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Tree rings and multiseason drought variability in the lower Rio Grande Basin, USA

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[1] Agriculture and ranching in semiarid regions often rely on local precipitation during the growing season as well as streamflow from runoff in distant headwaters. Where snowpack and reservoir storage are important, this pattern of reliance leads to vulnerability to multiseason drought. The lower Rio Grande basin in New Mexico, used as a case study here, has experienced drought conditions over the past 12 years characterized both by low local summer monsoon precipitation and by reduced availability of surface water supplies from the upper Rio Grande. To place this drought in a long-term context, we evaluate the covariability of local warm-season and remote cool-season hydroclimate over both the modern period and past centuries. We draw on a recently developed network of tree-ring data that allows an assessment of preinstrumental warm-season variations in precipitation over the southwest. Both instrumental and paleoclimatic data suggest that low runoff followed by a dry monsoon is not unusual, although over the full reconstruction period (1659–2008), years with wet or dry conditions shared in both seasons do not occur significantly more often than unshared conditions. Low flows followed by dry monsoon conditions were most persistent in the 1770s and 1780s; other notable periods of shared seasonal droughts occurred in the 1660s and 1950s. The recent drought does not yet appear to be unusually severe in either the instrumental or paleoclimatic context.

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1. Upper and Lower Rio Grande Basin Drought

[2] Summer precipitation can impact water demand and be an important source of water for irrigation in areas where streamflow may be largely driven by cool-season precipitation, such as the intermountain and southwestern United States. These semiarid regions often rely on multiple sources of water, including local precipitation during the growing season as well as streamflow derived from runoff in distant headwaters, leading to vulnerability to multiseason drought. Relatively little attention has been paid to the phasing of seasonal drought and the history of past concurrent warm- and cool-season moisture deficits, but these events can compound the effect of droughts, impact natural vegetation and phenological responses, and exacerbate water management challenges [e.g., *Crimmins et al.*, 2008; *Castro et al.*, 2009; *Phillips et al.*, 2009; *Weiss et al.*, 2009]. The lower Rio Grande basin in New Mexico is used as a case study here to examine the covariability of local warm-season and remote (upper Rio Grande basin) cool-season hydroclimate over both the modern period and past centuries, using paleoclimatic data.

[3] In southern New Mexico, summer rains associated with the North American monsoon contribute 50% or more of the annual total precipitation (based on July–September) [*National Weather Service Climate Prediction Center*, 2012b]. While monsoon rainfall may contribute little to reservoir levels, it can be a critical source of water for agriculture and ranching, as is the case in the lower Rio Grande basin. Agriculture in this region typically relies on summer rains to supplement surface water rights to the Rio Grande water and groundwater pumping. The Elephant Butte Irrigation District in southern New Mexico, the state's largest supplier of surface water, provides irrigation from the Rio Grande to over 36,000 ha of crops, including pecans, chilis, and cotton [*Bureau of Reclamation*, 2012; *Elephant Butte Irrigation District*, 2012]. Water year (October–September) streamflow in the headwaters of the upper Rio Grande, which is largely derived from snowmelt [*Dahm et al.*, 2005], has been below average in 8 of 12 years since 2000 (Rio Grande near Del Norte Colorado, data from Colorado Department of Water Resources and U.S. Geological Survey (USGS) gage 08220000, 1895–2010 average). As a consequence, Elephant Butte Reservoir, a major reservoir on the Rio Grande, has dropped to 5% of capacity as of 17 October 2012 [*Natural Resources Conservation Service*, 2012a]. Over the same time period, the lower Rio Grande region has suffered 8 years of below-average summer

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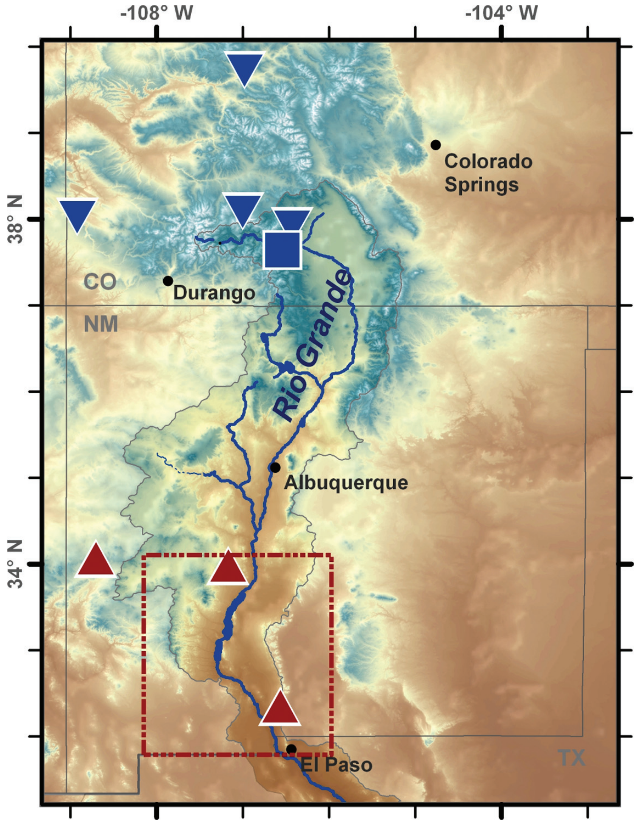

Figure 1. Rio Grande basin with locations of instrumental and tree-ring data used for this study. The blue square indicates the location of the Rio Grande gage near Del Norte, Colorado. Blue triangles show tree-ring chronologies used for the Rio Grande flow reconstruction. Red triangles show the locations of the chronologies used for the lower Rio Grande June–July precipitation reconstruction. The large rectangle outlined in the dotted red line indicates the lower Rio Grande region for which precipitation was reconstructed.

precipitation (June–August total, average across the region in Figure 1 from Parameter-elevation Regressions on Independent Slopes Model data [PRISM, *Daly et al.*, 2008], 1895–2010 average). There have been 5 years of coinciding the Rio Grande low flows and summer drought, including a run of three consecutive years 2002–2004. Impacts of this drought have included reduction in allocations of surface water for irrigation, the need to purchase supplemental livestock feed, low crop yields, and the Rio Grande flow releases to support the endangered silvery minnow [*Guido*, 2011; *New Mexico Governor's Drought Task Force*, 2011].

[4] In assessing the impacts of shared seasonal droughts (droughts occurring in both cool and monsoon seasons of the same year) and the potential for these conditions to continue, several questions arise. How does drought covary between the upper Rio Grande water year streamflow and the lower Rio Grande monsoon precipitation? How do the length, frequency, and occurrence of shared periods of low flow and dry monsoons of the past three centuries compare with similar features in the instrumental records? Is the ongoing drought anomalous in the context of past centuries? We address these questions through an analysis of instrumental and paleoclimatic records of headwater flow in the Rio Grande, using the gage near Del Norte, Colorado, and summer precipitation over the lower Rio Grande. Throughout this paper, "Rio Grande drought" refers to cool-season moisture deficits in the upper Rio Grande basin and warm-season deficits in the lower Rio Grande, as shown in Figure 1. In the analysis of these records, droughts are identified in two main ways: by the lowest tercile of flow and precipitation values and by the 15th (extreme drought) and 30th (moderate drought) percentile values based on 5 year running means of the two reconstruction series.

2. Rio Grande Basin Reconstructions of Water Year Streamflow and Monsoon Precipitation

[5] Tree-ring based reconstructions used in this study were the water year reconstruction of the Rio Grande near Del Norte [*Woodhouse et al.*, 2012] and a new reconstruction of monsoon precipitation for the lower Rio Grande region. Independent sets of tree-ring data were used for the two reconstructions. The reconstruction models for both were generated with multiple linear regression using cross-validation [*Michaelsen*, 1987].

[6] The Rio Grande near Del Norte gage record extends from 1890 to 2010, with only minor depletions upstream (data from Colorado Department of Water Resources and USGS gage 08220000). Flow at Del Norte contributes approximately 68% of the flow at the Otowi Bridge gage in northern New Mexico where allocations between New Mexico and Texas are determined. The flows at the two gages are highly correlated ($r = 0.89$, $p < 0.01$), and thus, the Del Norte gage is a good indicator of the upper Rio Grande basin conditions, particularly in the cool season. Because of its length, minimal impairment compared with other Rio Grande gage records, and its representativeness of the upper basin flows, the Del Norte record of the Rio Grande water year flow was used to calibrate the flow reconstruction. The Rio Grande flow reconstruction model contained four predictors (Figure 1) and accounted for 71% of the variance in the gage record (Figure 2; for more details, see *Woodhouse et al.* [2012]).

[7] The North American monsoon region is not homogeneous with respect to summer precipitation, and major subregions have been defined in several studies [*Comrie and Glenn*, 1998; *Gutzler*, 2004; *Gochis et al.*, 2009]. A common subregional boundary separates far western New Mexico and much of Arizona from a region to the east. Based on this split and the distribution of tree-ring data, we selected a reconstruction region centered on the Rio Grande, extending from approximately 34°N to the US/Mexico border (Figure 1). For summer precipitation, gridded monthly precipitation data (PRISM) [*Daly et al.*, 2008] were used to reflect monsoon conditions in the lower Rio Grande basin. All subsequent climate statistics reported are based on the PRISM data averaged over this region.

[8] In order to reconstruct summer precipitation, a new network of latewood-width tree-ring chronologies for the southwestern United States was used. This region has a bimodal precipitation regime, with both cool- and monsoon-season precipitation. By measuring the part of the growth ring that forms in the later part of the growing season (the latewood) separately from the part of the ring that forms

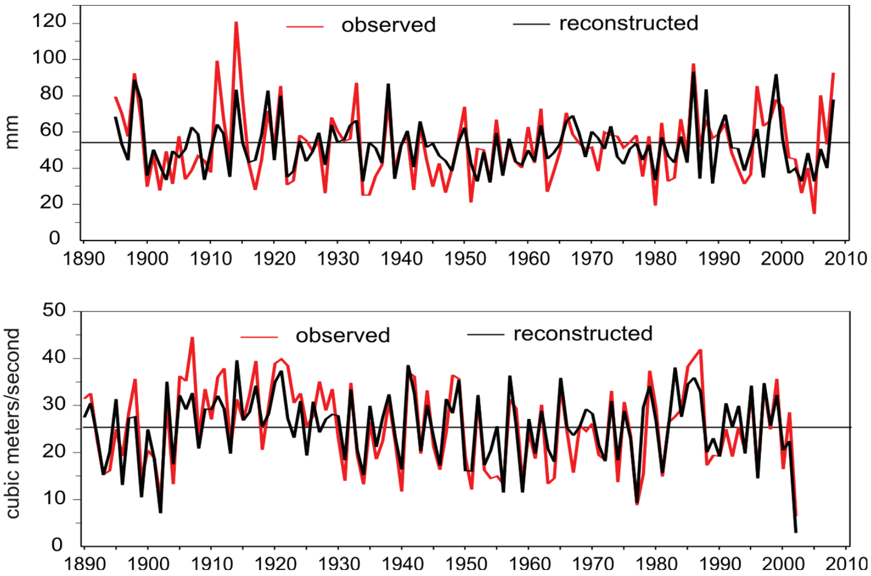

Figure 2. Observed and reconstructed (top) lower Rio Grande June–July total precipitation, 1895–2008 and (bottom) upper Rio Grande water year flow, 1890–2002. The observed record is shown by the red line and the reconstruction in black. The horizontal line indicates the average.

during the early part of the growing season (the earlywood), it is possible to obtain a strong correspondence between latewood growth increment and monsoon moisture [*Griffin et al.*, 2011]. Since there is often a biological relationship between growth in the early and late parts of the growing seasons, latewood-width measurements are adjusted using regression to remove the statistical dependence of the latewood width on the earlywood width [*Meko and Baisan*, 2001]. To date, only one other reconstruction of monsoon-season precipitation has been generated for the month of July at a location in western New Mexico [*Stahle et al.*, 2009].

[9] In the lower Rio Grande region targeted here, 46% of the annual precipitation falls in June–August. Because the latewood widths used in this study are strongly correlated with precipitation in June and July and much less so with precipitation in August, we selected the 2 month precipitation total, June–July, as a target variable, or predictand, for reconstruction. The June–July precipitation total is a fair representation of monsoon-season precipitation: June–July accounts for 55% of the June–August total on average, and the correlation between June–July and June–August is $r = 0.76$ ($p < 0.01$).

[10] Stepwise regression was used to develop a reconstruction model. The pool of candidate predictor chronologies from the southwestern U.S. network of 50 latewood chronologies was screened first to eliminate chronologies without complete time coverage for the period 1659–2008. A second screening step then eliminated chronologies not significantly correlated ($p < 0.05$) with the lower Rio Grande June–July precipitation over the full period 1895–2008, or over either the first or second half of this period. A total of 10 chronologies passed the two screening steps. A stepwise regression was run with the 10 chronologies as potential predictors, using an F-to-enter of 2.01 and F-to-remove of 2.00. The final reconstruction model contained three predictors and explained 54% of the variance in June–July precipitation (Table 1 and Figures 1 and 2). Residuals met regression assumptions, and the reduction of error statistic (RE) [*Fritts*, 1976] and root-mean-square error of the validation data (RMSE_v) indicated no model overfit. The common period for the Rio Grande flow and summer precipitation reconstructions was 1659–2002 (Figure 3).

3. Comparison of Shared and Unshared Droughts in Rio Grande Streamflow and Summer Precipitation

[11] To investigate the long-term relationship between cool-season-dominated streamflow and warm-season

Table 1. June–July Precipitation Regression Model and Statistics

Regression Summary:	$R = 0.736$	$R^2 = 0.542$	$R^2_{\text{adj}} = 0.530$	$F = 43.405$ ($p = 0.000$)	Standard Error of Estimate = 13.142
Validation Results:		RE = 0.509			$\text{RMSE}_v = 13.365$

$N = 114$	β[a]	Standard Error of β	B[a]	Standard Error of B	t	p value
Intercept			−6.916	6.434	−1.075	0.285
ORM	0.400	0.070	20.370	3.545	5.746	0.000
FMM	0.337	0.076	18.559	4.147	4.475	0.000
MMM	0.224	0.077	22.109	7.589	2.913	0.004

[a] β is the standardized regression coefficients, and B is the raw regression coefficients. The p values are rounded off, such that very small p values are reported as 0.0000. ORM = Organ Mts.; FMM = Fox Mt.; MMM = Magdelena Mts. tree-ring sites.

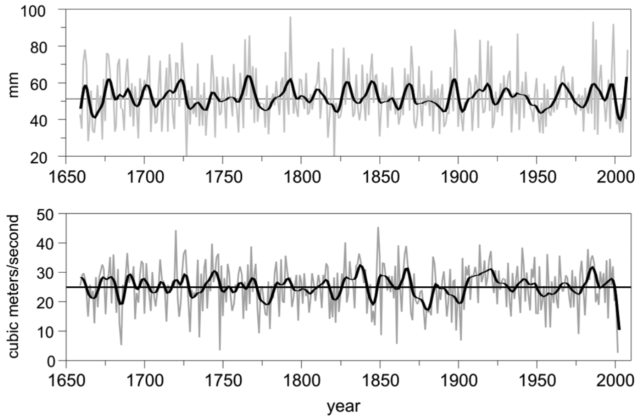

Figure 3. Reconstructed (top) lower Rio Grande region total June–July precipitation, 1659–2008 and (bottom) upper Rio Grande water year flow, 1659–2002, (light line) annual values and (heavy line) smoothing with a 10 year spline. The horizontal line is the long-term average.

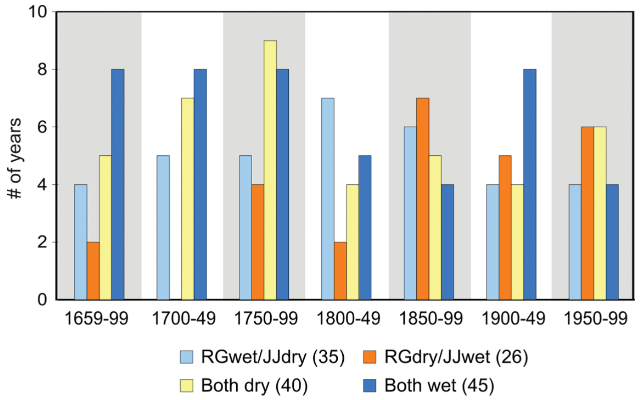

Figure 4. Numbers of shared and unshared wet and dry years (based on terciles) in reconstructed Rio Grande flow and June–July precipitation by half century periods 1659–1999 (n = 41 for 1659–1699). Totals for years in each of the four categories are listed in parentheses.

precipitation anomalies, tree-ring reconstructions of the Rio Grande headwater flow and the lower Rio Grande monsoon precipitation were evaluated. The highest and lowest tercile years were used to assess the distribution of years of shared and opposite hydroclimatic conditions over cool and monsoon seasons. An initial assessment of the reconstructions over the instrumental period shows that while counts are somewhat different than those from the instrumental data, the relative distribution of numbers of years in each of the four categories (high flow/wet monsoon, low flow/dry monsoon, high flow/dry monsoon, and low flow/wet monsoon) is similar (Table 2A).

[12] When assessed over 50-year periods, the reconstructions reveal variability in the distribution of each of the four categories through time (Figure 4). The numbers of years in the different categories differ only slightly in the nineteenth century and the twentieth century. The greatest contrast is in the eighteenth century, during which a much greater proportion of both shared wet and dry years occurs than do years with opposite seasonal moisture anomalies (32 shared versus 14 years of opposite conditions). Shared wet and dry years are almost equal in number during both halves of the eighteenth century. The first half of the eighteenth century is the only 50-year period for which any of the combinations (in this case, low flow and high monsoon precipitation) is not represented. A tendency for more shared seasonal wet and dry years is also evident in the second half of the seventeenth century. A chi-square test, based on a 9 × 9 matrix, performed for each half century period ($n = 50$ except the first period, $n = 41$), showed that only the distribution of values in the first half of the eighteenth century is significantly different from a random distribution ($p < 0.05$) [*Clark and Hosking*, 1986]. When the significance level is adjusted for multiple tests using the Bonferroni correction, none of the subperiods, nor the full period, show significant nonrandom distributions [*Snedecor and Cochran*, 1989].

[13] The coincidence of multiyear drought in both cool and warm seasons is of particular interest given the impacts of such conditions over the past decade. For the full 344 year (1659–2002) period of overlap, each of the two reconstructions has 115 years in its driest tercile, and 41 driest-tercile years are shared. The probability of this occurring by chance can be tested with the hypergeometric distribution, described by *Conover* [1980] and previously applied in climatology by *Dracup and Kahya* [1994] and in a tree-ring context by *Meko and Woodhouse* [2005]. Given a population of size M containing K members with a desired trait (e.g., driest tercile), the hypergeometric distribution gives the probability p that a random sample size N drawn without replacement will yield m or fewer hits, or members

Table 2. Comparison of Numbers of Shared and Unshared Wet and Dry Years[a]

	Both Cool Season and Monsoon Wet	Both Cool Season and Monsoon Dry	Dry Cool Season/ Wet Monsoon	Wet Cool Season/ Dry Monsoon
A. Rio Grande Flow and Lower Rio Grande Monsoon Precipitation, Instrumental and Reconstructed Records, 1895–2002				
Instrumental data				
June–August	15	15	16	7
June–July	12	14	14	9
Reconstructions				
June–July	13	11	13	9
B. Lower Rio Grande Cool-Season (October–March) and Monsoon Precipitation Instrumental Records, 1896–2010				
Reconstructions				
June–August	15	17	13	10
June–July	12	14	12	8

[a] Wet and dry years are based on terciles.

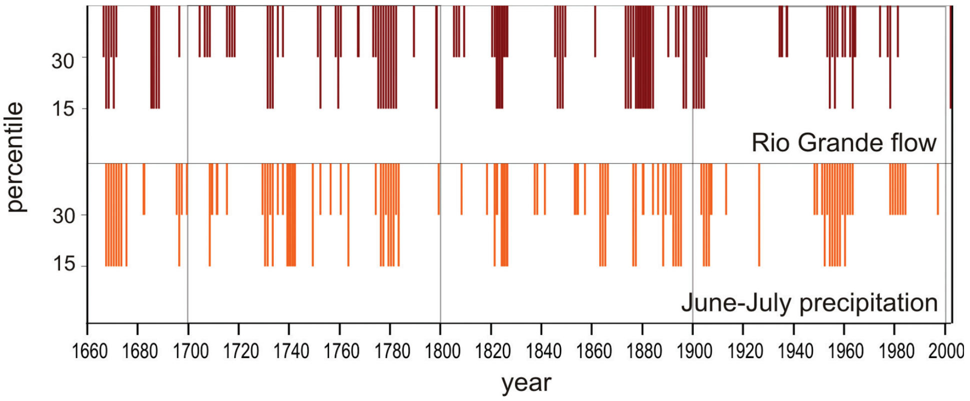

Figure 5. Reconstructed Rio Grande flow and June–July precipitation, 1659–2002, filtered with a 5-year running mean. Only periods with values in the 30th and 15th percentiles are shown. The percentiles are inverted to emphasize drought severity.

with the desired trait. Accordingly, $p' = 1 - p$ is the probability of drawing $m+1$ or more members with the trait. The stipulation "without replacement" is critical here because the probability of an additional hit decreases with each hit (remaining number of dry years in the defined population decreases). Settings of $m = 40$, $M = 344$, $K = 115$, and $N = 115$ yield a probability $p' = 0.31$ that 115 years drawn at random from the lower Rio Grande precipitation reconstruction will yield 41 or more years from the lowest tercile. The probability is therefore less than 50% that the observed coincidence of driest-tercile years occurred by chance, though for the given sample size we cannot reject the null hypothesis of no relationship at $\alpha = 0.05$.

[14] In order to highlight multiyear dry episodes, the upper Rio Grande streamflow and the lower Rio Grande June–July precipitation reconstructions were filtered with a 5-year running average. Moderately dry and extremely dry periods were defined as smoothed reconstructed flow or precipitation below the 30th percentile and 15th percentile, respectively, based on the full reconstructions. It is evident that extended periods of drought in both the Rio Grande flow and the monsoon precipitation have occurred over the past three centuries (Figure 5). Many periods of drought in the Rio Grande flow reconstruction have been recognized in other reconstructions that reflect cool-season drought [e.g., *Touchan et al.*, 2011; *Margolis et al.*, 2011], but this is the first time it has been possible to assess shared drought in both the lower Rio Grande monsoon precipitation and the headwaters that supply surface water to this region. The period from the 1950s into the 1960s stands out for persistent dryness in both seasons and regions, although cool-season drought in the upper Rio Grande is punctuated by several short intervals of less severe low flows. A period of even more severe, persistent two-season drought is evident in the 1770s and 1780s. Cool-season drought during this period is well documented by numerous tree-ring reconstructions for the western and southwestern United States [e.g., *Meko et al.*, 2001; *Fye et al.*, 2003; *Woodhouse et al.*, 2006], but it is now evident that summer drought was also a characteristic of this period in the lower Rio Grande region. The severity of low flow and monsoon precipitation deficits is greater than in the 1950s, with values in the 15th percentile for all but two periods in the sequence of eight consecutive 5-year running average periods. The impacts of this period of drought on Hopi and Navajo tribal communities are well documented and include famine, disease, and crop failure [e.g., *Donaldson*, 1893; *Titiev*, 1944; *Brugge*, 1994]. Low runoff and dry monsoon conditions in this region were also persistent in the 1660s and early 1670s, coinciding with social upheaval in the Puebloan and Spanish settlements of New Mexico [e.g., *Parks et al.*, 1996]. A cluster of shorter intervals of shared seasonal drought is indicated in the 1870s, 1890s, early 1900s, a stretch of decades distinguished by predominantly below-average flows in the upper Rio Grande basin [*Woodhouse et al.*, 2012]. The timing of monsoon-season droughts in the Rio Grande region generally agrees with the droughts in the July precipitation reconstruction for western New Mexico from *Stahle et al.* [2009], suggesting the spatial extent was not restricted to the lower Rio Grande region. Notable for a lack of shared seasonal drought is the early twentieth century pluvial [*Cook et al.*, 2011], during which years were predominantly wet in both cool and warm seasons (Figure 4).

4. Climatic Influences and Seasonal Drought Synchroneity

[15] Several studies have addressed causal mechanisms related to contrasting seasonal moisture anomalies in the North American monsoon region. Research has indicated that opposite moisture conditions in the cool and monsoon seasons may be expected due to Pacific Ocean influence [*Castro et al.*, 2001, 2007, 2009], with effects strongest in the monsoon subregion to the west of the Rio Grande region, including far western New Mexico and Arizona. Another body of work suggests that land surface feedbacks favor asynchronous cool-season and monsoon-season drought [*Adams and Comrie*, 1997; *Higgins et al.*, 1998; *Gutzler*, 2000], although these effects have been shown to be spatially and temporally variable [*Zhu et al.*, 2005].

[16] In contrast, our results for the upper Rio Grande headwater flow and the lower Rio Grande monsoon precipitation support a propensity for shared cool- and monsoon-season moisture conditions. Over the full period of the reconstructions, shared seasonal conditions are more the

rule than the exception, with a total of 86 years of shared and 61 years of opposite conditions over the past 344 years. As discussed previously, the observed flows and precipitation data also fail to show a tendency for opposite-sign moisture anomalies in the headwater flow and the lower Rio Grande precipitation (see Table 2A). While the two regions represented by the upper Rio Grande headwater flow and the lower Rio Grande monsoon precipitation are separated by some distance (Figure 1), instrumental precipitation records of cool- and warm-season precipitation for the same lower Rio Grande region likewise show a somewhat higher proportion of shared wet and dry years than years with opposite seasonal anomalies over the period 1896–2010 (Table 2B).

[17] One reason shared seasonal moisture anomalies may be more dominant in our study area than further west is that the lower Rio Grande is on the eastern edge of the area that reflects a strong monsoon/El Niño–Southern Oscillation signal with seasonal precipitation anomalies of opposite sign [*Castro et al.*, 2009]. Other research suggests a different set of circulation features is associated with summer precipitation extremes in the region including the lower Rio Grande basin, compared to other parts of the North American monsoon region [*Comrie and Glenn*, 1998]. Thus, the covariability of seasonal drought may not be as closely or consistently linked to Pacific Ocean conditions here as it is elsewhere in the monsoon region. Other controls and modes of circulation likely influence monsoon variability in the Rio Grande region [e.g., *Ding and Wang*, 2005; *Mo et al.*, 2009] that may at times result in synchronized cool- and monsoon-season droughts.

5. Conclusions

[18] Droughts have impacted both the upper Rio Grande runoff (representing cool-season moisture) and the monsoon precipitation in the lower Rio Grande basin over the past decade. Shared seasonal droughts have occurred in 5 of the past 12 years, with every indication that at least cool-season drought in the Rio Grande headwaters is continuing (projected runoff at Rio Grande Del Norte gage is 34% of average for June–September 2012) [*Natural Resources Conservation Service*, 2012b].

[19] A direct comparison of the recent and ongoing drought and the droughts of past centuries cannot be made since the reconstructions extend only to 2002. Analysis of instrumental records (1895–2011) suggests that the current drought, evaluated by several metrics, does not yet clearly exceed the severity of several twentieth century droughts. The 12-year period 2000–2011 contained 5 years with below-average conditions for both flow and monsoon precipitation, but the 12-year period 1945–1956 contained 7 years of below-average flows and monsoons (June–July or June–August totals). During the period 2000–2011, there have been 3 years with flow and monsoon precipitation both in their lowest tercile. Two other 12-year periods have also had 3 years in the lowest tercile: the overlapping periods 1951–1962 and 1954–1965.

[20] The most recent drought does have several notable characteristics. The period 2000–2011 is unique among 12 year periods for having two consecutive years in the lowest tercile. Moreover, the lowest 5-year flow on record, 2000–2004, overlaps the driest June–July precipitation total, 2001–2005. Drought conditions are continuing, and the current drought may yet become the most severe drought in the instrumental record. However, dry conditions would have to be quite persistent to reach the severity of the 1700s drought. In the instrumental record, the longest interval of consecutive 5-year running averages with flow and monsoon precipitation values below the 30th percentile was three 5-year periods (in the first decade of the twentieth century), compared to eight periods in the 1700s (Figure 5).

[21] From the reconstructions, the long-term probability is 36% that a dry winter on the upper Rio Grande is followed by a dry monsoon the following summer in the lower Rio Grande region. More generally, same-sign moisture anomalies (terciles) have been more frequent than opposite-sign anomalies over the 344 year tree-ring record. While statistical tests indicate that these results could have arisen by chance from sampling variability (the null hypothesis of no association at $\alpha = 0.05$ cannot be rejected), the frequent occurrence of shared drought still poses a challenge, and the effects of shared seasonal droughts are compounded in the semiarid Rio Grande region, where water resources are becoming increasingly stressed. Climate change, with increases in temperature already evident [*National Weather Service Climate Prediction Center*, 2012a], will only exacerbate the impacts of shared seasonal drought. The lower Rio Grande basin has been used as an example of a region where prolonged shared warm- and cool-season droughts have significant impacts on agriculture and ranching. However, the implications of these results may be relevant to other semiarid basins around the world where agriculture depends on both local and remote sources of water that originate from precipitation in different seasons. Multiseason drought can also have impacts on urban water management along the Rio Grande and in other parts of the southwest, where supply may rely heavily on water imported from remote regions, and demand may be modulated by local anomalies in warm-season precipitation. In exploring the frequency and distribution of warm- and cool-season droughts, paleoclimatic data from tree rings that capture both cool- and warm-season precipitation as shown here offer a way to quantify seasonal hydroclimatic variability and help inform future drought planning. A better understanding of the climatic drivers of cool- and monsoon-season hydroclimatic variability, and possible linkages between the two, is needed to inform water resource management and anticipate the effects of climatic change in these semiarid regions.

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