH); Region 06 Tennessee (TN); Region 07 Upper Mississippi (UM); Region 08 Lower Mississippi (LM); Region 09 Souris-Red-Rainy (RR); Region 10 Missouri (MR); Region 11 Arkansas-White-Red (ARK); Region 12 Texas-Gulf (GUL); Region 13 Rio Grande (RIO); Region 14 Upper Colorado (UC); Region 15 Lower Colorado (LCO); Region 16 Great Basin (GB); Region 17 Pacific Northwest (PN); Region 18 California (CA)

3.3 Methods

All analyses were carried out using the North American water year (1 October to 30 September) to facilitate later communication.

3.3.1 Remapping

For ease of comparison, model output were re-gridded using a conservative second-order remapping (Jones, 1999) to place both datasets on the same scale grid and assess anomalies. Data were also calculated as areal averages or totals over the 2-digit Hydrological Unit Code (HUC2) regions (Seaber et al., 1987). HUC2 basins represent 18 watersheds, covering areas ranging from 41,000 mi^2 (~105,000 km^2; Tennessee) to 520,960mi^2 (1,350,000 km^2; Missouri), shown in Fig. 2. While the scale of HUC2 regions may be large for some local decision-makers, it is also a more appropriate and conservative scale to compare to ESMs as demonstrated by Lehner et al. (2019).

3.3.2 Percentile-based thresholds

The threshold for very heavy rain days (Q95) was calculated at each individual grid cell using only days with ≥ 1 mm rain ("wet days"). Thresholds were derived empirically for each model ensemble member, with the ensemble mean threshold (Q95) used to identify the days per year exceeding the threshold (N95) and total annual rainfall from those days (P95).

Runoff was aggregated over each HUC2 watershed and multiplied by the respective area to generate total volume per day. Volume per day was then converted to measurements more familiar to users, such as acre feet per day or cubic meters per second. Daily time series of total volumetric runoff had a 7-day running mean smoother applied, then annual maximum, minimum and mean values were extracted. The highest and lowest 7-day average runoff expected once per decade (7Q90, 7Q10) were estimated empirically from the 25 ranked values of annual maxima and minima per watershed. Stationarity was assumed over the climatological period for the purposes of these analyses, acknowledging that changes may have already occurred in the frequency of these events.

4 Model Evaluation

The metrics used to evaluate CESM2's ability to reproduce large scale features and physical behaviors (e.g., Danabasoglu and Lamarque, 2021 and the associated Special Issue) are not necessarily those employed by decision makers. ESMs are designed to represent large-scale atmospheric processes and fluxes not specific local responses (Gettelman and Rood, 2016), but this design assumption may not be sufficiently well communicated to decision makers. The purpose of our evaluation is to establish whether CESM2 output is also fit for local decision purposes, or if the breadth of information from ESM ensembles remains unsuitable for immediate use in targeted water management decisions.

4.1 Rainfall metrics

While broad spatial patterns of seasonal mean daily rainfall are reproduced well (Danabasoglu et al., 2020; Feng et al., 2020; Simpson et al., 2022), CESM2 fails to capture details over high topography, and overestimates summer precipitation where convective extremes dominate summer rainfall (Appendix C). The seasonal mean precipitation also fails to capture some important watershed-level processes, such as the seasonal variability in the number of days with precipitation and the associated intensity.

Estimates of mean annual rainfall on wet days, or wet day volume, are in broad agreement between Livneh and CESM2 output. Figure 3 shows an example of the mean number of wet days per month (NWD), and mean wet day volume (WDV) averaged over the California and Pacific Northwest. While CESM2 represents the NWD annual cycle very well in regions such as California (Fig. 3a, 3c) and the Pacific Northwest (Fig. 3b, 3d), it does not capture NWD in many central and snow dominated regions (Fig. S1 and Fig. S2). This is likely due to the smoother topography of CESM2 missing the influence of orographic uplift, and large spatial scale missing sub-grid scale convective systems (e.g., over the Central Plains). The figures also highlight the scale of model (structural and internal variability) uncertainty present in the ensemble. As noted in previous sections, water management decision-makers are aware of the potential scale of uncertainty and expressed a desire for the full ensemble range to be presented to them instead of ensemble means.

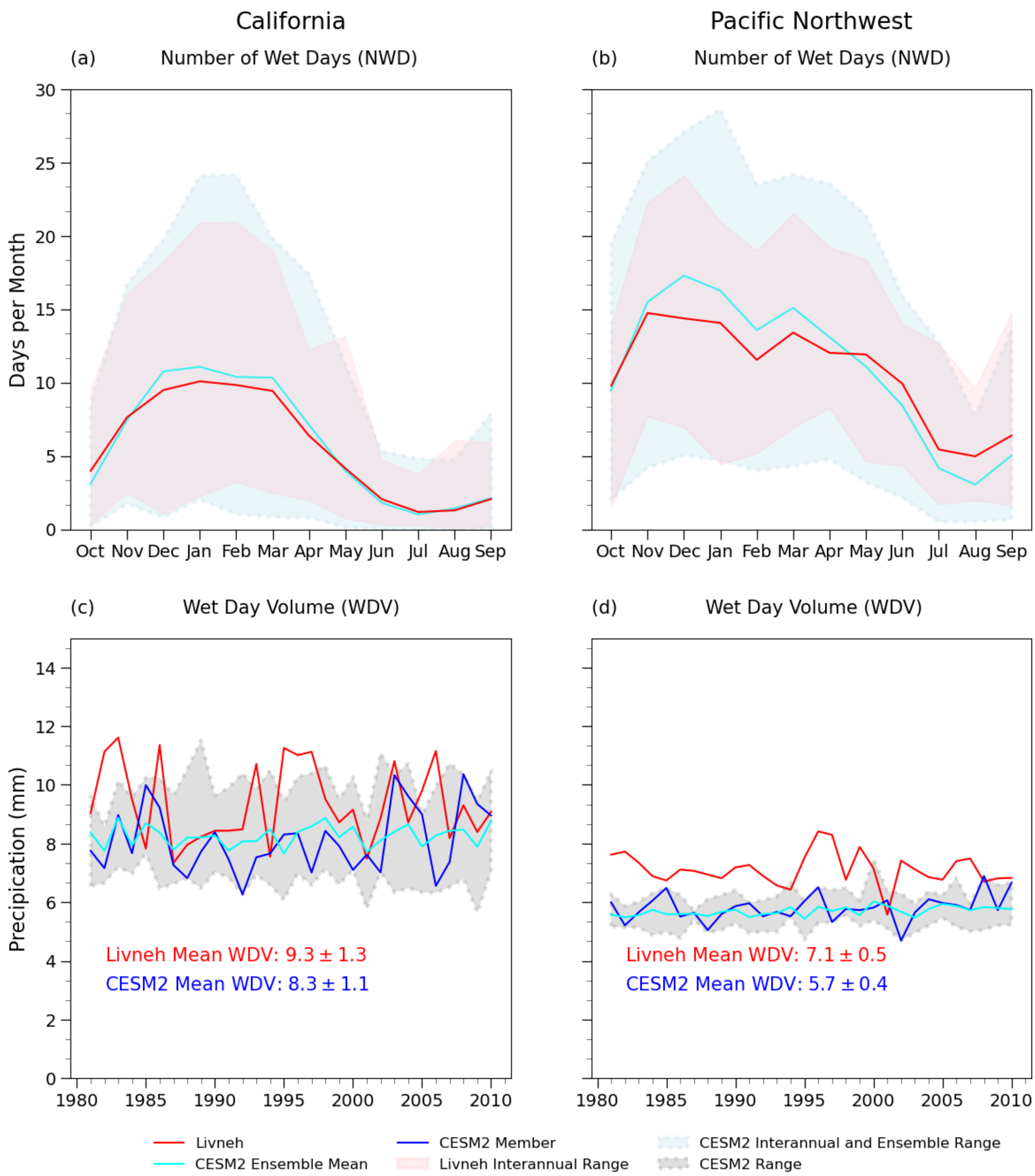


Figure 3: Average number of wet days per month (a, b) and interannual variability in mean annual precipitation on wet days for Livneh climatological mean (red) with interannual spread (pink) and CESM2 mean (cyan) with interannual and ensemble spread (gray); and (c,d) between 1981-2010 for observations derived from Livneh (red) and an individual CESM2 ensemble member (blue) and Ensemble spread (gray) in (a,c) Region 18 California (CA); and (b,d) Region 17 Pacific Northwest (PN).

The annual variability in WDV, both year-to-year variations as well as the overall range of minima and maxima, is well captured by each of the model members for the different HUC2 regions, even if the absolute values do not match (Fig. 3 c,d). As expected, the specifics of which years have high or low values of WDV are not the same for each ensemble member (i.e. demonstrating internal variability). As a result, the ensemble mean value of WDV (cyan)does not reflect the same year-to-year variability as the observations or individual ensemble members (blue). Decision makers expressed that the interannual variability demonstrated by each model member is more valuable to demonstrate the credibility of the data than the ensemble mean (Tye, 2023). We recommend that the full range of values of each metric (i.e. after computation for each ensemble member individually) are communicated in addition to the climatological means to help bound uncertainty around decisions (Wilby et al., 2021).

The magnitude of interannual variability in WDV (i.e., the absolute differences between the maximum and minimum values in each member time series) is typically within 10% of observations in all regions as illustrated for two regions in Fig. 3. Exceptions are the Lower Colorado, South Atlantic-Gulf and Upper Mississippi where the simulated distributions are too narrow. Many different sources of error may contribute to this discrepancy, such as the inability to resolve convective precipitation (Chen et al., 2021) in addition to elevation changes not captured by the coarse model resolution, or the "drizzle effect" that is common in GCMs (Chen et al., 1996; Dai, 2006).

CESM2 captures the longest spells of consecutive dry days per year (CDD; Fig. 4a) and consecutive wet days per year (CWD; Fig. 4b), and their variability. Many regions capture both the interannual variability and the climatological mean duration of CWD, particularly those regions that are subject to large-scale synoptic systems (e.g., Pacific Northwest, Mid Atlantic-Gulf, California). Several regions either overestimate (South Atlantic-Gulf) or underestimate (Great Lakes, Souris-Red-Rainy) the absolute durations of the longest wet spells, but do reflect the magnitude of interannual variability. The exception is Tennessee, where both interannual variability and mean CWD are overestimated. At the grid scale, broad spatial patterns of CWD are correct but the finer atmospheric processes arising from topographic features are incorrect, as expected from the coarse model resolution. A similar pattern is present in CDD, except that some drier regions with CDD >30 days do not capture the full range of interannual variability (Souris-Red Rainy, Missouri, Rio Grande). As GCMs have a tendency to produce drizzle, adjusting for a higher wet day threshold (e.g., 2 mm) might improve dry spell representation in those regions. It is also important to communicate such model sensitivities to users more effectively.

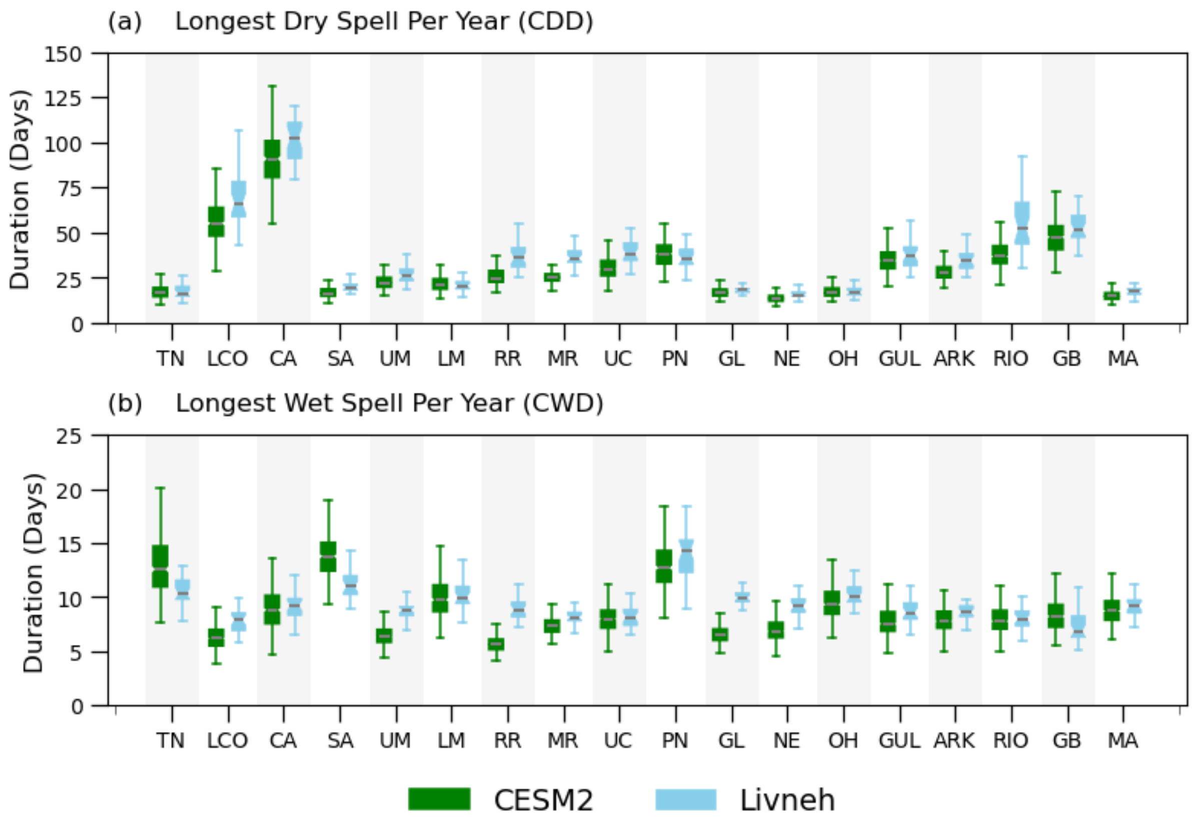


Figure 4: a) Longest duration per year of consecutive days <1 mm rain (longest dry spell) for Livneh over all years (green) and CESM2 ensemble range over all years (blue) for all HUC2 regions; and b) Longest duration per year of consecutive days with ≥1 mm rain (longest wet spell). Regional Acronyms defined in Fig. 2.

The thresholds for heavy and very heavy rain days (P95, P99) are defined with respect to the wet days, and calculated individually and compared for Livneh and CESM2 both to understand whether the intensity of more extreme rainfall is captured, and to evaluate model behavior. A comparison of the thresholds reflects the considerable improvements in modeling capabilities in recent years (Gettelman et al., 2022). For instance, earlier versions of CESM underestimated extreme precipitation intensity by 10-30 mm/day east of the Rockies, and overestimated intensity by 5-10 mm/day to the west (Gervais et al., 2014). We found CESM2 still underestimates the most extreme rainfall, but that errors have approximately halved. As these differences are still inadequate for many engineering and major infrastructure decisions (Wright et al., 2019), we focus on CESM2's ability to capture the relative contributions of P95 and P99 to the annual total and the interannual variability in their frequency. A result with considerable useability is the proportion of annual total precipitation derived from the heaviest rain days, or "Proportional Contribution of Extreme Days" (P95Tot). This proportion and its interannual variability is well represented by CESM2 at the HUC2 scale and has shown to be skillful in other models (Tebaldi et al., 2021).

The interannual variability in the frequency (N95) and intensity of extreme rainfall, as represented by P95Tot, are illustrated in Fig. 5 and 6. In several HUC2 regions the simulations report more frequent events, and proportionally higher totals (e.g., Rio-Grande, Missouri, Upper Colorado and Lower Colorado; Fig. S3). Overall, there is good subjective agreement between Livneh and CESM2, identifying an opportunity to inform local decisions from large scale ESMs.

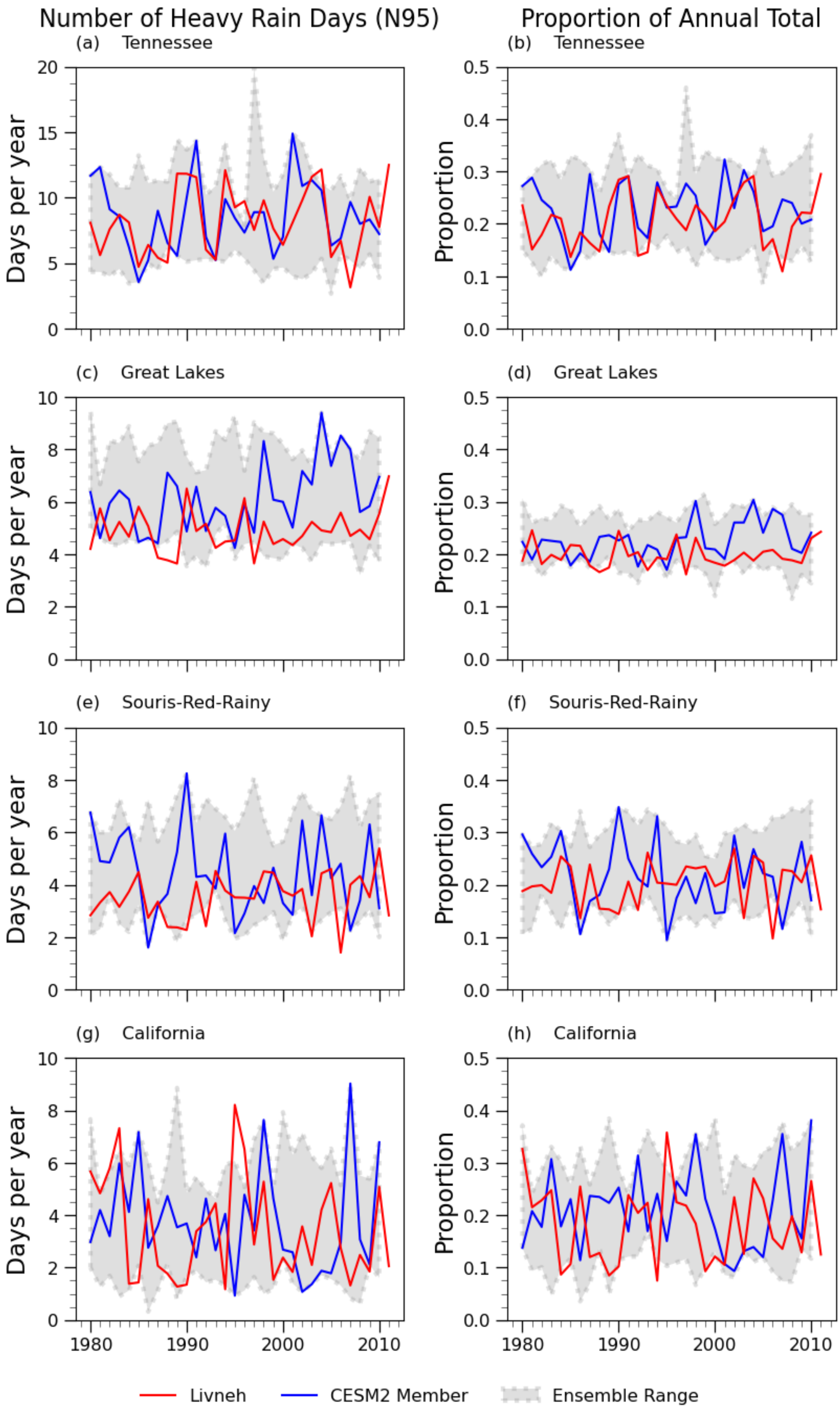


Figure 5: a, c, e, g) Number of very heavy rain days per year; and b, d, f, h) total rain from very heavy rain days as a proportion of the annual total for a, b) Tennessee (TN); c,d) Great Lakes (GL); e,f) Souris-Red-Rainy (RR); and g,h) California (CA) HUC2 regions. Observations in red; CESM2 ensemble spread in gray, single randomly selected ensemble member in blue.

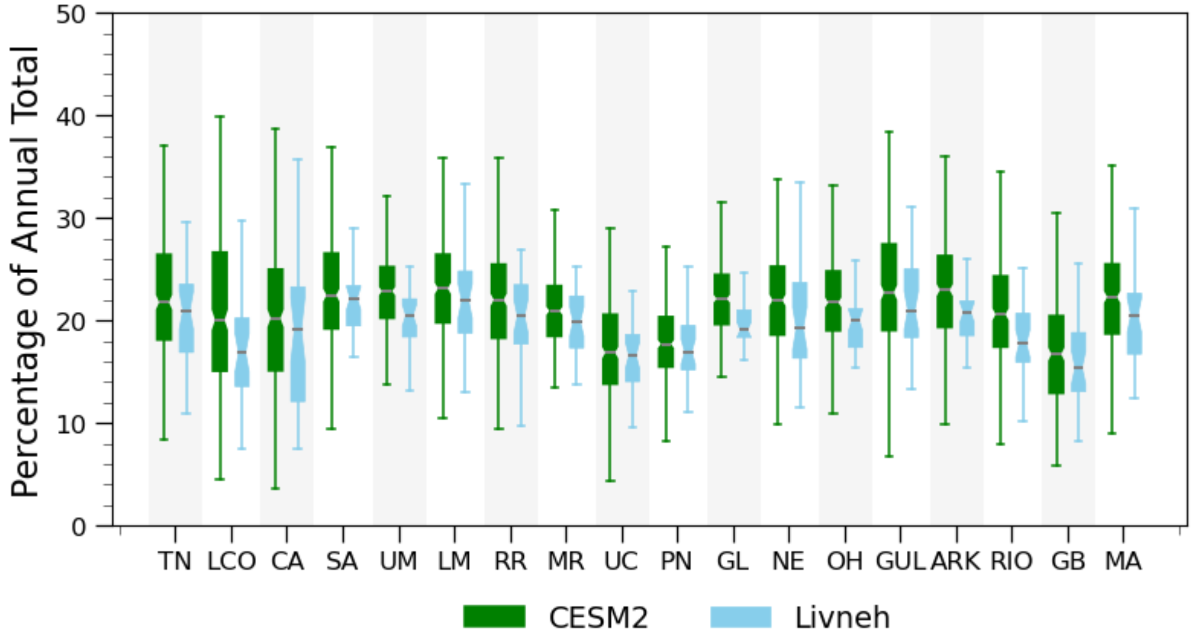


Figure 6: Box plots of the interannual range of contributions to annual total rainfall from very heavy days (P95Tot) shown as percentages for: Observations (light blue), and ensemble range for CESM2 (green) for all HUC2 regions. Boxes are bound by the interquartile range, black lines indicate the median, notches indicate the degree of spread from the median and bars extend to the full data range.

4.2 Runoff metrics

Runoff estimates are taken from the individual components of surface and subsurface runoff generated within CLM5 (Lawrence et al., 2019) and compared to the Livneh forced VIC runoff ("Livneh-VIC").

Assessing the skill of runoff in large-scale models is complicated by many factors, including the mismatch of scales between in-channel flow (~1-10^2 m) and the grid scale (~10^5 m). Thus, metrics of climate model runoff should be selected carefully and the runoff should be aggregated or combined with other metrics, rather than used directly (Lehner et al., 2019). Appendix D demonstrates the discrepancies between the grid-scale representation of runoff from Livneh-VIC and CESM2. The large discrepancies arise from different processes that are not captured adequately, such as groundwater, topography, and associated snow ablation and melt, in addition to meteorological biases.

However, water management decisions are made over watersheds in units such as acre-feet[1] or cubic meters, while model data are output as a depth of runoff over each grid cell (e.g., mm/day per km^2). We aggregated the 7-day running mean daily runoff (Q7) within each HUC2 region to generate Q7 time series in each basin. Fig. 7a illustrates the 25-year mean seasonal cycle for Livneh-VIC in red and CESM2 in blue, and the full range of values over all years and ensemble members for the Souris-Red-Rainy basin (HUC Region 9), additional basins are included in Fig. S4. Data are presented in millions of acre feet, to align with decision maker needs. The minimum simulated Q7 in any year considerably underestimates the lowest flows in this region compared to Livneh-VIC.

[1] 1 Acre-foot is the volume of water it would take to cover 1 acre of land to a depth of 1 foot. Equal to 325,852 gallons or 1,233 m^3 (USGS Water Science).

In contrast, the largest total runoff volume is overestimated and peaks too early in the water year. Figure 7b plots the same information as the cumulative runoff volume from the start of the water year, highlighting that the lowest runoff volume is underestimated by a factor of ten for this region, other regions are illustrated in Fig. S5. Low runoff volumes were typically underestimated in smaller regions (e.g., NE, TN). High runoff volumes were only underestimated in three regions (LM, ARK, GUL) and considerably overestimated in seven regions. Snow-dominated regions perform particularly poorly for both QMax and QMin as snowpack and the timing of associated runoff are not well simulated. Transitional regions that straddle both snow- and rain-dominated hydrology also fail to capture QMax, but better estimate Qmin (not shown). Only the South Atlantic region reproduces both QMax and QMin.

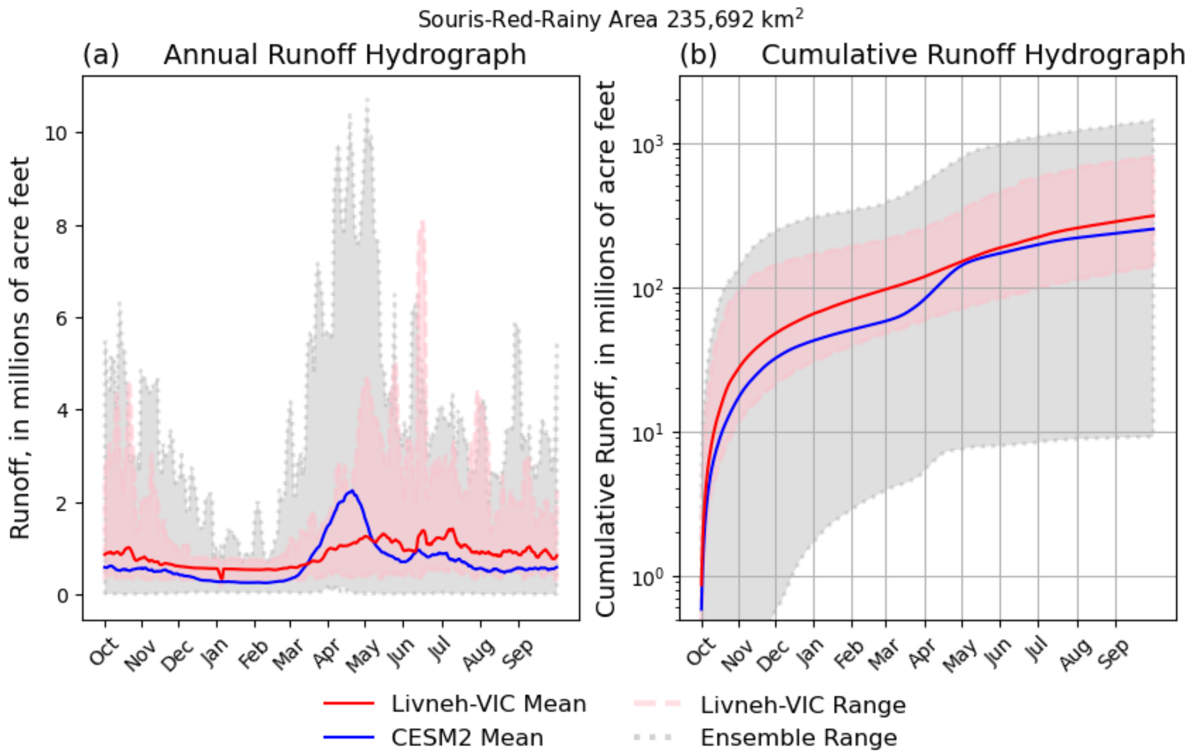


Figure 7: Interannual variability in runoff in Souris Red Rainy Region for a) the mean seasonal cycle; and b) the cumulative watershed runoff over the water year. Livneh-VIC climatological mean in red, range of all years in pink; CESM2 ensemble mean in blue and ensemble range in gray. Figure highlights the underestimation of the lowest runoff volume by CESM2 by a factor of ten.

We explored the relationship between the highest and total annual runoff (QMax/QTot), and lowest and total annual runoff (QMin/QTot). Some regions performed well for QMax/QTot, others performed better for QMin/QTot but there was no consistent relationship that could be utilized by decision makers.

Participants at the NSF NCAR workshop (Tye, 2023) emphasized that the exact numbers produced by climate models are not very important for future decisions. Others have also emphasized the importance of well-represented processes in the model (Reed et al., 2022) and correlations with known experiences (Mach et al., 2020; Shepherd et al., 2018). Focusing on fidelity to the historical climate exaggerates the importance of model performance instead of robustness to different conditions without ensuring that model predictions are useful or reliable (Brunner et al., 2021; Wagener et al., 2022). Runoff estimates in transitional catchments may be inadequate in the current climate but plausible in the future, if the model reproduces rain-dominated hydrological processes (McMillan, 2021).

Climatological mean runoff cycles are estimated from Pardé coefficients — calculated as Q7/QTot on each calendar day — a dimensionless value that enables comparison across regions. Figure 8 depicts the mean seasonal cycle for representative snow-dominated (Upper Colorado), transitional (Missouri) and rain-dominated (Tennessee) regions, demonstrating how an imperfect representation of snow in the Upper Colorado results in CESM2 peak runoff occurring two months earlier than Livneh-VIC (Fig. 8a). The runoff regimes display very different seasonal characteristics, with CESM2 having a "mid late spring" runoff regime rather than Livneh-VIC's "extreme early summer" regime (Fig. 8a; Haines et al., 1988). Peak runoff is also too early in transitional regions, but closer to Livneh-VIC than in snow-dominated regions (Fig. 8b). Rain-dominated regions capture both the timing of QMax and overall seasonal hydrograph shape (Fig. 8c).

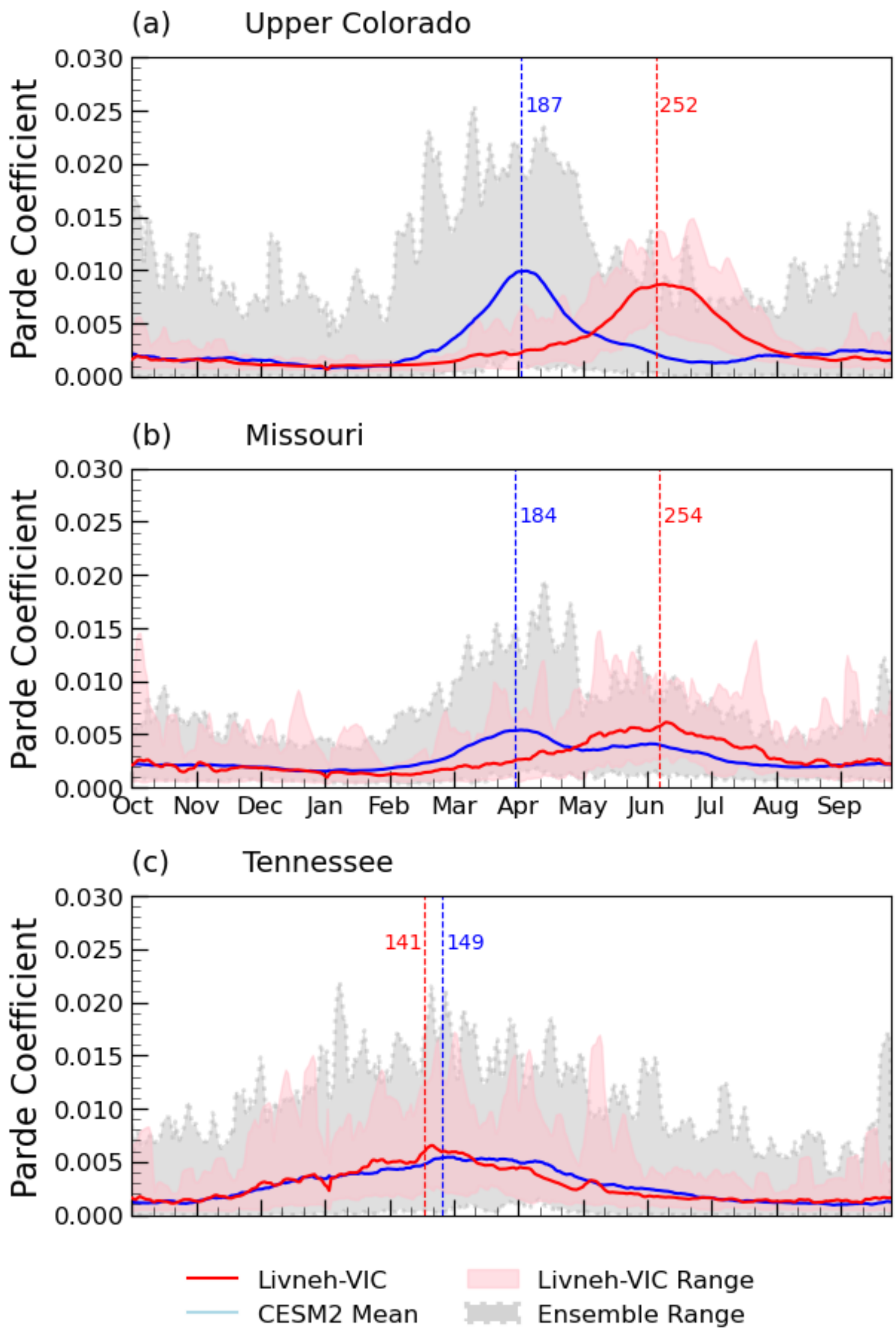


Figure 8 : Seasonal patterns of runoff for HUC2 regions a) Upper Colorado (UC); b) Tennessee (TN); and c) Missouri (MR). Constructed from normalized series of the ratio of 7-day mean runoff to the mean annual total. Livneh-VIC runoff climatological mean (red), climatological range (pink), CESM2 ensemble mean (blue) and ensemble range (gray with dashed border). Vertical lines indicate the mean date of peak runoff with number of days since the start of the water year.

7Q10 and 7Q90 are estimated empirically from annual minima and maxima as occurring once per decade. Projected changes in the frequency of very low or very high runoff volumes are deemed credible where CESM2 replicates the standard deviation of annual minima and maxima according to a χ^2 test at the 5% significance level. Table 1 reports CESM2 and Livneh-VIC regional estimates of 7Q10 and 7Q90 and standard deviations of the annual maxima and minima; values in bold indicate where estimates are statistically similar. It should be noted that the values in Table 1 have ≤10% of occurring in any year, and so represent the tails of the runoff distribution.

Table 1 : Very low (7Q10) and very high (7Q90) regional runoff, and standard deviation in regional annual minima (σ QMin) and annual maxima (σ QMax) for Livneh and CESM2. Values in bold indicate where CESM2 and Livneh-VIC regional runoff are statistically similar according to a χ^2 test.

Region		Livneh-VIC				CESM2			
		7Q10	7Q90	σ QMin	σ QMax	7Q10	7Q90	σ QMin	σ QMax
NE	1	4.1	132.4	1.3	25.5	8.6	215.1	4.7	39.9
MA	2	**6.9**	103.5	**2.5**	25.7	**7.4**	220.7	**3.6**	47.9
SA	3	**21.1**	**240.4**	**8.4**	**50.7**	**20.5**	**258.6**	**11.9**	**45.8**
GL	4	**6.9**	122.5	**2.2**	23.8	**7.8**	331.0	**4.3**	58.0
OH	5	**7.8**	187.6	**2.3**	53.0	**9.4**	260.9	**4.5**	56.4
TN	6	2.1	**90.5**	0.8	**23.1**	0	**98.7**	0.3	**21.7**
UM	7	2.1	78.2	1.7	16.9	7.9	122.3	4.7	31.5
LM	8	3.9	212.2	1.1	36.1	8.0	81.0	5.1	14.7
RR	9	1.0	**24.3**	0.5	**7.1**	0	**33.0**	0.1	**8.4**
MR	10	2.3	103.0	1.6	28.1	5.2	147.4	4.2	30.4
ARK	11	2.2	130.5	0.7	36.2	3.2	93.9	4.5	18.1
GUL	12	1.5	99.1	0.5	35.5	1.3	70.7	2.8	16.7
RIO	13	**0.5**	**22.5**	**0.2**	**5.8**	**0.4**	**29.5**	**1.3**	**7.3**
UC	14	0.6	27.3	0.2	7.2	0	74.7	0.2	15.3
LCO	15	0.5	19.4	0.2	7.5	0.3	46.7	0.7	11.6
GB	16	0.7	33.3	0.3	10.3	1.8	71.5	1.3	21.1
PN	17	20.6	266.5	7.9	50.2	4.4	449.6	2.6	87.3
CA	18	1.6	323.2	0.4	101.9	1.3	233.4	1.1	61.3

Grid-scale estimates such as mean daily runoff readily highlight why decision makers have low confidence in CESM2 output: the metrics are not salient and appear to have no skill. After aggregating the 7-day mean daily runoff to watershed scales, some skill emerges in the annual minima and maxima, and seasonal cycles. Snow-dominated watersheds perform poorly with regard to peak runoff volume and timing of the peaks and lows, as expected (McCrary et al., 2022). Rain-dominated watersheds capture the inter-annual variability and magnitudes of peak and low flows, and the seasonal hydrographs. While CESM2 at this coarse scale does not represent the local topography and cannot represent finer scale snow, our analysis indicates the land surface model correctly simulates the overall bulk water budget for most watersheds as illustrated in Figures 7 and 8. However, the tail behavior of highest and lowest total watershed runoff is only captured by a few basins and so caution needs to be exercised in the interpretation and use of model results, as biases may propagate into the future. This is premised on the understanding of *why* the model can produce accurate results, and whether the accuracy can be reliably reproduced for the future climate (Wagener et al., 2022).

While participants at the NSF NCAR workshop stated that precise estimates are not necessary, they also emphasized their desire for high confidence in the projected scale and direction of any changes. We note that “confidence” is derived from a combination of 1) credible process representation; 2) agreement with historical trends, given internal variability; 3) agreement across multiple models. It is worth noting that trends in extremes may be important without being statistically significant, as a limited sample of points (e.g. one per year) from a stochastic series is inherently noisy. However, some of these trends may emerge from the noise in the distribution and so are important to monitor.

6 Discussion

As decision makers have become more immersed in developing water management adaptation plans, the role of “climate services” in developing salient climate information has increased (Briley et al., 2020; Brugger et al., 2016; Dilling et al., 2019). We tested our hypothesis that recent improvements in ESMs can allow decision-relevant metrics to be produced directly, by leveraging the combined experience of the author team, results from the NCAR workshop, and the wealth of literature on actionable knowledge (Bremer et al., 2020; Jagannathan et al., 2021; Mach et al., 2020; Vano et al., 2014). Given that no model can perfectly address all decision needs, we identified and evaluated multiple metrics that can frame specific water management decisions within the known constraints of the data (Lempert, 2021), or within the decision makers’ experiences (Austin, 2023; Clifford et al., 2020; Reed et al., 2022; Shepherd et al., 2018).

It is important to communicate the original purpose of the model and associated weaknesses, so that decision makers fully understand which information is appropriate to use in other applications (Fisher and Koven, 2020; Gettelman and Rood, 2016; Wagener et al., 2022). Given the balance between model fidelity and model complexity (Clark et al., 2015) and the absence of detailed global scale observation data (e.g., Gleason and Smith, 2014; Reba et al., 2011) CESM2 provides a plausible representation of Earth system processes and moisture fluxes, but may not capture basin-scale specifics (Ek, 2018; Lehner et al., 2019). That said, there are continued efforts to improve the simulation of land surface processes and analyses such as those presented in this article can flag weaknesses for future improvement (Lawrence et al., 2019).

Establishing model fidelity also requires distinguishing an accurate representation of the climate processes from serendipitous correlation with observations. Whether the model has good process representation overall, or exactitude in one simulation can be established through internal variability analyses using large ensembles (e.g., Deser et al., 2020; Tebaldi et al., 2021). Repeating the analyses with several different ESMs to establish the degree of agreement (Mankin et al., 2020) would further strengthen the usability of metrics presented in this article. It is also worth noting that the analysis presented here only used one reference dataset. As different reanalysis and observational datasets can have large discrepancies, a thorough model evaluation would also benefit from comparison to several products (Kim et al., 2020; Newman et al., 2015), including an assessment of how removing temporal adjustments in observations affects the statistics of extremes (Pierce et al., 2021).

While the precise details of precipitation and runoff may not be well simulated by CESM2, we found some aspects are credible. The frequency of wet days highlighted regions where current seasonal behavior is well captured, and may support planning around flood and drought control or wildfire risk when used in combination with other models or data sources (Austin, 2023; Clifford et al., 2020; Jagannathan et al., 2021; Reclamation, 2016).

7 Conclusions

This paper presented an assessment of whether a standard resolution (~100 km grid) Earth system model is capable of producing information that water users typically employ in their decisions. Our motivation was to explore whether it is possible to reduce the need for intermediate downscaling, and to broaden the use of large model ensembles to quantify the influence of internal variability on localized decisions. We drew on the combined experience of the project team and workshop participants to identify potential metrics and familiar modes of visualization. This project used only CESM2 over the conterminous United States to develop example metrics that may be explored within other models and over other regions. CESM2 is unable to reproduce some metrics given the lack of topographical detail. A companion paper by Rugg et al. (2023) examines potential improvements to the subgrid-scale simulation of land processes to improve the representation of the hydrological cycle in mountainous regions.

We encourage others working in the decision space between climate data producers and users to be forthcoming about specific regions and reasons where model data are not credible, or where the model has particular weaknesses (such as the drizzle effect) that may be overcome with a different analysis approach.
For future model assessors, the following metrics were found to be salient for water users and were skillfully reproduced in many regions.

Rainfall:

- Number of wet days (≥ 1mm of rain) per year/season
- Mean precipitation on wet days
- Duration of the longest wet and dry spells per year
- Number of days with rain > 95th percentile of current climate wet day totals
- Proportion of the annual total derived from days > 95th percentile of wet day totals

Runoff (aggregated up to basin level, as a volume for 3- and 7-day averages):

- Annual maxima and minima

- Frequency of very high or very low flows (< 10% annual chance of occurring in the current climate)
- Proportion of averaged daily runoff to annual total

The work presented in this paper is a small step toward establishing greater usability of climate model output by decision makers. The present evaluation is also only the first step in evaluating ESM performance. Additional research is needed to support water managers placing these results and their uncertainty in the context of additional observational data (such as remote sensing) that may already be available to them. Continued collaboration is essential to improve the transfer of knowledge (e.g., data requirements, model assumptions, decision constraints) between communities.

Appendix A

Table A1: Hydro-meteorological responses used in water management decisions, and the specific metrics that have potential for representation in ESMs. Metrics in bold are presented in this article.

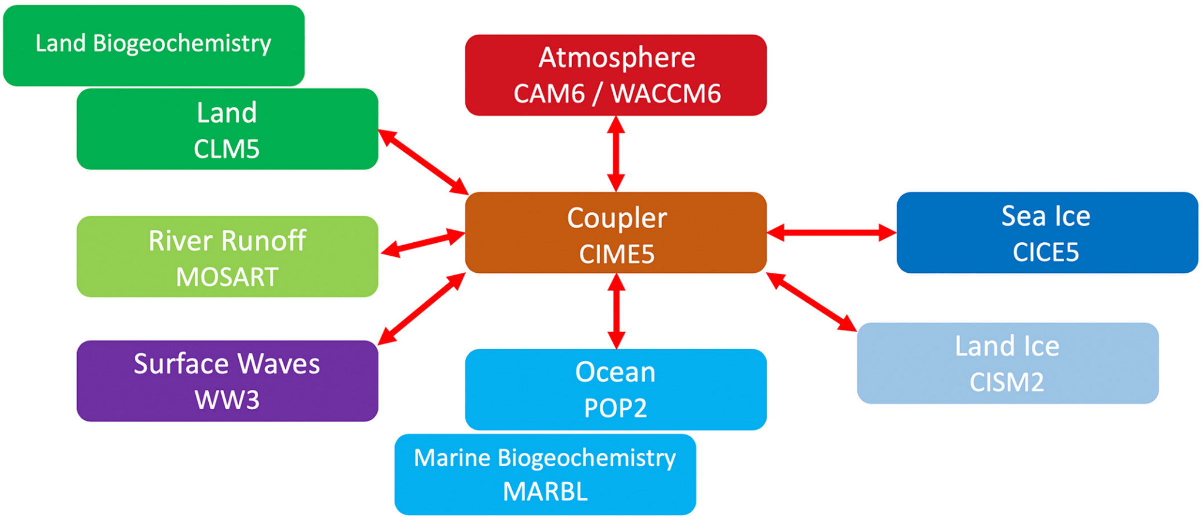
Hydro-meteorological Responses	**Typical Water Management Decision**	**Metric**	**Description**
Annual rainfall	Water supply and drought monitoring	**Total Precipitation (PRCPTOT)**	**Total annual precipitation measured as rainfall or snow water equivalent.**
Seasonal rainfall cycle	Seasonal water supply, reservoir operations management	**Number of Wet Days (NWD),** **Mean Wet Day Volume (WDV)**	**Frequency of days with ≥1mm precipitation (NWD)** per month, season or year, **Mean precipitation on wet days** calculated from PRCPTOT/NWD
Rainfall extreme	Flood and stormwater management	95th percentile (Q95) **Number of very heavy rain days (N95)** Very heavy rain volume (P95) **Proportional contribution of very heavy rain (P95tot)**	Rainfall percentile threshold that is exceeded by 5% rain events per year on average, and calculated from wet days only **Frequency of days with rainfall exceeding Q95** Total rain falling on days exceeding Q95 **Proportional of annual total derived from very heavy rain**, calculated as P95/PRCPTOT
Rainfall extreme (dry)	Water supply planning and drought monitoring/planning including water rights and restrictions.	**Consecutive dry days (CDD)**	**Maximum duration of spell with consecutive days measuring < 1 mm precipitation.**

Hydro-meteorological Responses	**Typical Water Management Decision**	**Metric**	**Description**
Rainfall extreme (wet)	Stormwater management, water supply planning	**Consecutive wet days (CWD)**	**Maximum duration of spell with consecutive days measuring ≥ 1 mm precipitation.**
High streamflow	Reservoir management and flood control, water quality management and water supply management, including use of supplemental water supplies	**Annual maximum runoff (QMax)** Description (JMaxF) Description (HFD)	**Annual maximum daily volume of basin-wide runoff** Julian day of QMax/ day of the water year Duration of high flows
Low streamflow	Water supply management, assessment of water shortages with respect to seasonal demands	**Annual minimum runoff (QMin)** Description (JMinF) Description (LFD)	**Annual minimum daily volume of basin-wide runoff** Julian day of QMin/ day of the water year Duration of low flows
Streamflow	Water supply planning, water quality management, reservoir operations management, planning future investment needs	**7-day mean runoff (Q7)**	**Daily volume of basin-wide runoff averaged over 7 days.** Often presented as percentage of annual total volume of runoff or Pardé coefficient (Pardé, 1933)
Very low streamflow	Water quality management for discharge permits, conservation management, drought planning	**7-day "10-year" low runoff (7Q10)**	**7-day averaged basin-wide lowest volume of runoff with <10% annual probability of occurring.** Estimated from Qmin series.
Very high flow	Flood management and planning, reservoir operations	**7-day "10-year" high runoff (7Q90)**	**7-day averaged basin-wide highest volume of runoff with <10% annual probability of occurring.** Estimated from Qmax series.
Streamflow	Water supply planning, reservoir operations management	Central Tendency (CT) Description (Q_{25}, Q_{50}, Q_{75})	Day of the water year when the cumulative annual runoff exceeds 50% of the total annual runoff Annual quartiles of cumulative annual runoff estimated from daily streamflow.
Snowpack	Reservoir operations and flood management, water supply planning	Snow Water Equivalent (SWE) Maximum (SWEMax) SWEMax Date	Volume of peak snow water equivalent Day of the water year when peak SWE occurs

Hydro-meteorological Responses	Typical Water Management Decision	Metric	Description
		SWE Duration	Total length of snow accumulation and ablation
Snowmelt	Flood management and reservoir operations	Snowmelt onset	Day of water year of snowmelt onset

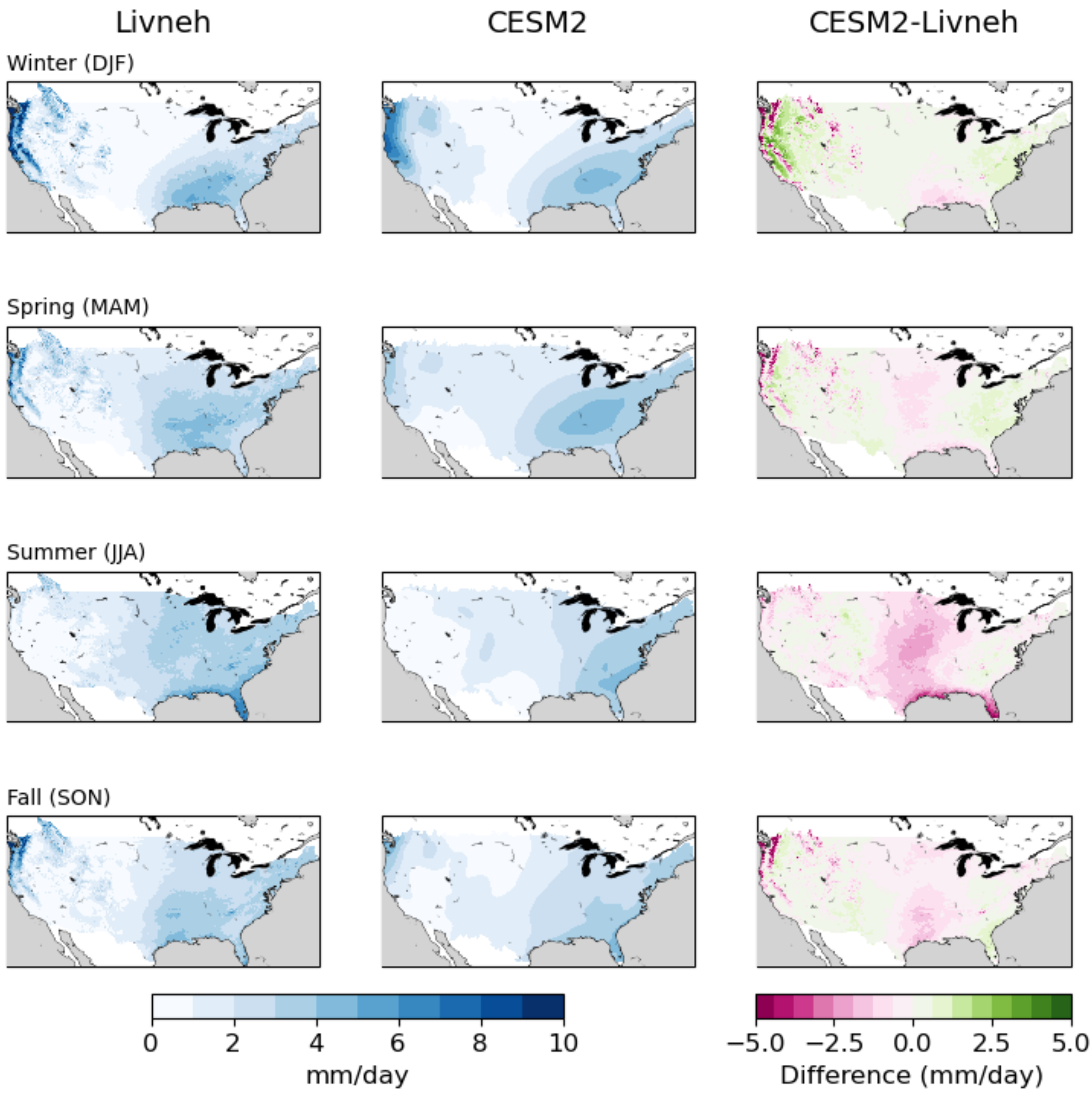
Appendix B

Schematic of the Community Earth System Model version 2 (CESM2) model components, reproduced from Danabasoglu et al. (2020) Figure 1.

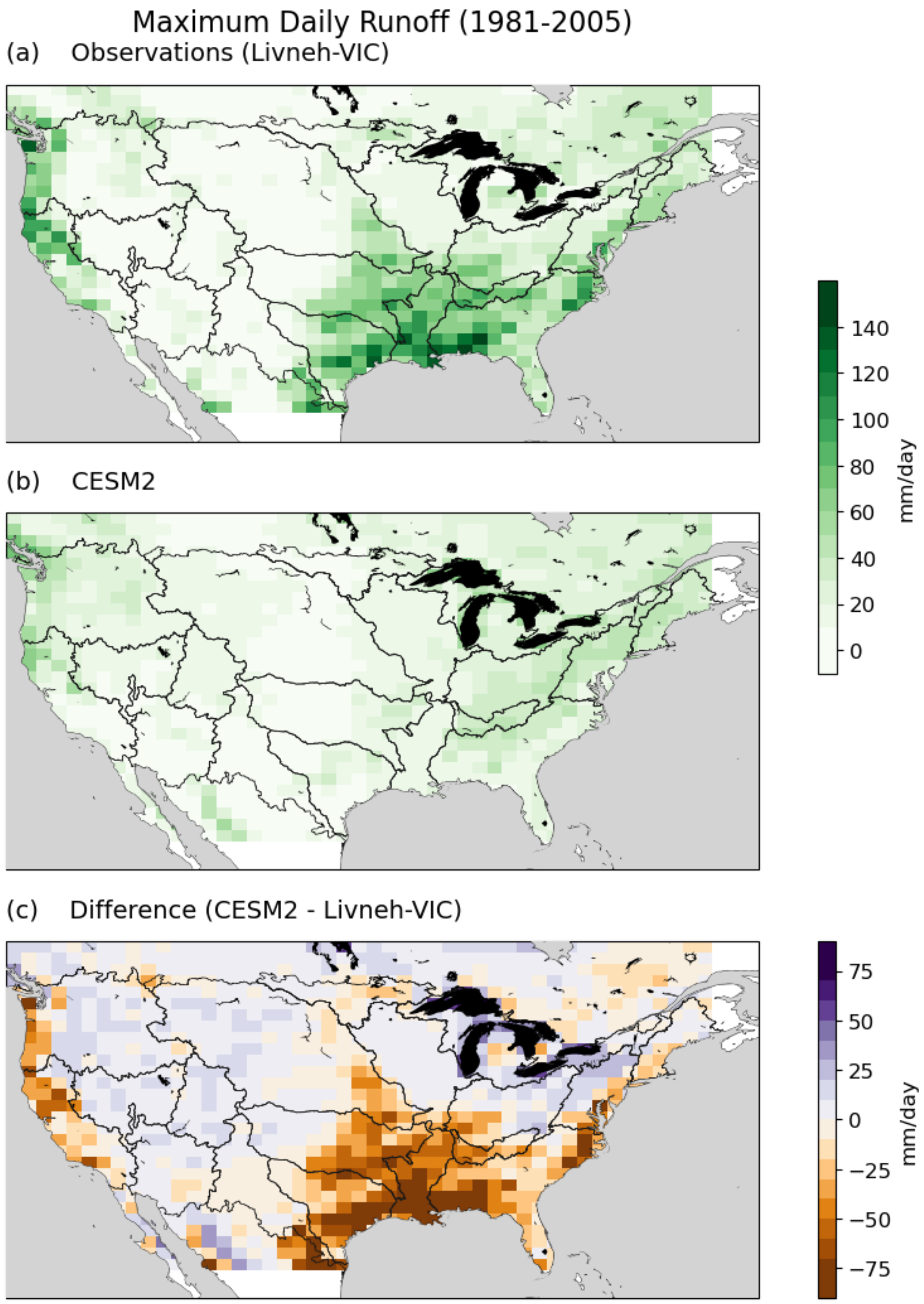


Appendix C

Seasonal Mean Precipitation for Winter (top row), Spring (row 2), Summer (row 3) and Fall (bottom row) as shown in Livneh (left column) and CESM2 (middle column), and difference CESM2-Livneh (right column)



Appendix D


Maximum Daily Runoff (1981-2005)
(a) Observations (Livneh-VIC)
(b) CESM2
(c) Difference (CESM2 - Livneh-VIC)
140
120
100
80
60
40
20
0
mm/day
75
50
25
0
−25
−50
−75
mm/day

Data availability

All data generated for this study (e.g., CESM2 and Livneh-VIC calculated indices) along with Jupyter notebooks to recreate tables and figures are available in the repository https://github.com/maritye/PSIF_water_avail

Author Contribution

Conceptualization, M.T., J.R., E.G., A.N., A.W. and R.M.; Methodology, M.T., J.R., E.G.; Investigation, M.G., M.T.; Data Curation, M.G., M.T.; Writing - original draft, M.T., A.R., and R.M.; Writing – reviewing and editing, M.T,, J.R., E.G., A.N., A.W., R.M., A.R., F.L., C.B., and S.H.; Visualization, C.B., M.G. and M.T.; Supervision, J.R., E.G., A.N., F.L. and A.W.; Funding Acquisition, J.R., E.G., A.N., A.W., F.L.,C.B., S.H. and M.T.; Project Administration J.R.

Competing Interests

The authors declare that they have no conflict of interest.

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References

ASCE: Standard Guidelines for the Design of Urban Stormwater Systems, Standard Guidelines for Installation of Urban Stormwater Systems, and Standard Guidelines for the Operation and Maintenance of Urban Stormwater Systems, 45th ed., American Society of Civil Engineers, Reston, VA, https://doi.org/10.1061/9780784408063, 2006.

Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M., Knutson, C., Smith, K. H., Wall, N., Fuchs, B., Crossman, N. D., and Overton, I. C.: Drought indicators revisited: the need for a wider consideration of environment and society, WIREs Water, 3, 516–536, https://doi.org/10.1002/wat2.1154, 2016.

Brekke, L. D.: Addressing Climate Change in Long-Term Water Resources Planning and Management: User Needs for Improving Tools and Information, Bureau of Reclamation, Technical Service Center, Denver, 2011.

Brekke, L. D., Kiang, J. E., Olsen, J. R., Pulwarty, R. S., Raff, D. A., Turnipseed, D. P., Webb, R. S., and White, K. D.: Climate change and water resources management—A federal perspective, U.S. Geological Survey, 2009.

Bremer, L. L., Hamel, P., Ponette-González, A. G., Pompeu, P. V., Saad, S. I., and Brauman, K. A.: Who Are we Measuring and Modeling for? Supporting Multilevel Decision-Making in Watershed Management, Water Resources Research, 56, https://doi.org/10.1029/2019WR026011, 2020.

Briley, L., Kelly, R., Blackmer, E. D., Troncoso, A. V., Rood, R. B., Andresen, J., and Lemos, M. C.: Increasing the Usability of Climate Models through the Use of Consumer-Report-Style Resources for Decision-Making, Bulletin of the American Meteorological Society, 101, E1709–E1717, https://doi.org/10.1175/BAMS-D-19-0099.1, 2020.

Brugger, J., Meadow, A., and Horangic, A.: Lessons from First-Generation Climate Science Integrators, Bulletin of the American Meteorological Society, 97, 355–365, https://doi.org/10.1175/BAMS-D-14-00289.1, 2016.

Brunner, M. I., Slater, L., Tallaksen, L. M., and Clark, M.: Challenges in modeling and predicting floods and droughts: A review, WIREs Water, 8, https://doi.org/10.1002/wat2.1520, 2021.

Cantor, A., Kiparsky, M., Kennedy, R., Hubbard, S., Bales, R., Pecharroman, L. C., Guivetchi, K., McCready, C., and Darling, G.: Data for Water Decision Making: Informing the Implementation of California's Open and Transparent Water Data Act through Research and Engagement, Wheeler Water Institute, Center for Law, Energy & the Environment, UC Berkeley School of Law, Berkeley, CA., 2018.

Chen, D., Dai, A., and Hall, A.: The Convective-To-Total Precipitation Ratio and the "Drizzling" Bias in Climate Models, JGR Atmospheres, 126, e2020JD034198, https://doi.org/10.1029/2020JD034198, 2021.

Chen, M., Dickinson, R. E., Zeng, X., and Hahmann., A. N.: Comparison of Precipitation Observed over the Continental United States to That Simulated by a Climate Model, Journal of Climate, 9, ,9, 2233–49, https://doi.org/10.1175/1520-0442(1996)009<2233:COPOOT>2.0.CO;2, 1996

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P., Kumar, M., Leung, L. R., Mackay, D. S., Maxwell, R. M., Shen, C., Swenson, S. C., and Zeng, X.: Improving the representation of hydrologic processes in Earth System Models, Water Resour. Res., 51, 5929–5956, https://doi.org/10.1002/2015WR017096, 2015.

Clifford, K. R., Travis, W. R., and Nordgren, L. T.: A climate knowledges approach to climate services, Climate Services, 18, 100155, https://doi.org/10.1016/j.cliser.2020.100155, 2020.

Dai, A.: Precipitation Characteristics in Eighteen Coupled Climate Models, Journal of Climate, 19, 18 , 4605–30, https://doi.org/10.1175/JCLI3884.1, 2006

Danabasoglu, G. and Lamarque, J.-F.: Building a Better Model to View Earth's Interacting Processes, Eos, 102, https://doi.org/10.1029/2021EO155818, 2021.

Danabasoglu, G., Lamarque, J. -F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., Neale, R., Oleson, K. W., Otto-Bliesner, B., Phillips, A. S., Sacks, W., Tilmes, S., Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J. E., Kinnison, D., Kushner, P. J., Larson, V. E., Long, M. C., Mickelson, S., Moore, J. K., Nienhouse, E., Polvani, L., Rasch, P. J., and Strand, W. G.: The Community Earth System Model Version 2 (CESM2), J. Adv. Model. Earth Syst., 12, https://doi.org/10.1029/2019MS001916, 2020.

Deser, C., Knutti, R., Solomon, S., and Phillips, A. S.: Communication of the role of natural variability in future North American climate, Nature Clim Change, 2, 775–779, https://doi.org/10.1038/nclimate1562, 2012.

Deser, C., Lehner, F., Rodgers, K. B., Ault, T., Delworth, T. L., DiNezio, P. N., Fiore, A., Frankignoul, C., Fyfe, J. C., Horton, D. E., Kay, J. E., Knutti, R., Lovenduski, N. S., Marotzke, J., McKinnon, K. A., Minobe, S., Randerson, J., Screen, J. A., Simpson, I. R., and Ting, M.: Insights from Earth system model initial-condition large ensembles and future prospects, Nat. Clim. Chang., 10, 277–286, https://doi.org/10.1038/s41558-020-0731-2, 2020.

Dilling, L., Daly, M. E., Kenney, D. A., Klein, R., Miller, K., Ray, A. J., Travis, W. R., and Wilhelmi, O.: Drought in urban water systems: Learning lessons for climate adaptive capacity, Climate Risk Management, 23, 32–42, https://doi.org/10.1016/j.crm.2018.11.001, 2019.

Donat, M. G., Angélil, O., and Ukkola, A. M.: Intensification of precipitation extremes in the world's humid and water-limited regions, Environ. Res. Lett., 14, 065003, https://doi.org/10.1088/1748-9326/ab1c8e, 2019.

Ek, M. B.: Land Surface Hydrological Models, in: Handbook of Hydrometeorological Ensemble Forecasting, edited by: Duan, Q., Pappenberger, F., Thielen, J., Wood, A., Cloke, H. L., and Schaake, J. C., Springer Berlin Heidelberg, Berlin, Heidelberg, 1–42, https://doi.org/10.1007/978-3-642-40457-3_24-1, 2018.

Ekström, M., Gutmann, E. D., Wilby, R. L., Tye, M. R., and Kirono, D. G. C.: Robustness of hydroclimate metrics for climate change impact research, Wiley Interdisciplinary Reviews: Water, 5, e1288, https://doi.org/10.1002/wat2.1288, 2018.

Feng, R., Otto-Bliesner, B. L., Brady, E. C., and Rosenbloom, N.: Increased Climate Response and Earth System Sensitivity From CCSM4 to CESM2 in Mid-Pliocene Simulations, J. Adv. Model. Earth Syst., 12, https://doi.org/10.1029/2019MS002033, 2020.

Fisher, R. A. and Koven, C. D.: Perspectives on the Future of Land Surface Models and the Challenges of Representing Complex Terrestrial Systems, J. Adv. Model. Earth Syst., 12, https://doi.org/10.1029/2018MS001453, 2020.

Fowler, H. J., Wasko, C., and Prein, A. F.: Intensification of short-duration rainfall extremes and implications for flood risk: current state of the art and future directions, Phil. Trans. R. Soc. A., 379, 20190541, https://doi.org/10.1098/rsta.2019.0541, 2021.

Gervais, M., Gyakum, J. R., Atallah, E., Tremblay, L. B., and Neale, R. B.: How Well Are the Distribution and Extreme Values of Daily Precipitation over North America Represented in the Community Climate System Model? A Comparison to Reanalysis, Satellite, and Gridded Station Data, Journal of Climate, 27, 5219–5239, https://doi.org/10.1175/JCLI-D-13-00320.1, 2014.

Gettelman, A. and Rood, R. B.: Usability of Climate Model Projections by Practitioners, in: Demystifying Climate Models, vol. 2, Springer Berlin Heidelberg, Berlin, Heidelberg, 221–236, https://doi.org/10.1007/978-3-662-48959-8_12, 2016.

Gettelman, A., Geer, A. J., Forbes, R. M., Carmichael, G. R., Feingold, G., Posselt, D. J., Stephens, G. L., van den Heever, S. C., Varble, A. C., and Zuidema, P.: The future of Earth system prediction: Advances in model-data fusion, Sci Adv, 8, eabn3488, https://doi.org/10.1126/sciadv.abn3488, 2022.

Haines, A. T., Finlayson, B. L., and McMahon, T. A.: A global classification of river regimes, Applied Geography, 8, 255–272, https://doi.org/10.1016/0143-6228(88)90035-5, 1988.

IPCC: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., Cambridge University Press, 2022.

Jagannathan, K., Jones, A. D., and Ray, I.: The Making of a Metric: Co-Producing Decision-Relevant Climate Science, Bulletin of the American Meteorological Society, 102, E1579–E1590, https://doi.org/10.1175/BAMS-D-19-0296.1, 2021.

Jeanine Jones: Drought and lessons learned: https://mavensnotebook.com/2023/03/01/jeanine-jones-drought-and-lessons-learned/, last access: 2 May 2023.

Jones, P. W.: First- and Second-Order Conservative Remapping Schemes for Grids in Spherical Coordinates, Mon. Wea. Rev., 127, 2204–2210, https://doi.org/10.1175/1520-0493(1999)127<2204:FASOCR>2.0.CO;2, 1999.

Kim, Y.-H., Min, S.-K., Zhang, X., Sillmann, J., and Sandstad, M.: Evaluation of the CMIP6 multi-model ensemble for climate extreme indices, Weather and Climate Extremes, 29, 100269, https://doi.org/10.1016/j.wace.2020.100269, 2020.

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., Kampenhout, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., Wieder, W. R., Xu, C., Ali, A. A., Badger, A. M., Bisht, G., Broeke, M., Brunke, M. A., Burns, S. P., Buzan, J., Clark, M., Craig, A., Dahlin, K., Drewniak, B., Fisher, J. B., Flanner, M., Fox, A. M., Gentine, P., Hoffman, F., Keppel-Aleks, G., Knox, R., Kumar, S., Lenaerts, J., Leung, L. R., Lipscomb, W. H., Lu, Y., Pandey, A., Pelletier, J. D., Perket, J., Randerson, J. T., Ricciuto, D. M., Sanderson, B. M., Slater, A., Subin, Z. M., Tang, J., Thomas, R. Q., Val Martin, M., and Zeng, X.: The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty, J. Adv. Model. Earth Syst., 11, 4245–4287, https://doi.org/10.1029/2018MS001583, 2019.

Lehner, F., Deser, C., and Terray, L.: Toward a New Estimate of "Time of Emergence" of Anthropogenic Warming: Insights from Dynamical Adjustment and a Large Initial-Condition Model Ensemble, Journal of Climate, 30, 7739–7756, https://doi.org/10.1175/JCLI-D-16-0792.1, 2017.

Lehner, F., Wood, A. W., Vano, J. A., Lawrence, D. M., Clark, M. P., and Mankin, J. S.: The potential to reduce uncertainty in regional runoff projections from climate models, Nat. Clim. Chang., 9, 926–933, https://doi.org/10.1038/s41558-019-0639-x, 2019.

Lempert, R. J.: Measuring global climate risk, Nat. Clim. Chang., 11, 805–806, https://doi.org/10.1038/s41558-021-01165-9, 2021.

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res., 99, 14415, https://doi.org/10.1029/94JD00483, 1994.

Livneh, B., Rosenberg, E. A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K. M., Maurer, E. P., and Lettenmaier, D. P.: A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions, J. Climate, 26, 9384–9392, https://doi.org/10.1175/JCLI-D-12-00508.1, 2013.

Lukas, J. and Payton, E.: Colorado River Basin Climate and Hydrology: State of the Science, https://doi.org/10.25810/3HCV-W477, 2020.

Mach, K. J., Lemos, M. C., Meadow, A. M., Wyborn, C., Klenk, N., Arnott, J. C., Ardoin, N. M., Fieseler, C., Moss, R. H., Nichols, L., Stults, M., Vaughan, C., and Wong-Parodi, G.: Actionable knowledge and the art of engagement, Current Opinion in Environmental Sustainability, 42, 30–37, https://doi.org/10.1016/j.cosust.2020.01.002, 2020.

Mankin, J. S., Lehner, F., Coats, S., and McKinnon, K. A.: The Value of Initial Condition Large Ensembles to Robust Adaptation Decision-Making, Earth's Future, 8, https://doi.org/10.1029/2020EF001610, 2020.

McCrary, R. R., McGinnis, S., and Mearns, L. O.: Evaluation of Snow Water Equivalent in NARCCAP Simulations, Including Measures of Observational Uncertainty, Journal of Hydrometeorology, 18, 2425–2452, https://doi.org/10.1175/JHM-D-16-0264.1, 2017.

McCrary, R. R., Mearns, L. O., Hughes, M., Biner, S., and Bukovsky, M. S.: Projections of North American snow from NA-CORDEX and their uncertainties, with a focus on model resolution, Climatic Change, 170, 20, https://doi.org/10.1007/s10584-021-03294-8, 2022.

McMillan, H. K.: A review of hydrologic signatures and their applications, WIREs Water, 8, e1499, https://doi.org/10.1002/wat2.1499, 2021.

Meehl, G. A., Goddard, L., Murphy, J., Stouffer, R. J., Boer, G., Danabasoglu, G., Dixon, K., Giorgetta, M. A., Greene, A. M., Hawkins, E., Hegerl, G., Karoly, D., Keenlyside, N., Kimoto, M., Kirtman, B., Navarra, A., Pulwarty, R., Smith, D., Stammer, D., and Stockdale, T.: Decadal Prediction, Bulletin of the American Meteorological Society, 90, 1467–1485, https://doi.org/10.1175/2009BAMS2778.1, 2009.

Mizukami, N., Rakovec, O., Newman, A. J., Clark, M. P., Wood, A. W., Gupta, H. V., and Kumar, R.: On the choice of calibration metrics for "high-flow" estimation using hydrologic models, Hydrol. Earth Syst. Sci., 23, 2601–2614, https://doi.org/10.5194/hess-23-2601-2019, 2019.

Moise, A., Wilson, L., Grose, M., Whetton, P., Watterson, I., Bhend, J., Bathols, J., Hanson, L., Erwin, T., Bedin, T., Heady, C., and Rafter, T.: Evaluation of CMIP3 and CMIP5 models over the Australian region to inform confidence in projections, AMOJ, 65, 19–53, https://doi.org/10.22499/2.6501.004, 2015.

Mukherjee, S., Mishra, A., and Trenberth, K. E.: Climate Change and Drought: a Perspective on Drought Indices, Curr Clim Change Rep, 4, 145–163, https://doi.org/10.1007/s40641-018-0098-x, 2018.

Newman, A. J., Clark, M. P., Craig, J., Nijssen, B., Wood, A., Gutmann, E., Mizukami, N., Brekke, L., and Arnold, J. R.: Gridded Ensemble Precipitation and Temperature Estimates for the Contiguous United States, Journal of Hydrometeorology, 16, 2481–2500, https://doi.org/10.1175/JHM-D-15-0026.1, 2015.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., and Solecki, W.: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change, 42, 169–180, https://doi.org/10.1016/j.gloenvcha.2015.01.004, 2017.

Pacchetti, M. B., Dessai, S., Bradley, S., and Stainforth, D. A.: Assessing the Quality of Regional Climate Information, Bulletin of the American Meteorological Society, 102, E476–E491, https://doi.org/10.1175/BAMS-D-20-0008.1, 2021.

Pardé, M.: Fleuves et Rivières, Collection Armand Collin. Section de Géographie (France), Fre No. 155, 1933.

Phillips, A., Deser, C., Fasullo, J., Schneider, D. P., and Simpson, I. R.: Assessing Climate Variability and Change in Model Large Ensembles: A User's Guide to the "Climate Variability Diagnostics Package for Large Ensembles," https://doi.org/10.5065/H7C7-F961, 2020.

Pierce, D. W., Su, L., Cayan, D. R., Risser, M. D., Livneh, B., and Lettenmaier, D. P.: An extreme-preserving long-term gridded daily precipitation data set for the conterminous United States, Journal of Hydrometeorology, https://doi.org/10.1175/JHM-D-20-0212.1, 2021.

Raff, D. A., Brekke, L. D., Werner, K. V., Wood, A. W., and White, K. D.: Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information, Bureau of Reclamation, U.S. Army Corps of Engineers and National Oceanic and Atmospheric Administration, 2013.

Reba, M. L., Marks, D., Seyfried, M., Winstral, A., Kumar, M., and Flerchinger, G.: A long-term data set for hydrologic modeling in a snow-dominated mountain catchment: A 25 YEAR DATA SET FOR HYDROLOGIC MODELING, Water Resour. Res., 47, https://doi.org/10.1029/2010WR010030, 2011.

Reclamation: Technical Guidance for Incorporating Climate Change Information into Water Resources Planning Studies, U.S. Department of the Interior. Bureau of Reclamation, Denver, Colorado, 2014.

Reclamation: SECURE Water Act Section 9503(c) - Reclamation Climate Change and Water. Prepared for United States Congress., U.S. Department of the Interior. Bureau of Reclamation, Denver, Colorado, 2016.

Reed, K. A., Goldenson, N., Grotjahn, R., Gutowski, W. J., Jagannathan, K., Jones, A. D., Leung, L. R., McGinnis, S. A., Pryor, S. C., Srivastava, A. K., Ullrich, P. A., and Zarzycki, C. M.: Metrics as tools for bridging climate science and applications, Wiley Interdisciplinary Reviews: Climate Change, 13, e799, 2022.

Regional Water Authority: Sacramento Regional Water Bank: A sustainable storage and recovery program, 2019.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., and Tavoni, M.: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environmental Change, 42, 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009, 2017.

Rodgers, K. B., Lee, S.-S., Rosenbloom, N., Timmermann, A., Danabasoglu, G., Deser, C., Edwards, J., Kim, J.-E., Simpson, I. R., Stein, K., Stuecker, M. F., Yamaguchi, R., Bódai, T., Chung, E.-S., Huang, L., Kim, W. M., Lamarque, J.-F., Lombardozzi, D. L., Wieder, W. R., and Yeager, S. G.: Ubiquity of human-induced changes in climate variability, Earth Syst. Dynam., 12, 1393–1411, https://doi.org/10.5194/esd-12-1393-2021, 2021.

Rugg, A., Gutmann, E. D., McCrary, R. R., Lehner, F., Newman, A. J., Richter, J. H., Tye, M. R., and Wood, A. W.: Mass-Conserving Downscaling of Climate Model Precipitation over Mountainous Terrain for Water Resource Applications, Geophysical Research Letters, 50, 20, e2023GL105326. http://dx.doi.org/10.1029/2023GL105326, 2023.

Seaber, P. R., Kapinos, F. P., and Knapp, G. L.: Hydrologic Unit Maps, U.S. Geological Survey, 1987.

Sedláček, J. and Knutti, R.: Half of the world's population experience robust changes in the water cycle for a 2 °C warmer world, Environ. Res. Lett., 9, 044008, https://doi.org/10.1088/1748-9326/9/4/044008, 2014.

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D., Martius, O., Senior, C. A., Sobel, A. H., Stainforth, D. A., Tett, B., Trenberth, K. E., Hurk, B. J., Watkin, N. W., Wilby, R. L., and Zenghelis, D. A.: Storylines: An alternative approach to representing uncertainty in physical aspects of climate change, Climatic Change, 151, 555–571, https://doi.org/10.1007/s10584-018-2317-9, 2018.

Simpson, I. R., Lawrence, D. M., Swenson, S. C., Hannay, C., McKinnon, K. A., and Truesdale, J. E.: Improvements in Wintertime Surface Temperature Variability in the Community Earth System Model Version 2 (CESM2) Related to the Representation of Snow Density, J Adv Model Earth Syst, 14, https://doi.org/10.1029/2021MS002880, 2022.

Tebaldi, C. and Knutti, R.: The use of the multi-model ensemble in probabilistic climate projections, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365, 2053–2075, https://doi.org/10.1098/rsta.2007.2076, 2007.

Tebaldi, C., Dorheim, K., Wehner, M., and Leung, R.: Extreme metrics from large ensembles: investigating the effects of ensemble size on their estimates, Earth Syst. Dynam., 12, 1427–1501, https://doi.org/10.5194/esd-12-1427-2021, 2021.

Tye, M.: Water Availability Metrics August 2021 Workshop Report, Open Science Framework, https://doi.org/10.17605/OSF.IO/M7NXD, 2023.

Tye, M. R., Holland, G. J., and Done, J. M.: Rethinking failure: time for closer engineer–scientist collaborations on design, Proceedings of the Institution of Civil Engineers - Forensic Engineering, 168, 49–57, https://doi.org/10.1680/feng.14.00004, 2015.

Underwood, E. C., Hollander, A. D., Flint, L. E., Flint, A. L., and Safford, H. D.: Climate change impacts on hydrological services in southern California, Environ. Res. Lett., 13, 124019, https://doi.org/10.1088/1748-9326/aaeb59, 2018.

Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., Hartmann, H. C., Hidalgo, H. G., Hoerling, M., McCabe, G. J., Morino, K., Webb, R. S., Werner, K., and Lettenmaier, D. P.: Understanding Uncertainties in Future Colorado River Streamflow, Bulletin of the American Meteorological Society, 95, 59–78, https://doi.org/10.1175/BAMS-D-12-00228.1, 2014.

Wagener, T., Reinecke, R., and Pianosi, F.: On the evaluation of climate change impact models, WIREs Climate Change, 13, e772, https://doi.org/10.1002/wcc.772, 2022.

Wood, R. R., Lehner, F., Pendergrass, A. G., and Schlunegger, S.: Changes in precipitation variability across time scales in multiple global climate model large ensembles, Environ. Res. Lett., 16, 084022, https://doi.org/10.1088/1748-9326/ac10dd, 2021.

Wright, D. B., Bosma, C. D., and Lopez-Cantu, T.: U.S. Hydrologic Design Standards Insufficient Due to Large Increases in Frequency of Rainfall Extremes, Geophys. Res. Lett., 46, 8144–8153, https://doi.org/10.1029/2019GL083235, 2019.

Yuan, H., Toth, Z., Peña, M., and Kalnay, E.: Overview of Weather and Climate Systems, in: Handbook of Hydrometeorological Ensemble Forecasting, edited by: Duan, Q., Pappenberger, F., Wood, A., Cloke, H. L., and Schaake, J. C., Springer, Berlin, Heidelberg, 35–65, https://doi.org/10.1007/978-3-642-39925-1_10, 2019.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B., and Zwiers, F. W.: Indices for monitoring changes in extremes based on daily temperature and precipitation data, Wiley Interdisciplinary Reviews: Climate Change, 2, 851–870, https://doi.org/10.1002/wcc.147, 2011.