The 21st Century Colorado River Hot Drought and Implications for the Future

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Key Points:

- Record Colorado River flow reductions averaged 19.3% per year during 2000-2014. One-third or more of the decline was likely due to warming.
- Unabated greenhouse gas emissions will lead to continued substantial warming, translating to 21st century flow reductions of 35% or more.
- More precipitation can reduce the flow loss, but lack of increase to date and large megadrought threat, reinforce risk of large flow loss.

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Abstract

Between 2000 and 2014, annual Colorado River flows averaged 19% below the 1906-1999 average, the worst 15-year drought on record. At least one-sixth to one-half (average at one-third) of this loss is due to unprecedented temperatures (0.9°C above the 1906-99 average), confirming model-based analysis that continued warming will likely further reduce flows. Whereas it is virtually certain that warming will continue with additional emissions of greenhouse gases to the atmosphere, there has been no observed trend towards greater precipitation in the Colorado Basin, nor are climate models in agreement that there should be a trend. Moreover, there is a significant risk of decadal and multidecadal drought in the coming century, indicating that any increase in mean precipitation will likely be offset during periods of prolonged drought. Recently published estimates of Colorado River flow sensitivity to temperature combined with a large number of recent climate model-based temperature projections indicate that continued business-as-usual warming will drive temperature-induced declines in river flow, conservatively -20% by mid-century and -35% by end–century, with support for losses exceeding -30% at mid-century and -55% at end-century. Precipitation increases may moderate these declines somewhat, but to date no such increases are evident and there is no model agreement on future precipitation changes. These results, combined with the increasing likelihood of prolonged drought in the river basin, suggest that future climate change impacts on the Colorado River flows will be much more serious than currently assumed, especially if substantial reductions in greenhouse gas emissions do not occur.

Index Terms: 1807 Climate Impacts; 1812 Drought; 1833 Hydroclimatology; 1880 Water Management; 1884 Water Supply

Keywords : Colorado River Basin, climate change, Colorado River Compact, megadrought,

1. Introduction

A large number of studies over the last twenty-five years have considered the future runoff of the Colorado River (Figure 1) under climate change. Nearly all of these studies have cautioned that future warming will deplete the flow of the river, but the results have varied from minor to major [*Nash and Gleick*, 1991; *Christensen et al.*, 2004; *Milly et al.*, 2005; *Brekke et al.*, 2007; *Christensen and Lettenmaier*, 2007; *National Research Council*, 2007; *Seager et al.*, 2007; *Barnett and Pierce*, 2008; *Ray et al.*, 2008; *Barnett and Pierce*, 2009; *Rajagopalan et al.*, 2009; *Cayan et al.*, 2010; *Reclamation*, 2011; *Harding et al.*, 2012; *Seager et al.*, 2012; *Vano et al.*, 2012; *Ficklin et al.*, 2013; *Vano et al.*, 2014; *Ayers et al.*, 2016; *Milly and Dunne*, 2016]. In contrast, the latest U.S Government assessment implies little or no change is likely because precipitation increases will be sufficient to maintain temperature-depleted flows [*Reclamation*, 2016]. Fifteen years into the 21st century, the emerging reality is that climate change is already depleting Colorado River water supplies at the upper end of the range suggested by previously published projections. Record setting temperatures are an important and underappreciated component of the flow reductions now being observed.

Between the start of the drought in 2000 and the end of 2014, our analysis period, annual flow reductions averaged 19.3% below the 1906 to 1999 normal period, and Lakes Mead and Powell, the nation's two largest reservoirs, ended the period at approximately 40% of maximum volume despite starting the period nearly full [*Wines*, 2014; *Colorado River Basin Stakeholders*, 2015] (Figure 2a). This drought has continued into 2015 and 2016 with higher, but still below normal, flows estimated at 94% in 2015 and 94% in 2016 with unusual late season May and June precipitation in both years that raised runoff by nearly 20% [*Alcorn*, 2015, 2016]. Despite these smaller recent reductions, Lake Mead continues to decline and in May of 2016 it hit a level not seen since its initial filling in the 1930s [*James*, 2016]. The overall Colorado River reservoir system stores 4 times the annual flow of the river, one of the largest ratios in the world. This storage provides a large drought buffer when full. However, when the reservoirs are low, shortage risk can be high for years because high demands, now equal to 20th century average flow, make it difficult to refill system storage [*Reclamation*, 2012]. While the multi-year California drought has been garnering more national attention, the more slowly unfolding Colorado River drought is every bit as serious and also has national and international ramifications [*Wines*, 2014].

The Colorado River Basin encompasses seven states and northern Mexico and is home to 22 federally recognized tribes. The river provides municipal and industrial water for 40m people distributed across every major Southwestern city both within and without the basin, including Los Angeles, San Diego, Las Vegas, Phoenix, Tucson, Salt Lake City, Denver and the entire Front Range of Colorado, Albuquerque and Santa Fe [*Reclamation*, 2012].

Continued low flows would result in additional declines at Lake Mead, eventually requiring Lower Basin (Arizona, California, Nevada) water delivery shortages with mandatory cutbacks imposed primarily on Arizona, but also Nevada and Mexico [*Verburg*, 2011]. At the same time, Upper Basin (Colorado, New Mexico, Utah, Wyoming) water users would continue to endure physical shortages from a lack of water. These initial Lower Basin Lake Mead delivery shortages and Upper Basin physical shortages are manageable to a point; however, under current operating rules with continued low flows during the next six to eight years Lake Mead would drop to elevation 305 m (1000 feet) above sea level, resulting in a number of serious and unprecedented problems [*Collum and McCann*, 2014].

In the Lower Basin, Arizona could theoretically lose its water allocation for the entire Central Arizona Project canal, a critical \$4.4B, 530 km cross-state 2 bcm/year water source for 4.7m people, multiple sovereign Indian nations, and over 120,000 irrigated hectares [*Glennon*, 1995; *Colorado River Basin Stakeholders*, 2015]. This canal currently relies on occasional but uncertain 'equalization' releases from Lake Powell that only occur with irregular and rare large Powell inflows. The extra water is delivered when Lake Powell reaches levels substantially higher than Lake Mead, a use allowed under the 1922 Colorado River Compact section III (e) and formalized most recently under rules established in a 2007 Record of Decision for coordinated operations of Lakes Powell and Mead and for shortage sharing in the Lower Basin [*Department of Interior*, 2007].

Under normal operating rules, without these extra inflows, Lake Mead has excess outflows of 1.5 bcm per year, the so-called Lower Basin “structural deficit” [*Collum and McCann*, 2014]. The structural deficit was created in 1968 when Congress authorized the Central Arizona Project (CAP). In order to obtain the support of the large California Congressional delegation, Arizona agreed to rely on this unused, but in the long run unreliable water, because there was not enough remaining unallocated Lower Basin water. The CAP had long been a desire of Arizona and the state was willing to make this bargain despite its flaws [*Johnson*, 1977]. This same water is first available for use by the Upper Basin under the Colorado River Compact, but heretofore has not been developed for Upper Basin use. A plan to augment the Colorado River with flows from outside the basin, discussed during the hearings on the legislation, but not included in the final package due to opposition from potential source areas, was never revisited by Congress. Reclamation in 2011 said that such augmentation was now unlikely.

The structural deficit only became a problem when the CAP was fully completed in the mid 1990s combined with the drought that began in 2000. Upper Basin demand growth has also played a small role, although Upper Basin demands are still much less than forecast in 1968 for the year 2000 [*Tipton and Kalmbach, Inc*, 1965; *Johnson*, 1977]. The recent Lake Mead declines are strongly influenced by this imbalance, and solutions to this deficit have been a recent focus of the Basin states and federal government [*Central Arizona Project*, 2016; *Davis*, 2016].

The Upper Basin also has serious issues, one of which ripples into the Lower Basin. When the surface of Lake Mead declines to an elevation 305 m (1000 feet) above sea level, Lake Powell will also be below its minimum power pool 75% of the time [*Collum and McCann*, 2014]. This occurs in part because low Mead levels make ‘equalization’ releases from Powell more likely thus driving Powell lower. Hydropower losses at Lake Powell could result in substantial rate increases for irrigators who rely on the reservoirs for long term lower cost power contracts, and would also dry up funding for basin-wide programs necessary for water delivery environmental compliance [*Adler*, 2007; *Collum and McCann*, 2014]. Under such low reservoir conditions, there is also a high likelihood that the Upper Basin states would have to curtail existing water deliveries to cities such as Denver, Colorado Springs, Albuquerque and Salt Lake City in order to make required deliveries to Lake Mead. Heretofore, largely because of the structure of the Colorado River Compact, the Upper Basin and Lower Basin have been managed separately. With permanent flow declines of approximately 20%, however, the required deliveries to Lake Mead would become a hardship on the Upper Basin, as well as create Lower Basin delivery shortages [*Reclamation*, 2007; *Barnett and Pierce*, 2009; *Rajagopalan et al.*, 2009]. The original compact, signed during one of the wettest periods in the last 450 years [*Woodhouse et al.*, 2006], did not envision how large scale flow declines would be managed between the basins, and such declines could cause an allocation crisis between the Upper and Lower Basins [*Adler*, 2008].

Understanding the cause of, and reacting properly to, the ongoing drought is critical to the future of the Southwest. Herein we investigate the role of precipitation versus temperatures as causes of the current drought, provide temperature- and precipitation-based 21st century flow projections and provide policy implications of these findings. Our approach separates the impacts of high-confidence temperature projections from those associated with the much lower-confidence projections of future precipitation using a simple but powerful sensitivity technique. Moreover, we make a novel – and important - case that there is a high likelihood that the impacts of continued atmospheric warming will overwhelm any future increases in precipitation because prolonged dry periods lasting multiple decades are likely to negate the beneficial impacts of additional precipitation during other times.

Causes of the 2000-2014 Drought

The 2000-14 drought is defined by the lowest average annual flows for any 15-year period in the historical record. To analyze this drought, gridded 4x4 km temperature and precipitation data from 1896-2014 for the area above Lees Ferry were obtained from the Precipitation-Elevation Regression on Independent Slopes (PRISM) model [*Daly et al.*, 1994]. In addition, we obtained reservoir contents and natural flows at Lees Ferry from the U.S. Bureau of Reclamation (Reclamation) (Text S1). Lees Ferry is situated just below Lake Powell and is the Compact dividing line between the Upper and Lower Basins. Approximately 85% of the flow originates above Lees Ferry [*Christensen and Lettenmaier*, 2007].

Historically, Upper Colorado River Basin precipitation has been the main Colorado River runoff driver such that high flow years (1920s, 1980s) were associated with high precipitation and low flow years (1930s, 1950s) with low precipitation (Figure 2b-c). The current drought (our study period is 2000-2014, but the drought is still on-going), with its modest -4.6% precipitation decline and -19.3% flow decline, stands in stark contrast to the second-lowest 15-year flow period (1953-1967), a precipitation-driven drought with averaged precipitation reductions of -6.1% per year and flow reductions of -18.1% per year (Figure 2b-c and Table 1). Compared to the 1950s drought, the 2000s feature much more (near normal) winter precipitation (-8.6% 1950s decline versus -2.7% 2000s) and significantly less summer precipitation (-3.6% 1950s decline versus -6.4% 2000s). The 2000s precipitation decline is only 75% of the decline in the 1950s, thus begging the question of why the recent drought was more serious. What has changed is that temperatures in the runoff producing Upper Basin are now 0.9 °C above the 1896-1999 average and are the highest in the gaged record; whereas temperatures during the 1953-1967 drought were much cooler and only slightly above the 1896-1999 average (Figure 2d and Table 2). This makes the current drought unprecedented in the gaged record.

In contrast to the more precipitation-driven current California drought [*Diffenbaugh et al.*, 2015; *Williams et al.*, 2015], lack of precipitation is only partially to blame for the Colorado River runoff declines during the last 15 years. Instead, approximately a third, or more, of the recent Colorado River flow reduction is most likely a result of record-setting warmth. Since 1988 an increase in the frequency of warm years has been strongly associated with lower flows than expected [*Woodhouse et al.*, 2016], suggesting an important role for temperature in flow losses. Such temperature-driven droughts have been termed 'global-change type droughts' and 'hot drought', with higher temperatures turning what would have been modest droughts into severe ones, and also increasing the odds of drought in any given year or period of years [*Breshears et al.*, 2005; *Overpeck*, 2013]. Higher temperatures increase atmospheric moisture demand, evaporation from water bodies and soil, sublimation from snow, evapotranspiration (ET) from plants, and also increase the length of the growing season during which ET occurs [*Pitman*, 2003; *Weiss et al.*, 2009; *Seneviratne et al.*, 2010; *Seager et al.*, 2015a]. Warm season (April to September) warming has been identified by models as especially important in reducing Colorado River flows because of the increases in ET from longer growing seasons [*Das et al.*, 2011]. Increases in measured vapor pressure deficits in the Southwest caused by warming and a decrease in water vapor provide strong support for higher ET during the recent drought [*Seager et al.*, 2015b]. As increasing temperatures drive further drying, additional positive feedbacks are possible in the form of lower humidity and less evaporative cooling, decreased cloudiness and increased incident radiation, as well as decreased snow cover and more radiative heating [*Betts et al.*, 1996; *Brubaker and Entekhabi*, 1996; *Pitman*, 2003; *Seneviratne et al.*, 2010]. In the 20th century, droughts were associated almost exclusively with a lack of precipitation. In this century, however, high temperatures alone can lead to anomalously dry conditions.

Estimates of 2000-2014 Temperature-induced Flow Loss

Over the last several years several studies specific to the Colorado River Basin have investigated the specific relationships among temperatures, precipitation and flow in the basin using the concepts of temperature sensitivity and precipitation elasticity [*McCabe and Wolock*, 2007; *Nowak et al.*, 2012; *Vano et al.*, 2012, 2014; *Vano and Lettenmaier*, 2014]. Temperature sensitivity is defined as the percent change in annual flow per degree rise in annual temperature. Precipitation elasticity is defined as the fractional change in annual flow divided by the fractional change in annual precipitation [*Vano et al.*, 2012]. Note that elasticity has been studied for both increases and decreases in precipitation, whereas sensitivity is typically investigated only for temperature increases. These numbers can be determined empirically and through model studies.

Previous studies on temperature sensitivity and precipitation elasticity show that future impacts to streamflow from increases in temperatures and changes in precipitation can be considered separately using sensitivity and elasticity, and then added together to produce flow estimates [*Vano et al.*, 2014; *Vano and Lettenmaier*, 2014]. Considering these effects separately and additively is a powerful conceptual tool for investigating climate change impacts because of the ease in measuring the two variables for current impacts and the wide availability of temperature and precipitation projections from global climate models for assessing future impacts. In addition, the large differences in certainty associated with future changes in the two variables (temperature will surely increase, whereas precipitation may increase or decrease – see below) helps to set apart the risk of future changes in flow associated with each variable.

Vano et al. [2012, 2014], McCabe and Wolock [2007] and Nowak et al. [2012] provide multiple estimates of the flow sensitivity of the Colorado River flow to temperature using three different methods. Vano et al (2012, 2014) utilized 6 high-resolution, commonly used hydrology models and two different temperature adjustment methods to obtain Lees Ferry temperature sensitivities. They report an average sensitivity of -6.5% / °C warming with a one standard deviation range from -3.0% to -10.0% / °C for the Upper Basin. Approximately 50% models show increasing sensitivity and 50% decreasing sensitivity as temperatures warm so we elect to use a constant sensitivity over all future temperatures. McCabe and Wolock (2007) constructed a simple water balance model that infers an average temperature sensitivity of -8.9%/ °C and Nowak et al (2012) found an empirical temperature sensitivity of -13.8%/ °C.

We use the complete one standard deviation range (-3% / °C to -10% / °C) of the Vano et al. (2012, 2014) temperature sensitivity estimates as they were the most conservative and rigorous of the three studies we investigated. Using this range, we found that recent warming of 0.9 °C has likely already reduced river flows from -2.7% to -9% from the mean 1906-1999 flow. This represents approximately one-sixth to one-half (average of one-third) of the total flow loss during the 2000-2014 drought.

The higher temperature sensitivities of the two other studies suggest the actual Colorado River temperature sensitivities are near the upper end and possibly exceed the Vano et al. (2012, 2014) estimates. These higher sensitivities imply much greater temperature-induced losses during the current drought (-7.9% to -12.3% vs -2.7% to -9%). Empirical results from the 2000-2014 drought also point to mid to high temperature sensitivities. Vano et al. (2012) report precipitation elasticities ranging from 2 to 3 at Lees Ferry. Thus, using a mid-range precipitation elasticity of 2.5, the 2000-2014 annual -4.6% precipitation decline implies runoff reductions of -11.4%, leaving the remaining -7.9% decline to be explained by other causes. If temperature were the sole cause of this remaining decline, the inferred temperature sensitivity is -8.8% /°C. Using a precipitation elasticity of 3.0 implies a temperature sensitivity of -6.2% /°C, very close to the mid-range Vano et al., sensitivity. These temperature sensitivities imply large losses as temperatures rise, the subject of the next section.

21st Century Flow Response to Changing Temperatures and Precipitation

For the analysis on how future temperatures and precipitation would affect runoff, and for investigating how well current linked climate-hydrology models can reproduce the current drought, we used Reclamation's climate projection datasets [*Brekke et al.*, 2013, 2014]. These datasets use Coupled Model Intercomparison Project 3 and 5 (CMIP3, CMIP5 after the class of climate models used) climate model projection data linked to the Variable Infiltration Capacity hydrology model to produce flows from 1950 to 2099 (Text S2, Figures S2, S3)] [*Liang et al.*, 1996; *Meehl et al.*, 2007; *Taylor et al.*, 2012].

The same temperature sensitivity and precipitation elasticity numbers discussed above can be used to estimate future flow reductions using climate model outputs under high (business-as-usual, SRES A2 and RCP8.5) and moderate (somewhat reduced by mitigation, SRES A1B and RCP4.5) greenhouse gas emissions to the atmosphere. By 2050, moderate and high emissions are projected to yield Upper Basin *mean* warming of 2.6 to 2.8 °C (Figure 3), three times recent warming, and by 2100, warming of 3.6 °C under moderate emissions and 5.4 °C under high emissions. This warming implies total multi-model mean temperature-induced flow losses at mid-range sensitivity of -6.5%/ °C of about -17% by mid-century and -25% to -35% at end-century (Figures 4 and 5). The multi-model mean complete flow loss *range* over both periods and both emissions is approximately -8% to -55% using the lower and upper temperature sensitivities (Figures 4 and 5). As discussed above, there is little empirical evidence that the true temperature sensitivity of flow to temperature increase is near the low sensitivity.

Temperature-induced losses may be somewhat buffered by projected additional precipitation that can increase runoff by 2% to 3% for every 1% change in precipitation [*Vano et al.*, 2012]. At mid-century precipitation increases of +4 to +11% given a mid-range elasticity of 2.5 would balance the range of temperature-induced flow losses at a mid-range – 6.5%/°C sensitivity (Figure 5, right y-axis). At end-century, with the same sensitivity and elasticity, additional precipitation increases of +4 to +20% would balance the range of possible temperature-driven losses. At a higher -10%/°C sensitivity, the balancing precipitation would need to be as great as +15% or more at mid-century and +25% or more at end-century. While these may seem like relatively small increases in precipitation, and thus possible, they would represent a major and unprecedented change in precipitation regime compared to the observed historical variation in precipitation (Figure 2c). During the 20th century, for example, the wettest 10-year period (1983-97) had only a +8% precipitation increase. This unusual period was marked by major floods downstream of Lakes Powell and Mead due to uncontrolled reservoir spilling and the near catastrophic loss of the spillways at Glen Canyon Dam [*Udall*, 1983].

Vano and Lettenmaier [2014] argue that the sensitivity-based approach used in our projections provides similar estimates of future streamflow to those generated with more computationally-intensive coupled-model methods, except for some (i.e., 10%) overstatement of flow reductions at the highest levels of possible warming by 2100 (e.g., the business-as-usual SRES A2 scenario used in the CMIP3 projections and the RCP8.5 in the CMIP5 projections). This would reduce the end of century high emissions mean flow reductions shown in Figure 5 to a still very significant -45% by 2100.

Recent studies have suggested that CO_2 fertilization may increase plant water efficiency thus reducing future evapotranspiration which could serve to mitigate our projected losses [*Milly and Dunne*, 2016; *Swann et al.*, 2016]. Both studies call into question results that show large portions of the globe drying in the 21st century [e.g., *Dai*, 2012; *Cook et al.*, 2014]. However, Milly and Dunne [2016] and Swann [2016] show that, despite this increase in plant water use efficiency, the Southwestern US will still dry, a finding that is consistent with multiple global assessments showing substantial drying risk to mid-latitude areas such as the Colorado River Basin. Moreover, a recent Australian study found that higher evapotranspiration associated with the increased plant growth stimulated by higher CO_2 outweighed any CO_2-related water-use efficiency effect, and served to reduce streamflows in semi-arid regions [*Ukkola et al.*, 2015], a trend that must be exacerbated by the temperature-induced lengthening of the growing season. These results suggest that plant physiological responses are likely consistent with our results, and in any case, do not invalidate them.

Megadrought Risks to Flows

Megadroughts lasting decades in the Colorado River Basin have occurred in the past, with resulting substantial flow reductions [*Meko et al.*, 2007]. Multiple papers now suggest there is high 21st century risk for megadrought in the American Southwest and that the risk will increase as temperatures rise [*Ault et al.*, 2014; *Cook et al.*, 2015; *Ault et al.*, 2016]. In addition, current GCMs underrepresent the frequency of megadrought [*Ault et al.*, 2012, 2013]. These findings provide additional support for large flow reductions during at least multi-decadal drought periods and suggest that current 21st century flow projections underrepresent this risk.

Significant Colorado River flow low losses occurred during previous multi-decadal megadroughts. During the twelfth century, flow reductions of approximately -16% occurred during one twenty-five year period [*Meko et al.*, 2007]. Evidence indicates that hemispheric and Southwest temperature anomalies were significantly smaller during past megadroughts than the rapid on-going current warming that could easily exceed 4-5 °C by the end of century under business-as-usual emissions [*Salzer and Kipfmueller*, 2005; *Mann et al.*, 2009; *Salzer et al.*, 2014, Figure 5]. Using the additivity concepts discussed above, additional warming of 1, 2 or 3 °C beyond the historic twelfth century megadrought temperatures would have reduced the -16% flow declines by an additional -6.5%, -13% or -19.5% at medium temperature sensitivity. These additional reductions would have thus turned a -16% flow decline into declines of -21.5%, -28% or -34.5%, losses near the middle of our projections.

There is recent strong evidence that continued warming over the next 80 years could increase the risk of multidecadal drought [*Ault et al.*, 2014, 2016; *Cook et al.*, 2015]. Independent of the added drought risk due to continued warming, the risk of a 35-year precipitation-deficit drought later in this century exceeds 15% within a 50-year period (Ault et al., 2014). In contrast, with continued anthropogenic warming, the risk of multidecadal megadrought in the Southwest increases to over 90% over this century if there is no increase in mean precipitation; even if modest precipitation increases do occur, the risk will still exceed 70% [*Ault et al.*, 2014, 2016]. At medium warming (4 °C), 20% to 30% precipitation increases will be needed to reduce megadrought risk below 50% and at high amounts of warming (>6 °C), it will take a ~40% increase in precipitation to reduce megadrought risk below 50% [*Ault et al.*, 2016]. These changes in precipitation are huge and unlikely, and they would still only reduce megadrought risk to below 50%.

Both the CMIP3 and CMIP5 Global Climate Models may not adequately reproduce the frequency of occurrence of known past decadal and multi-decadal precipitation droughts [*Ault et al.*, 2012, 2013]. In the Colorado River Basin empirical evidence of this problem can be found in the linked GCM-hydrology model results from Reclamation's projections for the basin [*Brekke et al.*, 2014]. Approximately half of the CMIP5 models and one-quarter of the CMIP3 models cannot simulate the 2000-2014 drought at any point in the 21st century (Text S3, Tables S1-S4). This wet bias significantly affects the mean flows of drought-capable and non-drought capable models. At the end of the 21st century the models unable to simulate the current drought are much wetter (109% of 20th century average Lees Ferry runoff for CMIP3, 113% for CMIP5) than the models that are able to simulate the current drought (85% of average runoff for CMIP3, 91% CMIP5) (Tables S1-S4). These flow differences are greater than 20%, and represent the difference between serious management challenges and significant oversupply.

Risk-Based Framing of Future Runoff Projections

At present, some outputs from global climate models are ready to support reliable risk-based policy while others are not as ready. A key novel aspect of our research is to provide more insight into where confidence is warranted, and where it is not, with respect to projections of future climate and flow change in the Colorado River Basin. In the case of the Basin, every single moderate and high emissions model simulation agrees that temperatures will continue to rise significantly with continued emissions of greenhouse gases to the atmosphere - this result is robust, highly certain and well-suited for informing policy choices. The fact that observations also show substantial warming only strengthens this assertion.

On the other hand, simulated future precipitation change in the Basin is clouded with much greater uncertainty due to substantial disagreement among models and a highly uncertain ability to simulate realistic change in key phenomena such as storm-track position or decadal and longer-scale drought. Whereas climate models are in general agreement that cool season (warm season much less certain) precipitation declines are likely in the Lower Colorado River Basin, these same models disagree when it comes to the sign and amount of precipitation change that is likely in the Upper Basin. This is because precipitation change in the Upper Basin will depend heavily on the exact changes in the position of cool season jet stream and storm-tracks, two aspects of climate change that are not simulated with confidence by global climate models [*Collins et al.*, 2013].

Moreover, there is strong evidence that the mean positions of both the jet stream and storm-tracks are likely to push poleward, expanding the area of aridity in the Colorado River Basin, but the amount of this expansion is poorly constrained [*Collins et al.*, 2013]. Multiple studies, including some focused on the American Southwest, suggest the proximate cause of this drying, Hadley Cell expansion, is already well underway and will continue [*Seager et al.*, 2007; *Scheff and Frierson*, 2012; *Feng and Fu*, 2013; *Norris et al.*, 2016; *Prein et al.*, 2016].

Our results regarding future changes in Colorado River flows agree with many previous studies in suggesting climate change translates to flow reductions, although our work is generally not directly comparable because we separate out high confidence temperature-related impacts from the possible effects of much less certain and highly variable precipitation projections. However, our work, as well as this larger body of literature, appears to be at odds with the recent Reclamation projections for the Colorado River Basin, which are widely cited and used. Reclamation's projections use a global climate model output that is downscaled to drive a hydrology model. It is worth understanding why our results emphasize substantially greater risks along with apparently greater flow losses.

The 2011 CMIP3 climate change flow projections by Reclamation indicate a modest multi-model median flow decline of -9% by 2060 for the river, but with a wide range of outcomes from flow increases to flow decreases [*Reclamation*, 2012] (Table S1). Reclamation's most recent CMIP5 projections show no change in mean and median basin-wide flow by 2070s [*Reclamation*, 2016], but also embody a wide range of results. Compared to CMIP3, the CMIP5 results show increased precipitation, especially in the northern parts of the basin including Northeast Utah, Northwest Colorado's Yampa River and the Green River in Wyoming [*Brekke et al.*, 2014; *Ayers et al.*, 2016] (Tables S1 and S3). The increased precipitation in the CMIP5 model runs compared to CMIP3 can be attributed to more southerly storm tracks in CMIP5 that occur in late spring [*Brekke et al.*, 2014].

Another issue arises in both the CMIP3 and CMIP5 datasets when GCM precipitation is adjusted by the downscaling techniques necessary for off-line hydrology models. The first step in Reclamation's downscaling is a bias correction step. This step can add approximately 5% more precipitation to the raw GCM precipitation, and this increase appears to not have a physical basis [*Reclamation*, 2011; *Brekke et al.*, 2013]. The final downscaling step, spatial downscaling, also increases GCM precipitation, although there is at least a plausible physical explanation for some of the increase: higher elevations in the Rockies receive large amounts of precipitation, but these elevations are not properly modeled by the GCMs. In one study of the CMIP5 dataset after downscaling, dry and average models show precipitation increases of approximately +~5% from the raw GCM output, but the wettest models show +~10% increases, doubling future precipitation increases from +10% to +20% [*Lukas et al.*, 2014]. This extra precipitation is manifested in a number of hydrology model runs that project huge and implausible flow increases in some years that are 150% of the highest known flows in the 20th century (Text S4, Figures S2, S3). The downscaling wetness problem has been identified, but has not been not resolved [*Lukas et al.*, 2014]. Reclamation acknowledges that the newer CMIP5 projections have not been determined to be better or more reliable [*Brekke et al.*, 2014]. It is noteworthy that internally consistent GCM-only Southwest runoff projections almost uniformly produce significant declines in both CMIP3 and CMIP5 runs [*Milly et al.*, 2005; *Seager et al.*, 2007, 2012; *Koirala et al.*, 2014; *Milly and Dunne*, 2016].

Our results are generally comparable to Reclamation's most recent results when considering the full range of our analysis when both precipitation and temperatures are included. However, our focus and emphasis is on the large near-certain temperature-induced flow declines with a separate analysis of precipitation. Reclamation, by contrast, has a focused on climate multi-model-ensemble median declines, including medians calculated across emission scenarios [*Reclamation*, 2011, 2012]. Decision makers often treat these median outcomes as a proxy for risk despite the fact that the median obscures the wide range of results and lumps wet and dry, warm and hot, large and small emission increases and, most critically, near certain temperature increases and very uncertain precipitation changes.

We assert that the large precipitation increases necessary to offset substantial temperature-induced flow decreases appear unlikely to occur for a number of reasons. These reasons include the potential for storm tracks to go north of the basin due to Hadley Cell expansion, the high potential for megadrought to increase evaporation while reducing precipitation and runoff for extended periods, the large size of the needed precipitation increases, especially when compared to decadal historical increases, the consistent identification by global assessments of the Southwest as an area likely to dry, and finally the lack of any trend over the last century or last 16 years (Figure 2c). Hence, we choose to focus on highly likely temperature-induced declines with separate analysis of the precipitation needed to offset these declines.

5. Policy Implications and Solutions

The climate science take-home messages for Colorado River managers are thus: (1) there is little doubt (i.e., high confidence) that temperatures will continue to increase as long as the emissions of greenhouse gases to the atmosphere continue; (2) there is also high confidence that continued temperature increases will cause river flows to decline, ranging from -11% to as much as -55% by end of century under moderate to high emissions (Figures 4 and 5); (3) there is only low confidence associated with the possibility of storms and precipitation in the Upper Basin increasing enough to even partially offset the temperature-driven declines in river flows; (4) the risk of multidecadal megadrought in the Basin is significant even in the absence of continued anthropogenic climate change, and this risk rises substantially with continued global warming; (5) the likelihood of drought and megadrought means that there will likely be decades-long periods with anomalously low runoff even if there is an increase in precipitation relative to the historical mean during some other periods due to anthropogenic climate change.

Temperature-driven threats to the flows of the Colorado are thus large and real. The only way to curb substantial risk of long term mean declines in Colorado River flow is thus to work towards aggressive reductions in the emissions of greenhouse gases into the atmosphere. Our work shows that modest (e.g., RCP4.5) reductions in greenhouse gas emissions, while having better outcomes than the business-as-usual future (e.g., RCP8.5), still imply large Colorado River flow losses.

The record warm nature of the on-going Colorado River drought indicates that this drought is not just a natural drought, and our work demonstrates that flows are unlikely to return to the 20th century averages if we only wait. Unusually wet periods like the 1920's and 1990's will still continue to occur, but they will co-occur with higher temperatures that will increase water demand from plants, soil, snow and humans.

Climate models and theory suggest that flow reductions would be more severe in the Southern portions of the Upper Colorado Basin affecting tributaries such as the San Juan, Dolores, and Gunnison more severely, with smaller impacts to more northerly tributaries such as the Yampa and Green [*Ayers et al.*, 2016] . Such spatial distribution would provide additional water management challenges in that the more southerly basins have in general more people, infrastructure and uses. Such a distribution would create new localized water supply shortages in addition to the overall basin-wide issues.

Other known threats to streamflows include the potential large scale loss of conifers [*Breshears et al.*, 2005; *Adams et al.*, 2009; *Allen et al.*, 2010, 2015] , and the impacts of dust on snow [*Painter et al.*, 2010; *Deems et al.*, 2013]. These factors along with the observed and projected temperature-induced Colorado River flow declines, the inability of many linked climate-hydrology models to simulate persistent droughts, and the increasing likelihood of hot drought and megadrought, all imply that future Colorado River water supply risk is high. It is imperative that decision-makers begin to consider seriously the policy implications of potential large-scale future flow declines. Stable 20th century Colorado River flow regimes may not reoccur for many centuries – the time scale of climate system readjustment to the complete cessation of greenhouse gas emissions [*Solomon et al.*, 2009; *Collins et al.*, 2013] .

The Colorado River declines do not stand alone as the only warming-related threat to Southwestern water supplies. The Rio Grande also has a grim prognosis [*Reclamation*, 2013; *Elias et al.*, 2015]. The drought in California has garnered national attention, and multiple studies have strongly implicated increasing temperatures as a contributor to these woes [*Griffin and Anchukaitis*, 2014; *Belmecheri et al.*, 2015; *Diffenbaugh et al.*, 2015; *Mann and Gleick*, 2015; *Seager et al.*, 2015a]. Southern California is particularly at risk, with a critical economy and a very large population, all coupled with a large reliance on both climate-threatened in-state, as well as Colorado River, water.

Adjusting to the new reality of rapid climate change will not be an easy or fast task; water management and water policy change slowly. The Colorado River is managed by a complex set of agreements, interstate compacts approved by Congress, international agreements, legislation and court decrees set in place over the last 100 years [*Verburg*, 2011]. Most agreements were derived from 20th century state-based negotiations with win/lose policy prescriptions that minimized basin-wide considerations of economic prosperity and potential harm [*Adler*, 2008]. None expressly includes climate change risk management, nor the provision for flow reductions that will be relentless on decadal timescales. New agreements often take years to put in place [*Department of Interior*, 2007]. The recently proposed structural deficit solution [*Central Arizona Project*, 2016], while important and laudable for the short term, will not solve the problem of large scale flow losses. With reduced water supplies, much will have to change in these agreements to address equity, economics and social concerns on regional, state, basin-wide and even national levels. Climate change threats to western water supplies are very real, and should prompt great concern and urgency among both water managers and the citizens of the Southwest.

Acknowledgments and Data

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Table 1: Winter/Summer/Annual Upper Basin Mean Water Year Precipitation

	1953-1967			2000-2014			1896-2014	
	mm			mm			mm	
	total	Anomaly	Anomaly % of mean	total	Anomaly	Anomaly % of mean	Mm	% Avg
Winter (Oct-Mar)	176	-16	-8.6%	187	-5	-2.7%	192	100%
Summer (Apr-Sept)	184	-7	-3.6%	179	-12	-6.4%	191	100%
Total	359	-23	-6.1%	365	-17	-4.6%	383	100%

Table 2: Upper Basin Water Year Flows and Temperatures

	Average Annual Flow		Average Annual Temperature	
Period	bcm	% 1906-1999	Deg. C	°C Anomaly to 1896-1999
1953-1967	15.38	81.9%	7.0	0.2
2000-2014	15.15	80.7%	7.7	0.9
1906-1999	18.77	100.0%	6.8	0.0
1906-2014	18.27	97.3%	6.9	0.1

Figure Captions

Figure 1. Map of the Colorado River Basin. Lower and Upper Basins, major U.S. cities receiving Colorado River water, major tributaries, and Lakes Mead and Powell are shown. The Central Arizona Project canal in red.

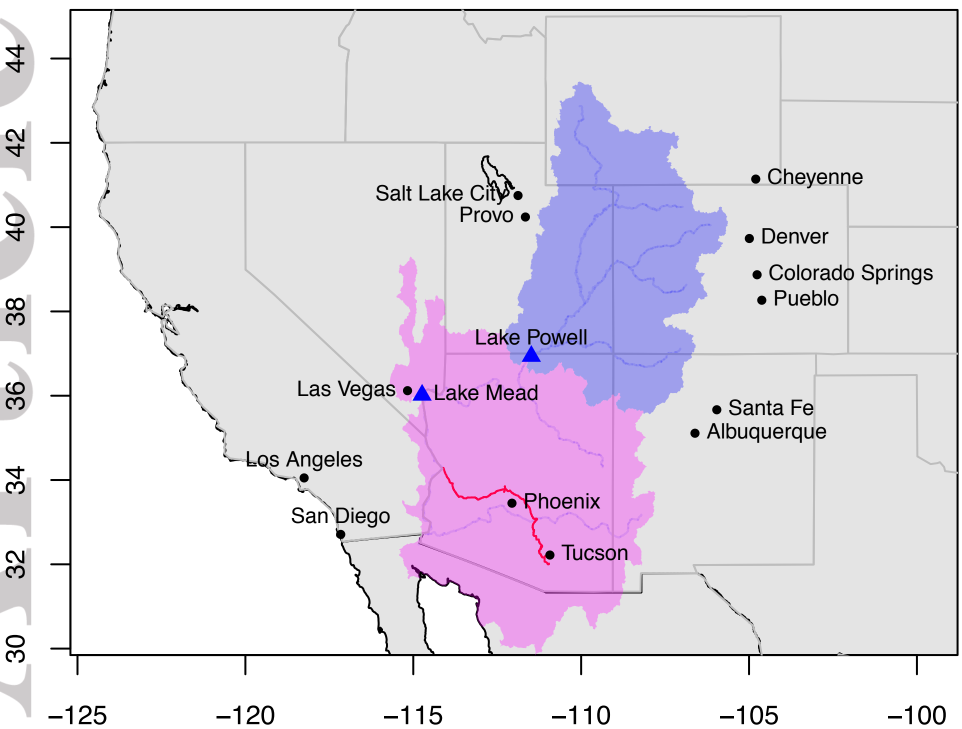
Figure 2. (a) Lakes Mead and Powell combined monthly contents. Upper Basin annual Colorado River (b) runoff at Lees Ferry from 1906-2014, (c) precipitation and (d) temperatures from 1896-2014. Mead first filled in 1935, Powell in 1963 (Text S1). Two fifteen-year drought periods, 1953-1967 and 2000-2014, are highlighted and discussed in main text.

Figure 3. Probability Density Functions of Upper Colorado River Basin temperature projections for mid-century and end-century under moderate (SRES A1B and RCP4.5) and high (SRES A2 and RCP8.5) emissions.

Figure 4. Probability Density Functions of Upper Colorado River Basin temperature-induced flow reductions for mid-century and end-century with the three temperature sensitivities (-3%, -6.5%, -10%) and the two levels of emissions (Moderate: SRES A1B and RCP4.5 and High: SRES A2 and RCP8.5).

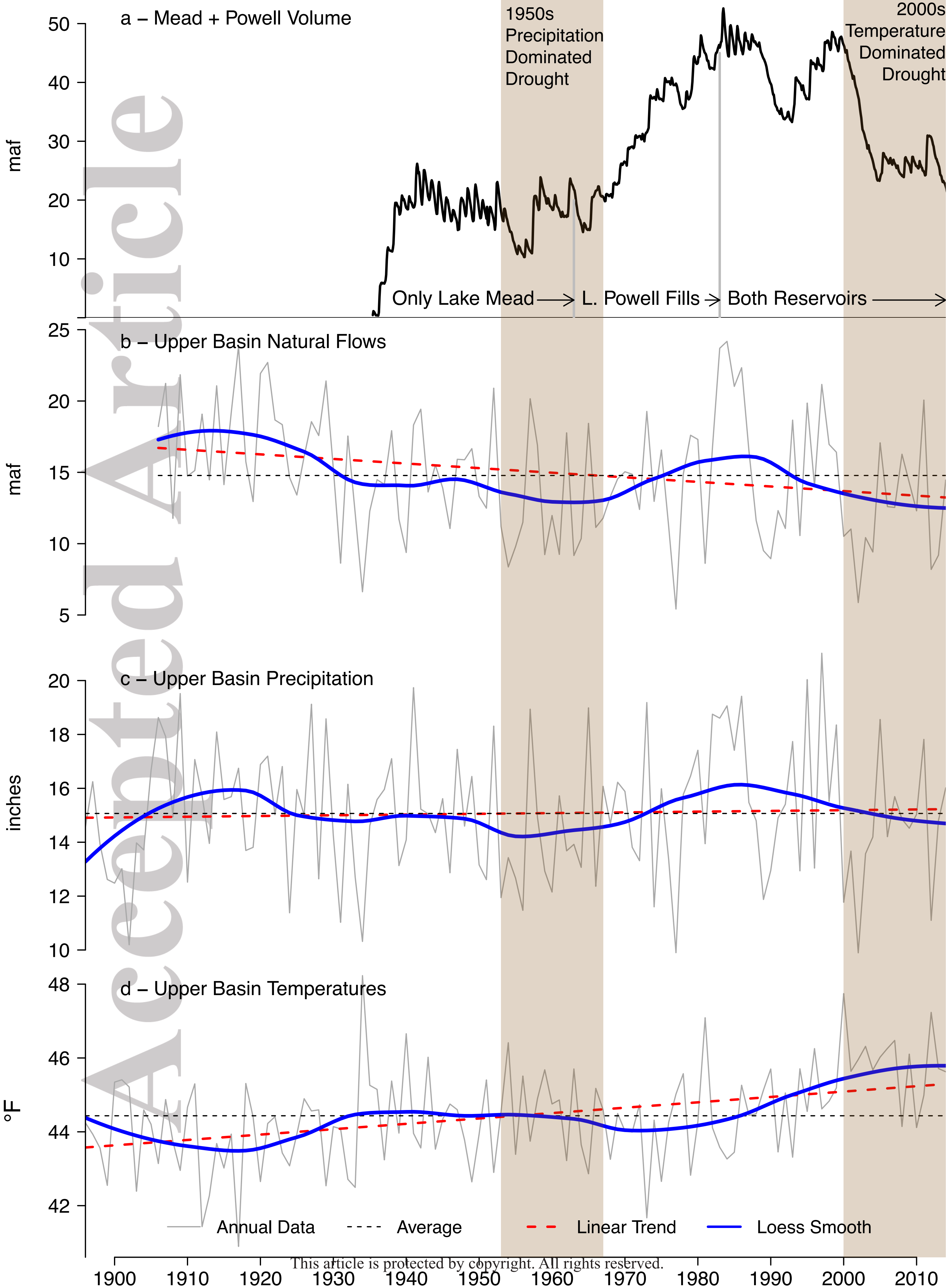
Figure 5**.** Temperature-induced flow losses by model run (one per dot) with temperature increases shown on horizontal axis. For each period (Mid-Century, End-Century) and emissions type (Moderate, High), flow losses for each model run are shown with the 3 (Low = -3%/°C, Medium = -6.5%/ °C, High = -10%/°C) temperature sensitivities. Black dots/circles are averages/medians for each sensitivity. Precipitation increases needed to counteract flow losses at right are based on 2.5 precipitation elasticity. Range for the temperature-induced losses during 2000-2014 drought are shown in shaded brown at the top (Text S5).

Figure 1.



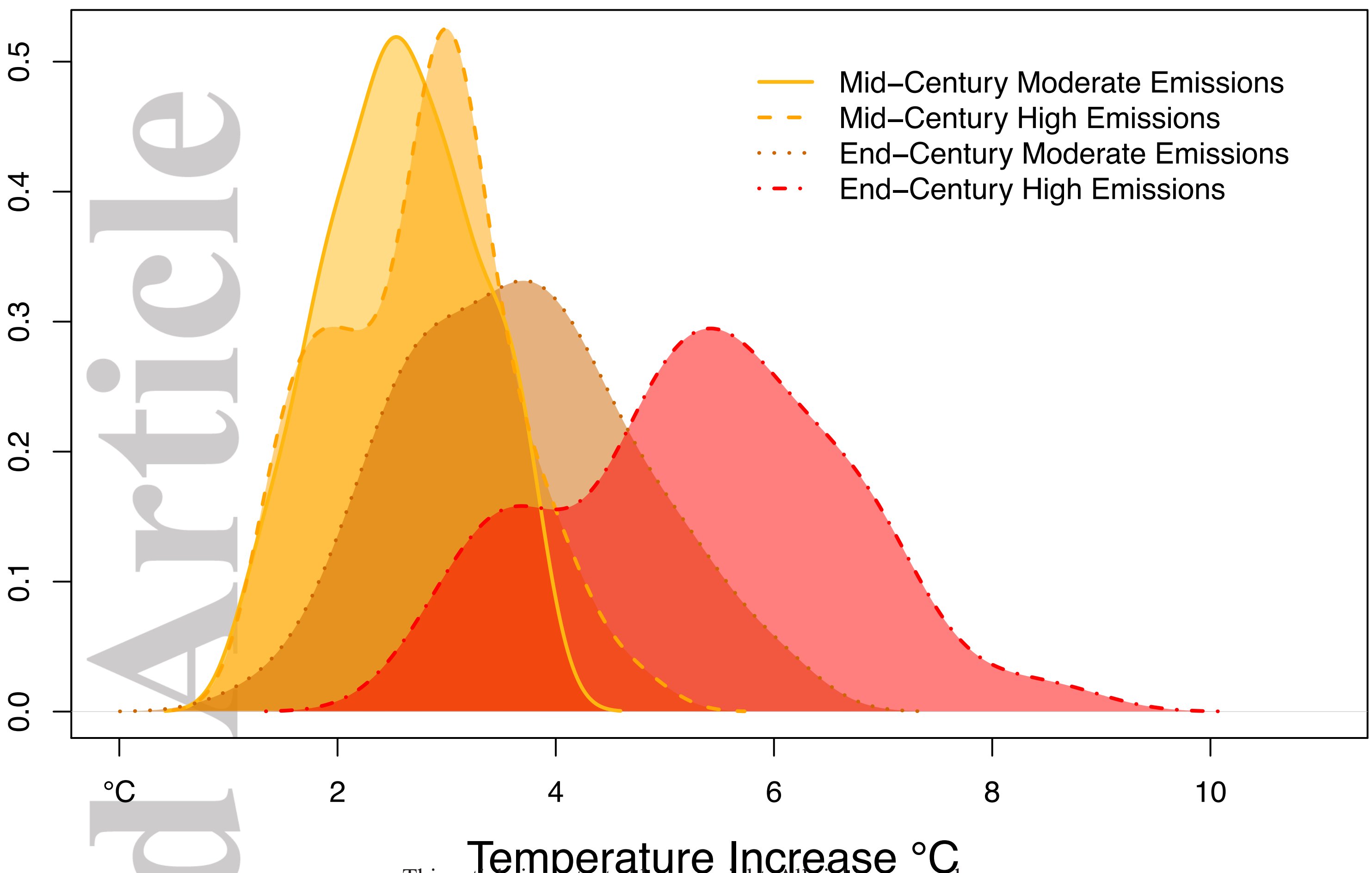
Cheyenne
Salt Lake City
Provo
Denver
Colorado Springs
Pueblo
Lake Powell
Las Vegas
Lake Mead
Santa Fe
Albuquerque
Los Angeles
Phoenix
San Diego
Tucson
44
42
40
38
36
34
32
30
−125
−120
−115
−110
−105
−100

Figure 2.



a – Mead + Powell Volume
1950s
Precipitation
Dominated
Drought
2000s
Temperature
Dominated
Drought
maf
Only Lake Mead
L. Powell Fills
Both Reservoirs
b – Upper Basin Natural Flows
maf
c – Upper Basin Precipitation
inches
d – Upper Basin Temperatures
°F
Annual Data
Average
Linear Trend
Loess Smooth
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Figure 3.



Mid−Century Moderate Emissions
Mid−Century High Emissions
End−Century Moderate Emissions
End−Century High Emissions
0.0
0.1
0.2
0.3
0.4
0.5
°C
2
4
6
8
10
Temperature Increase °C

Figure 4.

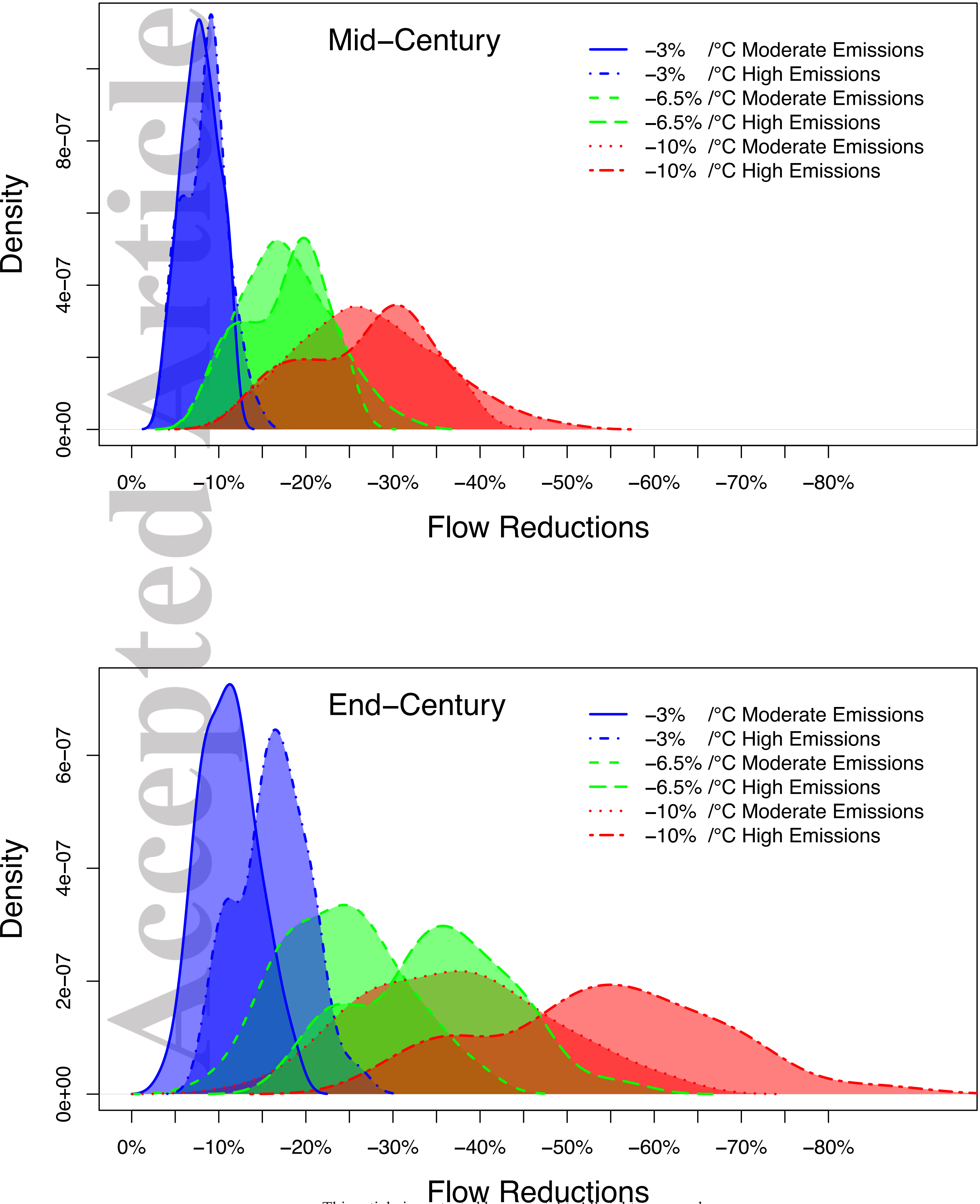
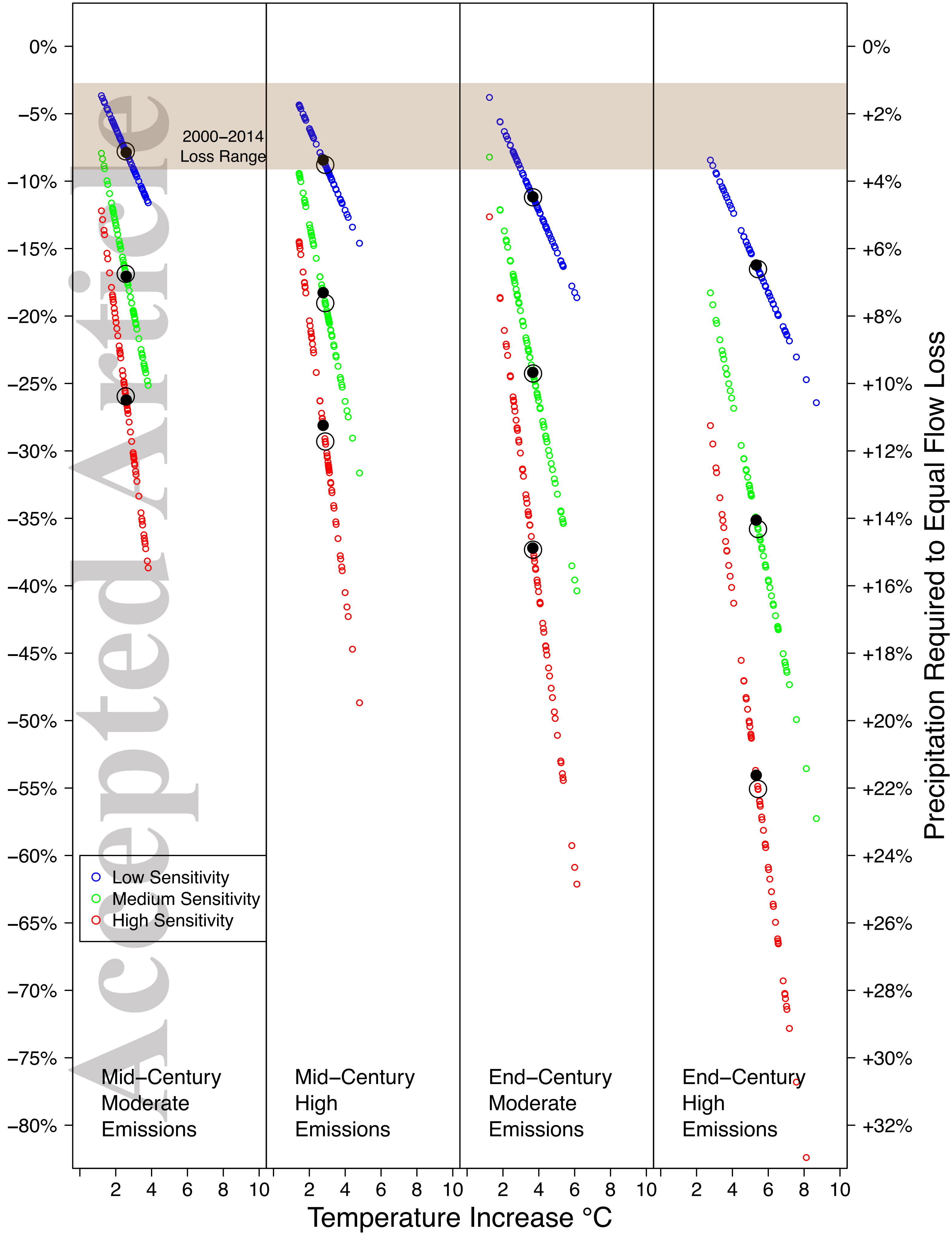

Mid−Century
−3% /°C Moderate Emissions
−3% /°C High Emissions
−6.5% /°C Moderate Emissions
−6.5% /°C High Emissions
−10% /°C Moderate Emissions
−10% /°C High Emissions
Density
0e+00
4e−07
8e−07
0%
−10%
−20%
−30%
−40%
−50%
−60%
−70%
−80%
Flow Reductions
End−Century
−3% /°C Moderate Emissions
−3% /°C High Emissions
−6.5% /°C Moderate Emissions
−6.5% /°C High Emissions
−10% /°C Moderate Emissions
−10% /°C High Emissions
Density
0e+00
2e−07
4e−07
6e−07
0%
−10%
−20%
−30%
−40%
−50%
−60%
−70%
−80%
Flow Reductions

Figure 5.


0%
−5%
−10%
−15%
−20%
−25%
−30%
−35%
−40%
−45%
−50%
−55%
−60%
−65%
−70%
−75%
−80%
0%
+2%
+4%
+6%
+8%
+10%
+12%
+14%
+16%
+18%
+20%
+22%
+24%
+26%
+28%
+30%
+32%
Precipitation Required to Equal Flow Loss
2000–2014
Loss Range
Low Sensitivity
Medium Sensitivity
High Sensitivity
Mid–Century
Moderate
Emissions
Mid–Century
High
Emissions
End–Century
Moderate
Emissions
End–Century
High
Emissions
2
4
6
8
10
Temperature Increase °C