Appendix C

Observed Climate Trends in the Upper Rio Grande Basin

USACE
CLIMATE CHANGE
ADAPTATION

Observed Climate Trends in the Upper Rio Grande Basin

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Mission Statements

The U.S. Army Corps of Engineers Mission is to deliver vital public and military engineering services; partnering in peace and war to strengthen our Nation's security, energize the economy and reduce risks from disasters.

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Sandia Laboratory Climate Security program works to understand and prepare the nation for the national security implications of climate change.

Acronyms and Abbreviations

cm	centimeters
COOP	Cooperative Observer Network
HCN	Historical Climatology Network 2
km	kilometer
NOAA	National Oceanic and Atmospheric Administration
SNOTEL	SNOwpack TELemetry
Tavg	Average annual temperature
Tmax	maximum high temperature
Tmin	minimum temperature
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program

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Observed Climate Trends in the Upper Rio Grande Basin

Observed climate trends for the Upper Rio Grande basin above Elephant Butte Dam were analyzed to better understand current rates of climate change in the study area. Topographic diversity is a key factor as this region encompasses the headwaters of the Rio Grande in the San Juan and Sangre de Cristo Mountains of Colorado, both with peaks exceeding 14,000 feet mean sea level;[1] the Tusas and Jemez Mountains of New Mexico, with peaks rising as above 11,000 feet ; the Rio Grande Rift extending from the San Luis Valley of southern Colorado past the southern boundary of the study area at Elephant Butte Dam at approximately 4,200 feet ; and areas to the west and east of the central valley that are nonetheless part of the drainage basin. The region is home to one of the largest remaining stretches of riparian cottonwood forest in the western United States and includes critical habitat for the federally-endangered Southwestern Willow Flycatcher (*Empidonax traillii extimus*) and Rio Grande silvery minnow (*Hybognathus amarus*).

I. Data and Methodology

Three sources of climate data were used to investigate recent climate trends in the Upper Rio Grande:

- U.S. Department of Agriculture (USDA) Natural Resource Conservation Service SNOwpack TELemetry (SNOTEL) stations provided temperature and precipitation data beginning in 1989 (slightly earlier for some stations). SNOTEL sites in this region are positioned to provide a representative spatial sample of snowpack conditions (Molotch and Bales 2006) and may not provide a spatially representative sample of climate data. Data from 13 SNOTEL sites were used in this study, providing the majority of data from high elevation settings. Monthly average values for temperature and precipitation were obtained from the National Climate Data Center (National Oceanic and Atmospheric Administration [NOAA] National Climate Data Center 2013) for the period of record ending in December 2012.

- NOAA National Weather Service Cooperative Observer Network (COOP) sites provided the bulk of the data from lower elevation settings. COOP sites are located to collect agriculturally-relevant climate data. Data are collected on a voluntary basis. COOP data at most sites contain recording

[1] Note that this report refers to feet above mean sea level as "feet."

gaps, notably during World War I, the Great Depression, and World War II. Consequently, although data exist prior to 1950, it is mainly discontinuous. The data collected since 1950 are more complete, and therefore the year 1950 is taken as the earliest reliable date for most COOP site data in the study area. Monthly average values for temperature and precipitation were obtained from the National Climate Data Center (NOAA National Climate Data Center 2013). The period of record for COOP sites in this study is January 1971 through December 2012.

- NOAA National Weather Service Historical Climatology Network 2 (HCN) data were used, where possible. Eleven HCN sites occur in the study area, primarily—but not exclusively— in valley floor settings. HCN data were originally collected as part of the COOP system, but have been extensively corrected for station inhomogeneities and gaps in the data have been rectified. Monthly average values for temperature and precipitation were obtained from the National Climate Data Center (NOAA National Climate Data Center 2013). The period of record for the HCN sites used in this study is January 1971 through December 2012.

Mountain climates are complex and vary over short distances due to aspect and relief, which influence temperature and precipitation via cold air drainage, down and up-canyon winds, variation in the duration of direct vs. indirect insolation, vegetation cover, duration of snow cover, and other factors (Beniston 2006 and Barry 2008). Changes at individual stations may differ from regional climate trends (Pepin et al. 2005) in ways that are strongly influenced by landscape position, topography and elevation (Lundquist and Cayan 2007). Valley floors may lag behind regional warming trends, particularly in winter months, due to the increasing frequency and severity of temperature inversions under more stable, anticyclonic conditions (Daly et al. 2010), which are anticipated to become more common in the southwestern United States (Seth et al. 2011).

Because of these complexities, additional data processing was not undertaken: some locations in each data set exhibited trends counter to the remainder of the sites, and these data may reflect real—but local—climate differences. They may also reflect changes to station equipment, setup and location, and National Climate Data Center data are corrected for many of these factors.

Because of the landscape diversity in the 300 kilometer (km) wide by 600 km long study area, the sites were grouped into physiographic units for analysis (see Table 1 and Figure 1).

Table 1.—Mountain Sites Used for Trends Analysis

Map Number	Station	ID	Type	Latitude	Longitude	Elev. (feet)	Aspect (degree)	Slope (degree)
San Juan Mountains								
1	Beartown	07M32S 327	SNOTEL	37.700000	-107.500000	11600	301.80	28.10
2	Hermit	53951	HCN	37.771670	-107.109720	9048	87.40	17.77
3	Middle Creek	07M21S 624	SNOTEL	37.77167	-107.033333	11250	106.54	20.81
4	Slumgullion	07M30S 762	SNOTEL	37.983330	-107.200000	11440	99.58	7.92
5	Upper Rio Grande	07M16S 839	SNOTEL	37.720000	-107.250000	9400	347.79	16.55
6	Upper San Juan	06M03S 840	SNOTEL	37.483330	-106.833330	10200	334.99	10.79
7	Wolf Creek Summit	06M17S 874	SNOTEL	37.466670	-106.800000	11000	60.51	8.72
Sangre de Cristo Mountains								
13	Gallegos Peak	05N18S 491	SNOTEL	36.180000	-105.550000	9800	287.37	22.48
14	Red River	297323	HCN	36.705830	-105.403610	8676	229.14	1.25
Tusas Mountains								
15	Bateman	06N04S 316	SNOTEL	36.500000	-106.316670	9300	268.95	8.09
16	Chamita	06N03S 394	SNOTEL	36.950000	-106.650000	8400	17.56	5.31
17	Cumbres Trestle	06M22S 431	SNOTEL	37.020000	-106.450000	10040	118.89	1.00
18	Hopewell	06N14S 532	SNOTEL	36.700000	-106.250000	10000	50.89	9.02
Jemez Mountains								
24	Los Alamos	295084	COOP	35.864440	-106.321390	7424	36.47	5.32
25	Quemazon	06P01S 708	SNOTEL	35.920000	-106.383330	9500	191.63	25.02
26	Senorita Divide	06P10S 744	SNOTEL	36.000000	-106.833330	8600	85.84	8.98
27	Wolf Canyon	299820	COOP	35.947780	-106.746940	8220	227.03	11.95

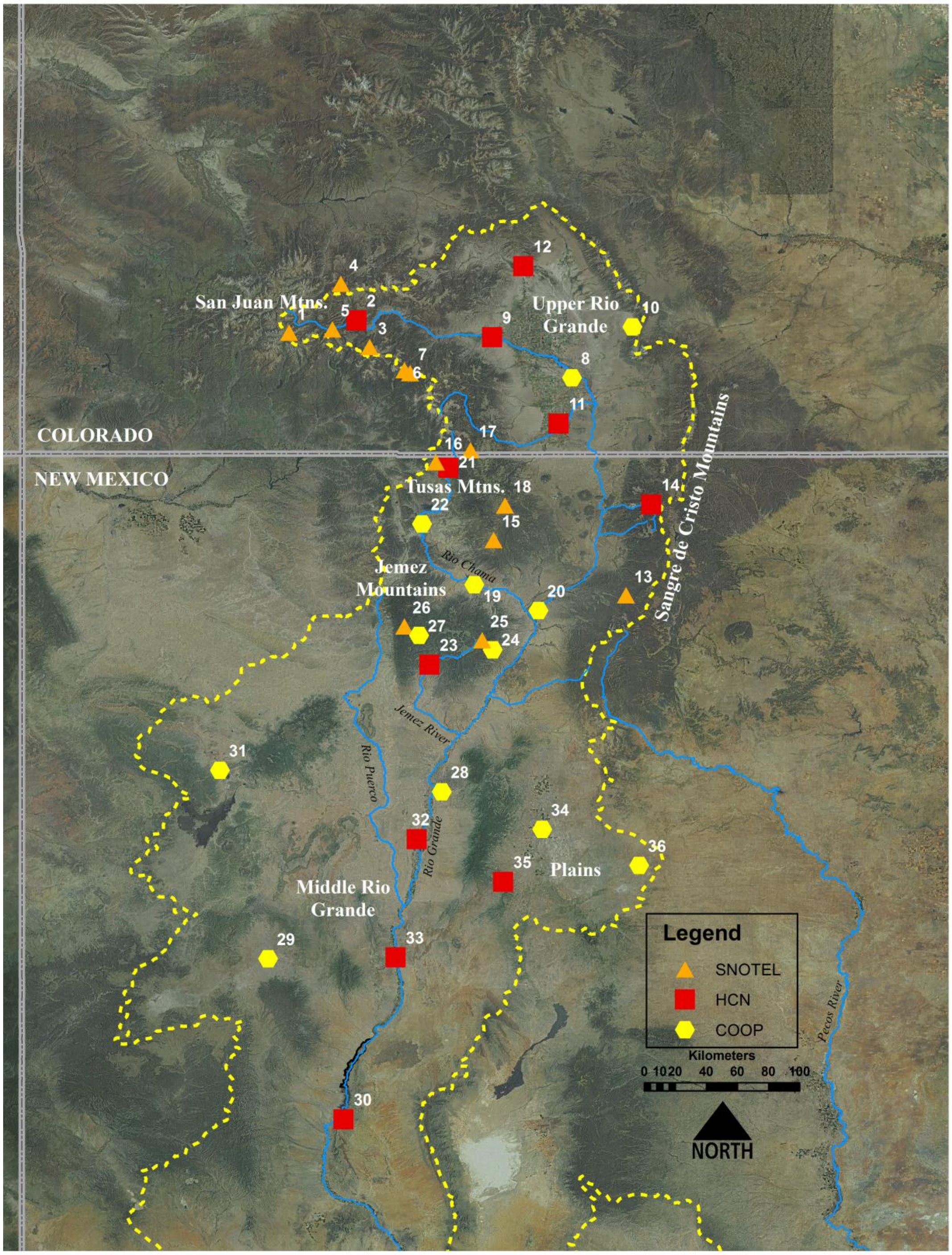

Figure 1.—Map showing sites used in the analysis (site numbers keyed to Tables 1 and 2).

Mountain sites include:

- **San Juan Mountains –** Seven sites are located in the eastern San Juan Mountains within the Rio Grande basin or near the drainage divide in adjoining drainages. Six of these sites are SNOTEL stations and the other is an HCN site. Site elevations range from 9,048 to 11,600 feet, with the HCN site at the lowest elevation in this region.

- **Sangre de Cristo Mountains –** Two sites are located in the southern Sangre de Cristo Mountains, consisting of one SNOTEL site and one HCN site. Because these mountains mark the boundary between the Southern Rocky Mountains and the Plains, they may be subject to different climate influences in some portions of the year from high elevation sites to the west in the San Juan Mountains. Site elevations range from 8,676 feet at the HCN site to 9,800 feet at the SNOTEL site.

- **Tusas Mountains –** Four sites are located in the Tusas Mountains. The Tusas Mountains have a lower average elevation from mountain ranges to the north. These sites include four SNOTEL sites (between 8,400 and 10,040 feet).

- **Jemez Mountains –** Three sites are located in the Jemez Mountains, which are southwest of the Tusas Mountains. These consist of two SNOTEL sites and one COOP site. The two SNOTEL sites are located in high elevation settings at 8,600 and 9,500 feet while the COOP site is at 8,220 feet. In addition, this category includes one COOP site located at Los Alamos on the Pajarito Plateau at 7,424 feet.

Valley sites used in this study of the Upper Rio Grande basin above Elephant Butte Dam (Table 2) were grouped into the following physiographic units:

- **Northern Valleys –** Five sites are located in the San Luis and Rio Grande Valleys in southern Colorado. These consist of two COOP sites and three HCN sites, and they range in elevation from 7,533 to 8,183 feet.

- **Rio Chama and Jemez River Valleys –** This category includes three sites located in the Rio Chama Valley. These sites consist of one HCN site and two COOP sites ranging in elevation from 6,380 to 7,850 feet. This category also includes one COOP site in the Española Basin at Alcalde (5,680 feet), in the vicinity of the Rio Chama-Rio Grande confluence, and the HCN Jemez Springs site in the Jemez River Valley at 6,262 feet.

- **Middle Rio Grande –** This category includes the COOP site of Albuquerque IAP and the HCN site of Elephant Butte Dam located on the bajada above the floodplain at 4,576 and 5,310 feet, respectively. It also includes the two HCN sites of Los Lunas and Socorro, which are located

Table 2.—Valley Sites Used for Trends Analysis

Map Number	Station	Id	Type	Latitude	Longitude	Elev. (ft.)	Aspect (deg.)	Slope (deg.)
Northern Valleys								
8	Alamosa	50130	COOP	37.438890	-105.861390	7533	147.69	0.11
9	Del Norte	52184	HCN	37.674170	-106.324720	7864	13.70	2.24
10	Great Sand Dunes	53541	COOP	37.733330	-105.511940	8183	303.97	3.58
11	Manassa	55322	HCN	37.174170	-105.939170	7690	12.99	0.26
12	Saguache	57337	HCN	38.085800	-106.144400	7701	87.47	0.34
Rio Chama and Jemez River Valleys								
19	Abiquiu Dam	290041	COOP	36.240280	-106.427780	6380	131.33	4.43
20	Alcalde	290245	COOP	36.090830	-106.056670	5680	268.89	4.12
21	Chama	291664	HCN	36.917780	-106.578060	7850	208.58	1.25
22	El Vado Dam	292837	COOP	36.592780	-106.730000	6740	159.58	2.58
23	Jemez Springs	294369	HCN	35.778330	-106.687220	6262	179.38	6.17
Middle Rio Grande								
28	Albuquerque IAP	290234	COOP	35.041670	-106.615280	5310	326.44	0.75
29	Augustine	290640	COOP	34.075000	-107.621110	7000	38.39	0.21
30	Elephant Butte Dam	292848	HCN	33.146110	-107.184440	4576	2.48	6.88
31	Socorro	298387	HCN	34.082780	-106.883060	4585	147.48	0.40
32	Los Lunas	295150	HCN	34.767500	-106.761110	4840	119.59	0.83
33	Grants Milan AP	293682	COOP	35.166390	-107.899170	6520	181.79	1.43
Plains								
34	Estancia	293060	COOP	34.824170	-106.034440	6140	134.96	0.17
35	Mountainair	295965	HCN	34.520830	-106.260560	6520	119.09	5.26
36	Pedernal	296687	COOP	34.615280	-105.473890	6150	128.80	2.62

directly in the floodplain of the Rio Grande at 4,585 and 4,840 feet, respectively. The Middle Rio Grande also includes the COOP site of Grants Milan Airport at 6,520 feet in the Rio Puerco Valley, and the COOP site of Augustine (7,000 feet) in the Plains of San Agustin.

- **Plains –** Three sites within the Rio Grande basin located east of the Manzano Mountains in a an area potentially subject to different climate conditions from Middle Rio Grande sites. Two of these are COOP sites (6,140 and 6,150 feet), the other is an HCN site (6,520 feet).

II. Observed Trends for the Period 1971 through 2012

Despite the noise in the data introduced by measurement changes, errors, instrumentation, changes in station microclimate due to movement and wildfire, and other problems, a coherent regional picture of temperature and precipitation emerges when the data are aggregated into mountain and valley sites.

II.A. Annual Trends

For the entire Upper Rio Grande study area, temperatures increased substantially over the four decade period 1971 through 2012. Average annual temperatures (Tavg) increased at a rate of 0.35°C (0.63°F) per decade (Table 3), with a faster increase in nighttime minimum temperature (Tmin) of 0.37°C (0.67°F) per decade (Table 5) offset by a slower increase in daytime high temperature (Tmax) of 0.25°C (0.45°F) per decade(Table 4). Precipitation was unchanged at the regional scale (Table 6).[2]

Because the distribution of monthly means is skewed, trends are assessed nonparametrically using the Regional Kendal Test (Helsel and Frans 2006). For this analysis, the Regional Kendall Test yields the annual trend (Thiel-Sen's slope) and statistical significance of the trend by physiographic unit. All analyses are conducted using the RKT package in R (an open-source statistical software) (Marchetto 2012). Statistical significance was evaluated at the 0.1 (90% confidence) level. Annual trends are computed as the median of the monthly trends.

[2] Tables 4 through 6 denote statistically significant changes. Statistical significance takes into account the magnitude of the change and the amount of normal variation in that month. If there's typically a wide range of temperatures in a month, then a large change may not be identified as "significant," whereas the same-size change might be statistically significant in a month where the range of variation is small.

Table 3.—Rate of Change in Average Monthly Temperature (Tavg) in °C/Year for 1971 Through 2012

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual °C/yr*	°C/ 10 yr*
San Juan Mountains	0.083	-0.012	0.071	0.033	0.030	0.039	0.038	0.017	0.038	0.005	0.088	0.044	0.04	0.38
Sangre de Cristo Mtns.	0.100	0.033	0.043	0.050	0.050	0.039	0.024	0.037	0.028	0.025	0.071	0.047	0.04	0.41
Tusas Mountains	0.148	0.006	0.065	0.050	0.081	0.100	0.092	0.079	0.080	0.067	0.200	0.100	0.08	0.81
Jemez Mountains	0.032	-0.012	0.040	0.029	0.042	0.028	0.028	0.033	0.029	0.014	0.037	-0.012	0.03	0.29
All Mountain Sites	***0.075***	***0.000***	***0.050***	***0.036***	***0.044***	***0.039***	***0.037***	***0.033***	***0.037***	***0.020***	***0.077***	***0.030***	***0.04***	***0.37***
Upper Rio Grande	0.058	-0.005	0.034	0.027	0.040	0.019	0.026	0.025	0.017	0.003	0.036	-0.005	0.03	0.26
Rio Chama / Jemez Valleys	0.060	0.016	0.036	0.029	0.037	0.024	0.023	0.034	0.025	0.000	0.023	-0.004	0.02	0.25
Middle Rio Grande	0.050	0.024	0.033	0.050	0.078	0.055	0.048	0.056	0.050	0.036	0.045	0.016	0.05	0.49
Plains	0.037	-0.007	0.008	0.033	0.045	0.032	0.025	0.036	0.032	0.010	0.017	0.000	0.03	0.29
All Valley Sites	***0.050***	***0.012***	***0.030***	***0.036***	***0.050***	***0.033***	***0.031***	***0.039***	***0.032***	***0.014***	***0.033***	***0.000***	***0.03***	***0.33***
Region (All Sites)	***0.058***	***0.007***	***0.036***	***0.036***	***0.050***	***0.034***	***0.033***	***0.037***	***0.033***	***0.015***	***0.043***	***0.011***	***0.04***	***0.35***

Tan: Increasing, with correlation significant at 90% (0.1) confidence level.
Purple: Decreasing, with correlation significant at 90% (0.1) confidence level.
*Significance not calculated.
Decadal trend (°C/10 year) calculated as Annual Trend x 10.

Table 4.—Rate of Change in Tmin (°C/Year) by Region for 1971 Through 2012

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual °C/yr*	°C/ 10 yr*
San Juan Mountains	0.118	0.040	0.126	0.100	0.067	0.070	0.073	0.055	0.073	0.071	0.114	0.073	0.07	0.73
Sangre de Cristo Mtns.	0.150	0.068	0.059	0.077	0.056	0.061	0.051	0.064	0.044	0.059	0.084	0.106	0.06	0.63
Tusas Mountains	0.193	0.054	0.133	0.122	0.103	0.150	0.160	0.120	0.138	0.140	0.228	0.159	0.14	1.39
Jemez Mountains	0.057	0.015	0.036	0.033	0.040	0.036	0.046	0.038	0.037	0.038	0.044	0.013	0.04	0.38
All Mountain Sites	***0.108***	***0.036***	***0.075***	***0.070***	***0.060***	***0.064***	***0.067***	***0.057***	***0.062***	***0.067***	***0.095***	***0.067***	***0.07***	***0.67***
Upper Rio Grande	0.073	0.019	0.029	0.036	0.050	0.025	0.032	0.040	0.025	0.015	0.033	0.011	0.03	0.31
Rio Chama / Jemez Valleys	0.054	0.024	0.003	0.030	0.023	0.012	0.025	0.036	0.015	0.000	0.000	-0.003	0.02	0.19
Middle Rio Grande	0.037	0.038	0.033	0.075	0.087	0.067	0.056	0.056	0.045	0.038	0.035	0.024	0.04	0.42
Plains	-0.007	-0.032	-0.022	0.020	0.020	0.018	0.023	0.030	0.000	0.000	-0.029	-0.018	0.00	0.00
All Valley Sites	***0.039***	***0.018***	***0.014***	***0.043***	***0.050***	***0.033***	***0.037***	***0.043***	***0.023***	***0.015***	***0.013***	***0.006***	***0.03***	***0.28***
Region (All Sites)	***0.058***	***0.022***	***0.029***	***0.050***	***0.050***	***0.041***	***0.044***	***0.045***	***0.033***	***0.029***	***0.033***	***0.023***	***0.04***	***0.37***

Tan (underline): Increasing, with correlation significant at 90% (0.1) confidence level.
Purple (underline): Decreasing, with correlation significant at 90% (0.1) confidence level.
*Significance not calculated.
Decadal trend (°C/10 year) calculated as Annual Trend x 10.

Table 5.—Rate of Change in Monthly Maximum Temperature (Tmax) in °C/year for 1971 through 2012

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual °C/yr*	°C/ 10 yr*
San Juan Mountains	0.054	-0.064	0.006	-0.024	-0.011	0.009	0.018	-0.025	0.008	-0.052	0.080	0.025	0.01	0.07
Sangre de Cristo Mtns.	0.044	-0.012	0.033	0.012	0.037	0.023	0.000	0.012	0.014	0.007	0.060	0.008	0.01	0.13
Tusas Mountains	0.100	-0.037	0.000	-0.012	0.014	0.068	0.029	0.040	0.016	-0.024	0.173	0.036	0.02	0.23
Jemez Mountains	0.003	-0.046	0.047	0.026	0.042	0.020	0.013	0.023	0.021	-0.011	0.037	-0.044	0.02	0.21
All Mountain Sites	***0.042***	***-0.043***	***0.027***	***0.000***	***0.019***	***0.022***	***0.013***	***0.006***	***0.014***	***-0.023***	***0.075***	***0.000***	***0.01***	***0.14***
Upper Rio Grande	0.036	-0.033	0.037	0.013	0.029	0.013	0.020	0.011	0.006	-0.014	0.030	-0.021	0.01	0.13
Rio Chama / Jemez Valleys	0.067	0.008	0.067	0.032	0.052	0.035	0.022	0.033	0.032	0.009	0.045	0.000	0.03	0.33
Middle Rio Grande	0.050	0.000	0.033	0.029	0.064	0.044	0.036	0.058	0.053	0.038	0.054	0.007	0.04	0.41
Plains	0.067	0.007	0.047	0.047	0.060	0.050	0.033	0.043	0.060	0.026	0.072	0.013	0.05	0.47
All Valley Sites	***0.056***	***0.000***	***0.045***	***0.029***	***0.050***	***0.033***	***0.027***	***0.035***	***0.036***	***0.014***	***0.048***	***0.000***	***0.03***	***0.34***
Region (All Sites)	***0.050***	***-0.060***	***0.150***	***-0.040***	***-0.220***	***0.052***	***-0.081***	***0.087***	***0.000***	***0.073***	***0.175***	***-0.020***	***0.03***	***0.25***

Tan (underline): Increasing, with correlation significant at 90% (0.1) confidence level.
Purple (underline): Decreasing, with correlation significant at 90% (0.1) confidence level.
*Significance not calculated.
Decadal trend (°C/10 year) calculated as Annual Trend x 10.

Table 6.—Net Change in Precipitation (Centimeters [cm]) by Region for 1971 Through 2012

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Net Ann. Change*	Decadal Rate*
San Juan Mountains	0.007	-0.015	-0.074	-0.001	-0.053	-0.053	-0.016	-0.026	-0.010	0.000	-0.096	0.060	-0.28	-2.77
Sangre de Cristo Mtns.	0.002	0.027	-0.080	0.008	-0.042	-0.048	0.001	0.013	0.033	-0.001	-0.079	0.004	-0.16	-1.62
Tusas Mountains	-0.060	-0.099	-0.306	0.031	-0.040	-0.078	-0.051	-0.202	0.037	-0.022	-0.225	0.112	-0.90	-9.03
Jemez Mountains	-0.027	0.000	-0.053	0.018	-0.035	-0.007	-0.023	-0.014	-0.023	0.021	-0.050	0.048	-0.15	-1.45
All Mountain Sites	***-0.009***	***-0.007***	***-0.085***	***0.009***	***-0.043***	***-0.041***	***-0.019***	***-0.031***	***-0.001***	***0.001***	***-0.087***	***0.048***	***-0.27***	***-2.65***
Upper Rio Grande	-0.004	0.001	0.000	0.011	-0.014	-0.009	-0.011	0.008	0.011	0.000	-0.020	0.000	-0.03	-0.27
Rio Chama / Jemez Valleys	-0.006	0.004	-0.015	0.029	-0.017	-0.011	0.010	0.001	0.001	0.009	-0.028	0.020	0.00	-0.03
Middle Rio Grande	-0.009	-0.005	0.000	0.000	-0.011	0.001	0.017	-0.039	-0.024	-0.004	-0.011	0.003	-0.08	-0.82
Plains	-0.005	-0.003	0.000	0.000	0.000	0.003	0.000	-0.004	-0.033	0.017	-0.023	0.014	-0.03	-0.34
All Valley Sites	***-0.006***	***0.000***	***-0.001***	***0.005***	***-0.011***	***-0.003***	***0.004***	***-0.007***	***-0.007***	***0.002***	***-0.019***	***0.007***	***-0.04***	***-0.36***
Region (All Sites)	***-0.006***	***-0.001***	***-0.010***	***0.006***	***-0.016***	***-0.009***	***-0.001***	***-0.011***	***-0.006***	***0.002***	***-0.028***	***0.012***	***-0.07***	***-0.68***

Tan (underline): Increasing, with correlation significant at 90% (0.1) confidence level.
Purple (underline): Decreasing, with correlation significant at 90% (0.1) confidence level.
*Significance not calculated.

Mountain and valley regions responded differently to warming. Mountain Tavg increased at a rate of 0.37°C (0.67°F) per decade over the period 1971 through 2012. This change was driven by increases in nighttime minimum temperatures (Tmin) of 0.67°C (1.21°F) per decade that were significant in every month but February. Daytime high temperatures (Tmax) rose at the slow rate of 0.14°C (0.25°F) decade, and this trend was not significant in most areas. By contrast, valley Tavg temperatures increased at a rate of 0.39°F (0.33°C) per decade over the period 1971 through 2012, driven by both increases in Tmax (0.34°C [0.61°F]) per decade) and Tmin (0.28°C [0.50°F] per decade). At valley sites, increases in May through September temperatures were statistically significant, increasing at a rate of 0.3 to 0.5°C (0.54 to 0.90°F) per decade in these months.

Among the mountain sites, temperature increases were greatest at the four sites in the Tusas Mountains, where Tavg increased at a rate of 0.81°C (1.46°F) per decade, driven by increases in Tmin at a rate of1.39°C (2.50°F) per decade. The San Juan and Sangre De Cristo Ranges saw temperatures increase at approximately half this rate. Further south in the Jemez Mountains, temperatures increased at about a quarter of the rate of the Tusas Mountains.

Among valley sites, the rates of temperature increase were greatest for sites in the Middle Rio Grande than elsewhere, with Middle Rio Grande Tavg increasing at a range of 0.49°C (0.88°F) per decade from 1971 through 2012, with comparable increases in both Tmin and Tmax. On the plains, Tmin was unchanged over this period, but Tmax increased by 0.47°C (0.85°F) per decade, the fastest increase in Tmax among the regions studied.

II.B. Monthly and Seasonal Trends

The rates of increase in Tmin, reflecting warming of overnight temperatures, are significant for most months in most mountain regions. February is the only month where change is positive but consistently not significant. The rate of increase in Tmin is significant across all spring (April, May, June) and summer (July, August, September) months. By contrast, changes in mountain Tmax are smaller. February shows a declining trend in Tmax across all four mountain regions. Strong, positive increases in Tmax occur in November, which also shows a strong increase in Tmin as well as statistically-significant declining precipitation trends across all mountain regions. Precipitation also declined significantly in March in all mountain areas except the Sangre de Cristo Mountains, which coincides with statistically-significant increases in Tmin but not Tmax. The increasing Tmin and decreasing precipitation in March and November are important because these contribute to a longer growing season and decreased period of snowpack accumulation in winter months.

Valley regions exhibit statistically significant increases in late spring (May and June) and summer temperatures: a rate of about 0.3 to 0.5°C (0.5 to 0.9°F)/decade in both Tmin and Tmax occurs across all valley sites in spring and summer months. Rates of increase in fall and winter Tmax are comparable (except for February), but the rate of increase in Tmin is lower (0 to 0.4°C [0 to 0.72°F]) per decade). As with mountain areas, the trend of decreasing precipitation in November is significant across the region (except in the Middle Rio Grande), and coincides with a rate of increase in Tmax of 0.3 to 0.7°C (0.54 to 1.26°F) per decade. The rate of increase in Tmin in November is smaller (0 to 0.35°C [0 to 0.63°F] per decade) in valley sites, and the rate of change in Tmin is negative on the plains.

The monthly patterns of change for mountain and valley Tmin are similar, but differ in magnitude. Two factors may be at play. Valley Tmin is affected by cold air drainage; under warming, nighttime inversions may be becoming more frequent (Daly et al. 2010) and this may reduce the rate of gain in valley Tmin. By contrast, warming in mountain areas in the presence of soil moisture or snowpack contributes to daytime evaporation of that moisture; condensation under cooler, nighttime temperatures releases heat in the atmosphere and may contribute to faster nighttime warming in higher altitude settings, particularly in winter (Rangwala 2012).

The rate of temperature change (degrees/decade) was not constant over the period 1971 through 2012 (Table 7). This was assessed by computing the Regional Mann-Kendall test for two periods: 1971 through 2000 and 2001 through 2012 for both mountain and valley sites in aggregate. In the first 30 years of this period, 1971 through 2000, positive rates of change in Tmax, Tmin, and, therefore, Tavg occurred across mountain sites, valley sites, and the region as a whole. The rate of increase in Tmin was larger than the gains Tmax for both mountains and valleys.

Table 7.—Median Rates of Temperature Change (°C per Decade) for Different Time Periods

		Early 1971-2000	Late 2001-2012	1971-2012
Tmax	Mountains	0.17	0.39	0.14
	Valleys	0.25	-0.13	0.34
	Region	0.22	0.25	0.25
Tmin	Mountains	0.62	1.75	0.67
	Valleys	0.36	-0.38	0.28
	Region	0.42	0.75	0.37
Tavg	Mountains	0.42	1.07	0.37
	Valleys	0.39	-0.07	0.33
	Region	0.36	0.07	0.35

In the 11 years beginning in 2001, the trend in Tmax (-0.13 °C [-.23°F] per decade) and Tmin (-0.38°C [-0.68°F] per decade) has been negative in valley areas. By contrast, mountain regions have been characterized by accelerated increase in rates of warming: Tmax rose from 0.17°C (0.31°F) per decade to 0.39°C (0.70°F) per decade while the rate of increase in Tmin went from 0.62°C (1.12°F) per decade over 1971 through 2000 to 1.75°C (3.15°F) per decade over the period 2001 through 2012. It is not clear why the direction of temperature varies by topographic position.

III. Comparison of Observed Rates of Temperature Change

Temperature rises observed in this study are comparable to two other regional studies (Figure 2, Figure 3, and Figure 4). Tebaldi et al. (2012) use linear regression with HCN data to estimate the rate of change in temperature for the period 1912 through 2011 as compared to the period 1970 through 2011 for the states of New Mexico and Colorado. For New Mexico, the rate of change in Tavg from 1912 through 2011 was 0.10°C (0.177°F) per decade and for Colorado, 0.13°C (0.225°F) per decade. For New Mexico, the rate of change in Tavg from 1970 through 2011 was 0.34°C (0.603°F) per decade, more than three times as fast as the century average. Over this shorter period, the rate of increase in Colorado was 0.27°C (0.483°F) per decade. The same accelerating pattern occurs in the Tmax and Tmin data taken separately (Tebaldi et al. 2012).

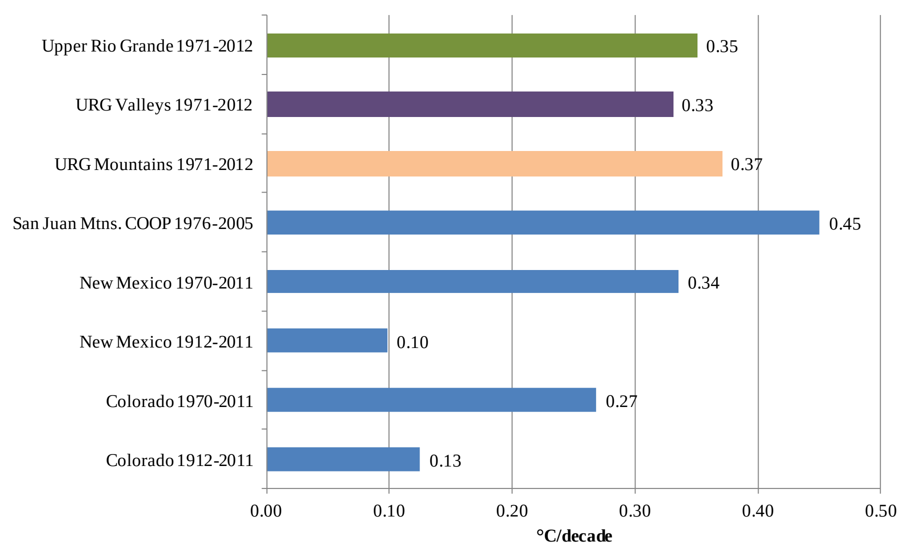

Figure 2.—Comparison of rates of observed change in Tavg with values reported in Rangwala and Miller 2010 and Tebaldi et al. 2012.

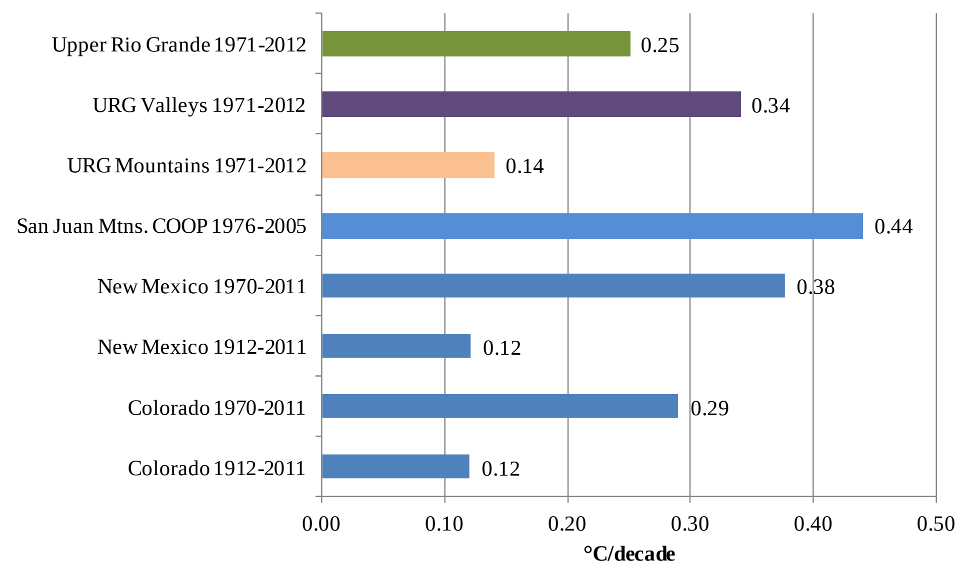

Figure 3.—Comparison of the rates of observed change in Tmax with values reported in Rangwala and Miller 2010 and Tebaldi et al. 2012.

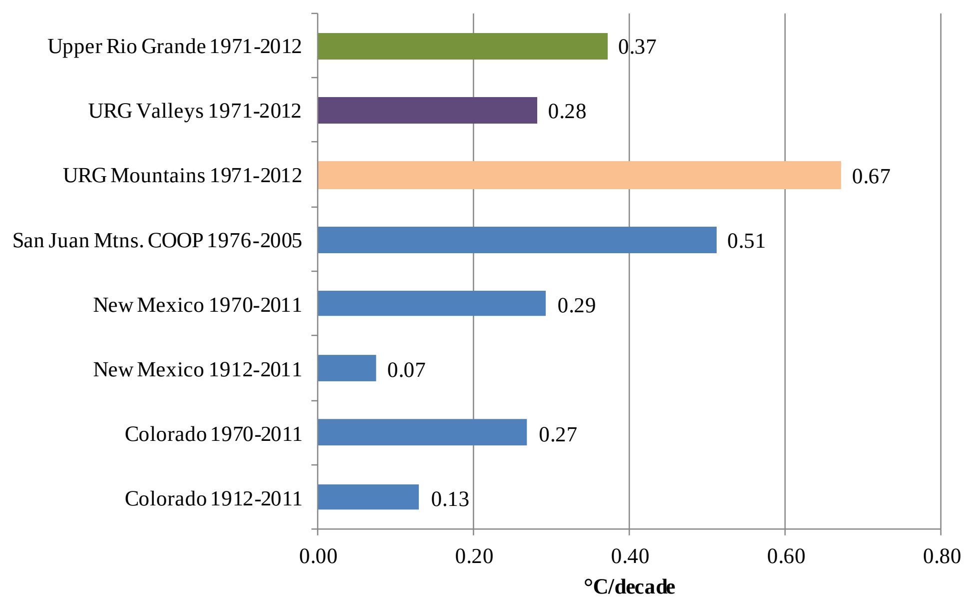

Figure 4.—Comparison of the rates of observed change in Tmin with values reported in Rangwala and Miller 2010 and Tebaldi et al. 2012.

In the San Juan Mountains and adjacent valleys for the period 1990 through 2005, Rangwala and Miller (2010) find an average warming of nearly 1°C (1.8°F) across a combination of COOP and SNOTEL site data. Tmin and Tmax increase at approximately the same rate. Warming at high elevation SNOTEL sites was gradual over the period, but occurred primarily from 1995 through 2000 at the lower elevation COOP sites, with negligible change in temperature at low elevations after 2000. The authors conclude that the spring and summer warming in the San Juan Mountain region from 1995 through 2005 is unprecedented, but winter warming is not outside the range of variation. Parsing the data into progressively shorter intervals shows a pattern of accelerated change since 1931 (Table 8).

Table 8.—Trends (°C per Decade) in Climate Change in the San Juan Mountains (modified from Table 1, Rangwala and Miller 2010)

Time Period (Sites)	Tavg	Tmax	Tmin
1931-2005 (NWS COOP)	0.08	-0.02	0.17
1956-2005 (NWS COOP)	0.16	0.11	0.20
1976-2005 (NWS COOP)	0.45	0.44	0.51
1990-2005 (NWS COOP)	1.03	1.15	0.87
1990-2005 (SNOTEL)	1.00	0.94	1.04

Tan (underline): increase significant at the 90% (0.1) confidence level (Mann-Kendall test).

The trends in Tavg, Tmin, and Tmax in low elevation settings in the Upper Rio Grande are comparable to those observed by Tebaldi et al. (2012) for the period after 1970, reflecting overlapping datasets. Although the rate of change in Upper Rio Grande mountain Tavg is similar between the two studies, there are large differences in Tmin and Tmax. Mountain Tmax in the Upper Rio Grande is increasing at the relatively slow rate of 0.14°C (0.25°F) per decade, approximately 1/3 the rate of the Tebaldi et al rate of 0.38°C (0.68°F) per decade in New Mexico and 0.29°C (0.52°F) per decade in Colorado. Upper Rio Grande mountain Tmin grew at twice the rate of Tmin increase observed in the Tebaldi et al. (2012).

For a broader region encompassing the entire San Juan Mountain Range, Rangwala and Miller (2010) investigated temperature trends using a similar mix of SNOTEL and COOP sites as used in this study, and also computed trends using the Thiel-Sen nonparametric slope estimator. The 30-year trend (1976 through 2005) for NWS COOP data in their study area yielded trends slightly larger than, but comparable to the results of this study. However, the trend estimates for Rangwala and Miller's high elevation SNOTEL sites are much larger than observed in this study. Interestingly, they observe no strong differences in rates of increase in Tmin and Tmax in the data from the San Juan Mountains SNOTEL sites.

The rate of temperature change in the Upper Rio Grande is approximately double that of the world as a whole. A recent study observed a global trend of 0.16°C (0.29°F) per decade for the period 1980 through 2011, and 0.18°C (0.32°F) per decade for 1990 through 2011 (Foster and Rahmstorf 2011 and Rahmstorf et al. 2012). The observed rate of warming in the Upper Rio Grande basin appears to be in alignment with climate model projections for continental interior regions such as the Southwestern United States under warming scenarios.

IV. Comparison of Observed Trends with Model Projections

Comparison of observed trends with model projections provides a means of assessing the significance of current rates of change, should they continue, with respect to responses of the natural environment. Observed trends in annual temperature are compared to trends projected by models for areas encompassing the Upper Rio Grande (Table 9).

The rates of future change in stream flow and vegetation models depend on the rates of change in the climate model(s) driving them. In other words, projections of vegetation and stream flow change for particular decades make critical assumptions about the rate of future change in temperature and precipitation. In short, vegetation and streamflow display a given sensitivity[3] to a given amount of temperature and precipitation change—changing faster if under faster climate change and slower under slower rates of climate change. Thus, it is important to understand how fast climate is actually changing relative to climate model projections to better understand the likely rates of resulting environmental change.

If temperatures in the Upper Rio Grande basin continue to rise at the rate of the forty years, average warming for the period 2010 through 2039 would be 0.86°C (1.55°F); net warming by 2050 would be 1.94°C (3.49°F). This is the second highest observed range of change among published studies. Observed rates of change, when multiplied out, are approximately in the middle of the range of model estimates of future warming, reaching approximately 1.75°C (3.15°F) by 2050 and 3.5°C (6.3°F) by 2100.

[3] The amount of response to a stimulus of a given magnitude – in this case, a 1°C temperature change is anticipated in a particular model to result in so much change in evaporation, soil moisture, plant growth, etc.

Table 9.—Observed Rates of Change vs. Model Projections in °C

Area	Source	Tavg Change (°C/decade)	Tavg 2010-2039 (°C)	Tavg 2020-2039 (°C)	Tavg 2041-2070 (°C)	Tavg 2050 (°C)	Change in precip. (%)	Notes
Model Projections (SRES scenario)								
Rio Grande Basin (A1B)	Hurd and Coonrod (2007)	--	--	2.35	--	--	-9.07	Dry model, baseline 1971-2000
Rio Grande Basin (A1B)	Hurd and Coonrod (2007)	--	--	1.27	--	--	-0.03	Medium model, baseline 1971-2000
Rio Grande Basin (A1B)	Hurd and Coonrod (2007)	--	--	2.31	--	--	0.97	Wet model, baseline 1971-2000
New Mexico (A1B)	Gutzler et al. (2006)	0.30	0.75	0.90	1.65	--	--	At least 3°C by 2100 ≈0.30C/decade
Colorado (B1, A2B, A2)	Ray et al. (2008)	--	--	--	--	1.4	--	Low estimate, baseline 1950-1999
Colorado (B1, A2B, A2)	Ray et al. (2008)	--	--	--	--	3.1	--	High estimate, baseline 1950-1999
Upper Colorado River Basin (B1)	Ray et al. (2008)	--	--	1.30	--	--	1.00	Difference, baseline period vs. 2020-2039
Upper Colorado River Basin (A2)	Ray et al. (2008)	--	--	1.20	--	--	1.00	Difference, baseline period vs. 2020-2039
San Juan Mountains (A2)	Cozzetto et al. (2011)	--	--	--	2.95	--	-6.75	Median values of model runs
Observed Trends								
New Mexico and Colorado	Tebaldi et al. (2012)	0.12	0.29	0.35	0.67	0.60	--	Average of rates for NM and CO HCN sites, 1912-2011.
New Mexico and Colorado	Tebaldi et al. (2012)	0.31	0.76	0.91	1.72	1.55	--	Average of rates for NM and CO HCN sites, 1970-2011.
San Juan Mountains	Rangwala and Miller 2010	0.45	1.10	1.33	2.50	2.25	-7.56	Average of rates for NWS sites, 1976-2005.
Upper Rio Grande	This report	0.35	0.86	1.03	1.94	1.75	---	Across all HCN, COOP and SNOTEL sites, 1971-2012.

The observed regional trend is in line with the most recent North American Regional Climate Change Assessment Program model projections used in the 2013 National Climate Assessment (U.S. Global Change Research Program [USGCRP] 2013). These models project that the Upper Rio Grande area will warm by 4.1 to 4.9°C (7.5 to 8.5°F) by 2070 through 2099 under the A2 (high emissions) scenario and by 2.5 to 3.1°C (4.5 to 5.5°F) by 2070 through 2099 under the B1 (low emissions) scenario.

V. Discussion

The observed trends in temperature indicate warming is occurring at the middle end of model projections. However, whether the true average regional rate of change is 0.35°C (0.63°F)/decade, or higher as some models project, warming of 1 to 2.5°C (1.8 to 4.5°F) by 2040 is likely to exert profound changes on every part of the landscape and is likely to cause significant changes to the availability and quality of surface and ground water in the region. Warming in early spring and late fall contributes to an expansion of the growing season and, therefore, greater transpiration demand and more demand for soil moisture. Declines in soil moisture are likely to contribute to altered fire regimes and changes in vegetation communities, changes that are likely to alter existing rainfall-runoff relationships. Concomitant changes to flood frequency curves and other relationships are likely, with increases in both the frequency of low flow and highest flow years. The current rate of warming exceeds the rate of warming at the end of the last Ice Age (15,000 years ago), and, as during that time, the changes are widely expected to contribute to both species and habitat loss on both global and local scales.

Although mitigation measures may yet reduce net warming by 2100, significant reductions in anticipated warming by 2030 or 2040 are much less likely as much of the warming that will occur in this time frame will be due to greenhouse gases already in the atmosphere. Thus, adaptation will likely be necessary to address climate changes in a region that is likely to be 1 to 2.5°C (1.8 to 4.5°F) warmer by 2040.

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