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SPECIAL FEATURE: SUSTAINABILITY ON THE U.S./MEXICO BORDER

Regional climatic considerations for borderlands sustainability

David S. Gutzler†

Earth & Planetary Sciences Department, University of New Mexico, Albuquerque, New Mexico 87131 USA

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Abstract. Regional climate and its variability pose severe challenges to sustainability of ecosystems and human habitability in the U.S./Mexico border region. The region is semiarid, located far from oceanic sources of evaporated water. Its latitudinal position near the descending branch of the global atmospheric Hadley circulation means that cold season precipitation totals are suppressed relative to the average latitude of the winter storm track to the north. Furthermore, tree ring histories of climate variability demonstrate that the region is prone to shifts in the storm track that lead to very pronounced decadal variations in precipitation, which are manifested regionally as swings between severe droughts and pluvial periods. The El Niño-Southern Oscillation in tropical Pacific Ocean temperature forces shorter term (year-to-year) shifts in the storm track. The border region is strongly affected by ongoing and projected century-scale climate change, probably derived in large part from human-caused increases in greenhouse gases. There is a very strong regional warming trend in recent temperature data, continued into the future in greenhouse gas-forced model simulations of climate change. The warming trend modifies natural drought/pluvial precipitation fluctuations by enhancing evaporative losses and decreasing snowpack in mountainous regions to the north. These changes lead to projections of significantly diminished stream flow and drier surface conditions, thereby shifting the regional climate system farther toward aridity.

Key words: climate change; drought; precipitation; southwestern North America; Special Feature: Sustainability on the U.S./Mexico Border; stream flow; temperature.

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† **E-mail:** gutzler@unm.edu

INTRODUCTION

Climate in southwestern North America has been a dominating factor in limiting sustainable societies here for as long as humans have inhabited the region (e.g., Scurlock 1998). Water availability, in particular, has presented a huge challenge for sustained human habitation (Bawden and Reycraft 2000). This is still true today in the U.S.-Mexico border region, despite the stupendous hydrologic engineering achievements of the 20th Century that have promoted tremendous population growth in urban areas throughout the region (Diaz and Morehouse 2003).

Ecosystems and human societies have adapted to the desert climate of the middle Rio Grande region, but during prolonged drought periods, when not even an average amount of precipitation materializes, life in the desert can become extraordinarily harsh and difficult. Drought causes widespread plant and wildlife mortality, dry riverbeds, failed crops, and contributed to the collapse of regionally dominant human societies in recent centuries (e.g., Bawden and Reycraft 2000, Diamond 2005).

Two observed features of recent climate variability should serve as a warning to the current inhabitants of the Rio Grande borderlands region. The first decade of the 21st Century included both exceptionally dry and exceptionally wet years, continuing a record of extreme variability that extends back for centuries. In addition, a clear warming trend is apparent in recent data. A growing body of evidence indicates that the late 20th Century warming trend may not simply be an extension of natural variability in southwestern North America, but instead may be just the beginning of a large, long-term shift in average climate toward warmer and potentially more arid conditions (IPCC 2007, Seager et al. 2008).

Global climate models suggest that the ongoing warming trend may be due in large part to global radiative forcing associated with increasing greenhouse gases. This forcing will continue to increase for the foreseeable future, as long as humans depend largely on fossil fuels for energy. The current observed warming trend is unambiguous in the data, but is still modest and manageable. Continued projected warming, however, would raise temperatures beyond the envelope of historical variability since humans populated the Southwest, leading to potentially dramatic changes in surface dryness and streamflows as a result of the warmer temperatures.

In the short term, therefore, the climatic influence on sustainability in the Rio Grande borderlands involves coping with annual or decadal variations in temperature and precipitation, much as people have encountered in previous centuries. In the longer term, by the end of the current century, the inhabitants of this region may find themselves confronting a substantially different, drier landscape, posing a more extreme challenge for sustainability.

CLIMATE VARIABILITY IN THE HISTORICAL RECORD

Episodic, severe long-term drought has been a ubiquitous feature of climate in southwestern North America for many centuries. The Southwest has an abundance of old trees whose annual growth is sensitive to precipitation and whose growth rings therefore represent a record of annual precipitation extending back far before the advent of instrumental climate records. Fig. 1 shows a dendrochronological record back to the mid-15th Century AD, from a set of trees whose variations in growth are correlated with streamflow in the upper Rio Grande at Otowi, NM (data from Meko et al. 2010). The graph shows the time series of reconstructed streamflow anomalies after a smoothing function has been applied to emphasize long period fluctuations, so short-term (sub-decadal) dry or wet spells are averaged out. Several features are worth emphasizing:

1. Frequency analysis of this time series suggests that episodes of pronounced deficits in streamflow, indicative of severe drought, occur at least once per century. This approximate recurrence interval is observed in similar dendrochronological reconstructions throughout the interior of western North America (e.g., Gray et al. 2003, as elaborated below).
2. The major 20th Century drought, in the 1950s, was very substantial but several previous droughts in the record (e.g., the drought in the late 16th century) were more severe.
3. The late 20th Century wet spell at the end of the record is clearly a pluvial period of historic proportions. Like the mid-20th Century drought, there are other roughly equivalent wet spells in the record.

For establishing policies to promote sustainability, these observations lead to several sobering considerations. The 1950s drought is well-documented and well-remembered, and for planning purposes is often considered to be the "drought of record". However the results in Fig. 1 clearly show that there have been drought episodes in the reconstructed time series that may have been both longer and more severe than the 1950s drought. Evidence for the "megadrought" of the 16th Century mentioned above exists in similar tree ring chronologies throughout the interior west (e.g., Grissino-Mayer et al. 1997, Ni et al. 2002, Gray et al. 2003).

Compared to the 1950s, however, demand for

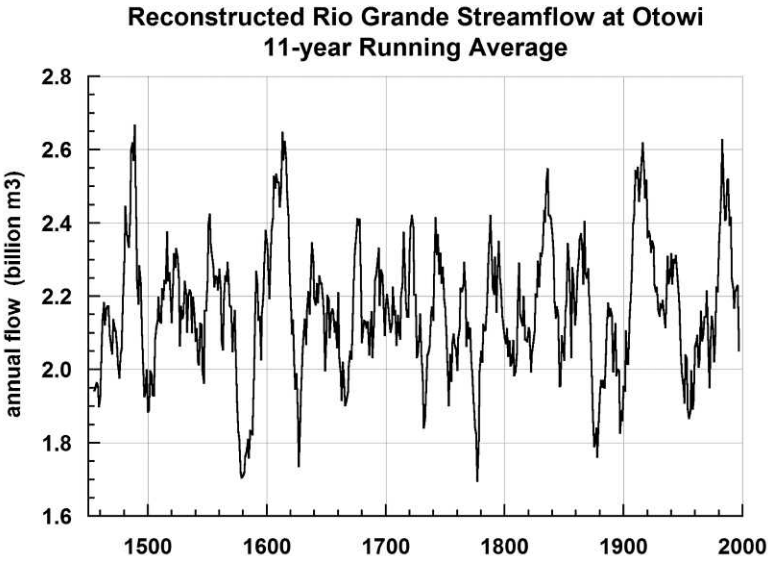

Fig. 1. Reconstructed annual streamflow in the Rio Grande at the Otowi gauge in northern New Mexico, 1450–2000, derived from tree ring records that are correlated with measured Otowi flow in the 20th Century (Meko et al. 2010). Annual values have been smoothed with an 11-year moving average to emphasize decade-scale fluctuations.

water from a much-increased urban population base has increased very substantially, despite recent successful efforts to reduce water consumption per capita. Much of the recent, huge urban population growth in the middle Rio Grande region has taken place during an anomalously wet period in the late 20th Century that is not at all typical of millennial average conditions.

We do not currently have a thorough understanding of what causes the swings between multidecadal drought and pluvial episodes such as those seen in Fig. 1. Recent research suggests that extended cold spells in the tropical Pacific Ocean—long periods when oceanic temperatures may have stayed similar to the conditions observed during the winter of 2010/11, which was been exceptionally dry in the border region—may be related to long-term drought (Cole et al. 2002, Seager et al. 2005). The first half of 2011 subsequently evolved into the most extreme six-month precipitation deficit on record across much of the borderlands region. Meanwhile heavy snowpack in the 2010–2011 winter in Colorado and Wyoming generated much above-average streamflows in the Colorado River basin in late spring and early summer 2011. It is impossible to determine in real time whether or not this extraordinary short term climate anomaly will correlate with a longer, multi-year anomaly; in other words, the demise of multi-year drought conditions is not predictable.

Other climate modeling studies have suggested that prolonged anomalies in the Atlantic Ocean (Schubert et al. 2009) or the Indian Ocean (Hoerling and Kumar 2003) could also affect atmospheric circulation in this region so as to suppress precipitation, particularly in the winter season. Despite considerable research progress on this problem, knowledge of how these hypothesized long-term ocean anomalies are generated and maintained is insufficient to provide reliable forecasts of when the next huge drought might occur, or (perhaps more importantly) to predict when an existing drought might end. This is an area of active current research.

Unlike the inhabitants of the Southwest in previous centuries, however, we are now fully cognizant that long-term episodic droughts have been endemic here for centuries. Even if we cannot make specific predictions of the timing of these droughts, we can still justify preparation for water management whenever another prolonged drought occurs.

Current Observed Climate Variability and Change

A pronounced trend toward warmer temperature has been ongoing across southwestern North America during the late 20th Century, continuing to the present day. Regional temperature is more than 1°C warmer at present than was the case a half-century ago, as will be discussed further in the next section. An average temperature change of 1°C probably does not seem like much to most people, but this seemingly modest difference in average temperature actually represents a very significant shift toward warmer conditions.

One measure of the magnitude of this trend is shown by the perennial seasonal outlook for "above normal temperature" across the southwestern U.S. in the suite of forecasts issued by the U.S. NOAA Climate Prediction Center (accessible online at http://www.cpc.ncep.noaa.gov/products/predictions/long_range/). The principal justification for persistent probability of above-normal temperature in the seasonal outlooks is that, for operational purposes, "normal" temperatures are defined as 30-year averages for any particular three-month season. The current 30-year averaging period defining "normal" temperature is 1981–2010. Temperature across the southwestern U.S. has increased so much and so steadily relative to interannual variability—especially in the warm season—that temperatures from the first half of the 30-year averaging period are considerably colder than temperatures in more recent years, or expected temperatures in future years. Thus the seasonal outlooks almost always indicate enhanced probability of "above normal" temperature in the middle Rio Grande region (Livezey et al. 2007).

Another example of the magnitude of recent warming trends is shown by plotting annual totals of Heating Degree-Days (HDDs), which is the metric used by utilities to define the climatic component of cold season heating needs. A daily value of HDDs is typically calculated by taking the difference between the daily average temperature (T_{avg}, expressed in °F) and a threshold value that is assumed to mark the warmest temperature for which buildings require heating (typically defined as 65°F). If the difference is positive, the daily HDD value is set to zero, so $T_{avg} = 70$°F becomes 0 HDD for that day, $T_{avg} = 60$°F becomes 5 HDDs for that day, and $T_{avg} = 30$°F becomes 35 HDDs for that day. The annual accumulation of HDDs thus represents an estimate of average cold season temperature.

A time series of HDDs for Fort Bayard, NM, a relatively high-elevation rural site near Silver City in the southwestern part of the state, is shown in Fig. 2. Decadal averages of annual HDD accumulations, shown by the solid horizontal lines on the plot, have declined (i.e., cold season temperatures have gotten warmer) very significantly—as much as 25% by this metric—since the decade of the 1960s. A change of this magnitude affects the demand for heating in a significant way. Whether or not this is a desirable economic effect, it is real and demonstrates that climate change is already clearly observed in the recent data record.

A time series of observed annual precipitation, averaged across Texas Climate Division 5, covering the trans-Pecos region of far western Texas, shows the 1950s drought period starkly (to be discussed in more detail in the next section). Several decades of relatively abundant average precipitation, with the continuation of considerable interannual variability, followed in the 1970s and 1980s. Another pronounced multi-year drought occurred around the turn of the 21st Century. There is less evidence for the initiation of a long-term change in the precipitation record compared to the temperature record.

Projections of Future Regional Climate

Temperature and precipitation

A deep, diverse, and growing body of evidence suggests that anthropogenic climate change, caused principally by the steady increase of greenhouse gases that are being emitted at an increasing rate, is likely to continue through the 21st Century (IPCC 2007). On a global scale surface temperature is projected to increase substantially due to anthropogenic enhancement of the greenhouse effect. The global Hadley Circulation is projected to expand poleward in

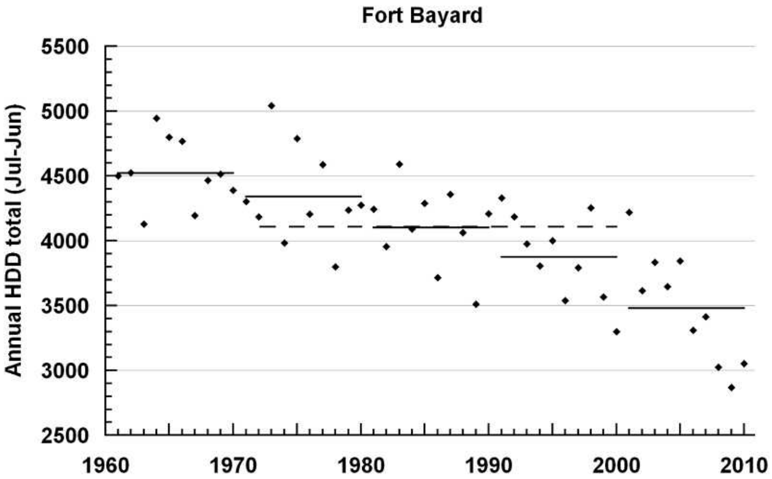

Fig. 2. Time series of annual heating degree-day (HDD) accumulation (°F) since 1961 at Fort Bayard, New Mexico, relative to a daily base temperature of 65°F. Solid horizontal lines depict decadal averages. Dashed horizontal line represents the 1971–2000 30-year climatological average.

association with global warming, so the zone of precipitation-suppressing subsidence in the downward branch of the Hadley Circulation also expands poleward. Winter precipitation is thereby reduced in subtropical latitudes, including the US-Mexico border region (IPCC 2007). Temperature trends are readily apparent in global and regional averages (as discussed in the previous section), although it is not yet possible to definitively attribute regional-scale trends to any specific cause (Stott et al. 2010). Expansion of the Hadley Circulation consistent with expectations for a warming climate is already observed (Seidel et al. 2008, Karl et al. 2009), although interannual variability of precipitation due to other, natural causes is too large to conclusively define a long-term trend in the data.

Several recent studies have examined the effects of projected 21st Century temperature and precipitation changes on southwestern North America, using global climate model projections produced for the 2007 IPCC climate change assessment (Meehl et al. 2007). Seager et al. (2008) showed that the projected climate change would result in pronounced trends in the surface water budget (precipitation minus evaporation) in the region toward drier conditions. The trend toward increased aridity results from both decreasing precipitation, especially in the winter season (the Hadley Circulation effect) and increasing evaporation, associated with warmer temperatures. To the north of the borderlands region, snowpack is projected to decline significantly as winter temperatures increase, exacerbated by a decrease in winter precipitation (Brown and Mote 2009).

Time series of observed regional temperature for winter and summer from 1901–2007, extended using a projection of the 21st Century temperature trend from 2008–2100, are shown in Fig. 3. The blue segment of each time series represents observed data through 2007 for Texas Climate Division 5 (TX05, the trans-Pecos division, covering western Texas). Although Division-averaged observations are not designed to provide quantitative long-term trend estimates (Guttman and Quayle 1996), the late 20th Century increase in temperature discussed in the previous section is evident in this time series. It is apparent from a comparison of winter (Fig. 3a) and summer (Fig. 3b) data that temperature exhibits considerably more year-to-year variability in winter than in summer, a well-known feature of climate outside the tropics.

The segment of each time series from 2008–2100 is derived from a combination of global climate model projections and 20th Century observations, using a technique described by Gutzler and Robbins (2011). Linear trends in future temperature were derived from an 18-model average of CMIP3 climate simulations forced by the A1B scenario of increasing green-

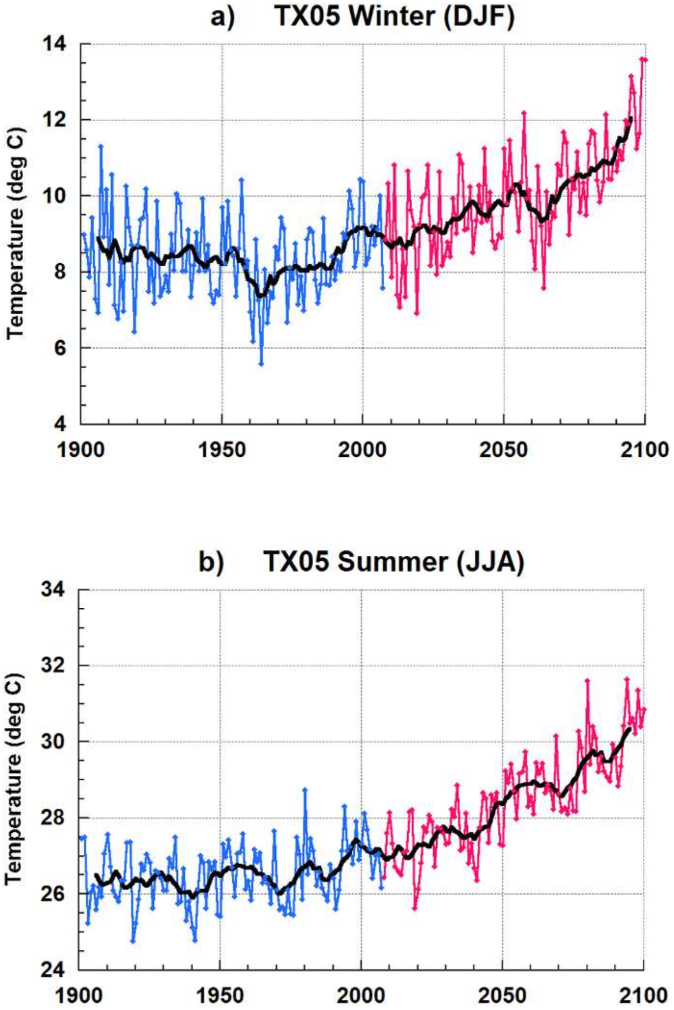

Fig. 3. Time series of observed (blue) and projected (red) winter and summer seasonal temperature values averaged across Texas Climate Division 5 for the 20th and 21st centuries. In each panel, the blue segment depicts observations from 1901–2007, derived from climate divisional averages obtained from the Western Regional Climate Center and converted from native units (°F) to °C. Future values (2008–2100, shown in red) are derived from a linear climate trend based on global model projections forced by the A1B scenario from the CMIP3 archive (Meehl et al. 2007). Future interannual variability has been artificially constructed by repeating 20th Century observations from exactly 100 years earlier, as described by Gutzler and Robbins (2011). The thick black line is an 11-year moving average through the annual time series of seasonal values. (a) Winter months (Dec–Jan–Feb). (b) Summer months (Jun–Jul–Aug).

house gas concentrations (Meehl et al. 2007). The A1B scenario was developed to depict a midrange projection of possible 21st Century greenhouse gas emissions. Simulated climate variables from the model grid cells were spatially interpolated to climate divisions by the NOAA Earth Systems Research Laboratory to form division-average time series that correspond to the 20th Century observations.

Because coarse-resolution models used for climate change projection may not reproduce regional interannual variability with high fidelity, the long-term trend is the principal feature that we expect these models to simulate. Furthermore, the process of averaging 18 models smooths out simulated interannual variability almost entirely. A linear trend provides an excellent fit to the projected 21st Century change in the 18-model average (Gutzler and Robbins 2011). To portray realistic interannual and decadal variability, the observed sequence of detrended interannual divisional anomalies from the 20th Century is repeated, exactly one century later starting in 2008, superimposed on the model-projected trend for 2008–2100 to form the future sequence of projected temperatures for the 21st Century.

The linear temperature trends for the period 2008–2100 shown in Figs. 3a and 3b are respectively 3.1°C/century in winter and 3.8°C/century in summer. The projected rates of warming associated with the A1B scenario represent approximately a continuation of the trends already observed over the last several decades, with a slight acceleration of the trend in the summer season.

The projected 21st Century change in summer temperature is considerably more pronounced than the winter trend in two respects. First, as noted above, the rate of change of temperature is slightly greater in summer than in winter. Second, interannual variability is greater in winter than in summer, so that the climate change trend stands out from shorter term variability in summer. In the scenario shown in Fig. 3b, summer temperature increases beyond the historical range of 20th Century variability by the mid-21st Century. Even "anomalously cold summers" late in the 21st Century are warmer than the warmest summer ever observed to date. Interannual variability in winter temperatures is more pronounced so that "very cold winters" in the late 21st Century are about the same temperature as "very warm winters" in the current climate. Annual average temperature (not shown), like summer seasonal averages, increases far beyond the historical range of variability before the end of the current century.

It must be emphasized that the projections depicted in Fig. 3 are "scenarios", as distinct from "forecasts". The projected trends are highly dependent on the choice of greenhouse gas scenario chosen to force the models, and even if it were possible to predict greenhouse gas forcing exactly (an impossibility) there is considerable modeling uncertainty (IPCC 2007). Obviously it is not expected that 21st Century interannual variability will exactly reproduce the 20th Century observations; this construct is intended merely to incorporate realistic statistics of interannual variability. Therefore the projected 21st Century temperature changes shown in Fig. 3 are quantitatively very uncertain. However a strong consensus exists for projecting some significant rate of warming, together with considerable (and mostly unpredictable) interannual variability, as atmospheric greenhouse gas concentration increases during this century.

Corresponding time series of precipitation for Texas Climate Division 5, derived from the analogous combination of observations and climate model projections, are shown in Fig. 4. Unlike the temperature changes seen in Fig. 3, long-term trends in precipitation are modest in both observations and model projections, relative to interannual and decadal variability. The 18-model average for the 21st Century does project a slight decrease in precipitation, consistent with the analysis of Seager et al. (2008) who used essentially the same model output, but projected trends in precipitation are small relative to the much larger interannual and decadal fluctuations. There is some consensus among the different models that winter precipitation will decrease, but no such agreement is evident for summer precipitation (IPCC 2007, Karl et al. 2009). The largest climate signals in precipitation remain the interannual and decadal fluctuations, which are by construction exactly repeated from the 20th to the 21st Century in Fig. 4.

As climate warms, the energy available for generating intense storms increases. Climate model simulations generate an increasing fraction of total precipitation from intense rainfall events, and correspondingly less from low-intensity storms (Tebaldi et al. 2006, IPCC 2007, Allan and Soden 2008). Several recent observational studies (Groisman et al. 2005, 2008, Alexander et al. 2006, Allan and Soden 2008) suggest that trends toward more intense precipitation events are starting to become detectable in the data. These results imply that the overall projected trend toward drier conditions in the Rio Grande borderlands could be punctuated by infrequent, but increasingly intense, storm events—that is, a trend toward more severe

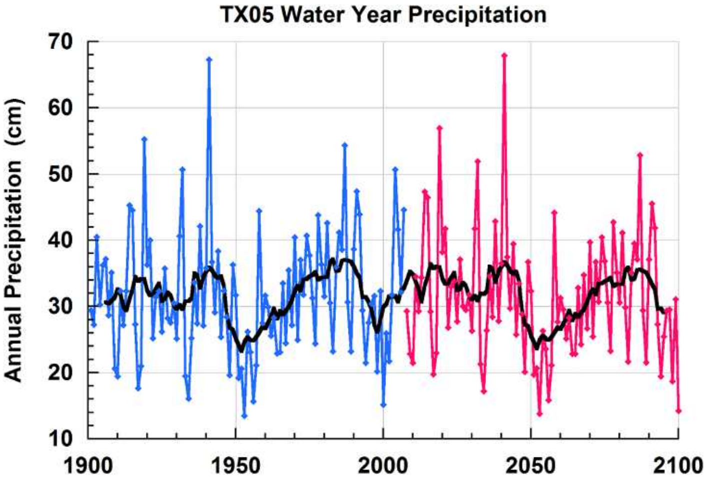

Fig. 4. Like Fig. 3, but for annual precipitation (cm), accumulated over water years extending from October through the following September, for Texas Climate Division 5.

droughts together with the potential for more severe floods. Note that the procedure used to repeat 20th Century interannual variability in Figs. 3 and 4 assumes that the statistics of climate variability remain stationary in the 21st Century, so the constructed 21st Century variability in those time series may represent an underestimate of likely future variability.

Streamflow and drought

Temperature and precipitation projections similar to those shown in Figs. 3 and 4 have been used to drive hydrologic models, to simulate the effect of projected climate change on major rivers. Hurd and Coonrod (2008) carried out such a study for the Rio Grande in central New Mexico, upstream of the borderland area. They used a simplified water balance model to estimate inflows to, and outflows from, this stretch of the river using multiple climate change projections. As expected, the projected future spring flood pulse is both weaker and earlier in the year, a result of the diminished snowpack in the Rio Grande headwaters, and the earlier melt date of snowpack as climate warms later in the century. Total annual streamflow is reduced between 8% and 29% by the late 21st Century in the various scenarios, a result that indicates both the potential for truly deleterious reduction in streamflow, and the high level of uncertainty in making any such projection. Post-snowmelt spring season flows are particularly reduced relative to current climatic conditions, which could severely impact irrigated agriculture at the start of the growing season.

A striking finding of Hurd and Coonrod (2008) is that precipitation plays a secondary role in the diminished Rio Grande streamflow projection relative to warmer temperature. Projected flows decline, especially in springtime, regardless of the assumption made about precipitation change. They deliberately explored a future scenario in which precipitation increases somewhat over current climate, at the far "wet" end of the range of available projections. In the wet scenario streamflow still declines during this century, because the diminished snowpack during the cold season, and much-increased evaporation rate during the warm season, deplete streamflow beyond the level for which a hypothesized precipitation increase might compensate.

As described above, Hurd and Coonrod (2008) diagnosed streamflow for projected climatological conditions. But climatological conditions are not what decimated previous societies in this part of the world; drought did that. Planning for sustainability requires that we consider the possible changes in average temperature, precipitation, and streamflow suggested by global climate models, then superimpose a major drought on top of that.

Future droughts (defined principally in terms of precipitation deficits) would be significantly exacerbated by a long-term shift toward warmer temperature. This stark expectation is a primary conclusion of multiple recent studies (Burke et al. 2006, Sheffield and Wood 2008). Gutzler and Robbins (2011) showed that the major southwestern drought of the 1950s, which is repeated by construction in the decade of the 2050s, is much more severe in the future climate. The reason for the enhanced severity in future climate is the effect of increased temperature on evaporation rates, shifting the surface water budget toward aridity, consistent with the results of Seager et al. (2008). Enhanced severity of drought has already been observed in other studies comparing of the recent turn-of-the-century drought with the earlier 1950s drought in the southwest (Breshears et al. 2005, Weiss et al. 2009).

Discussion and Conclusions: Climate and Regional Sustainability

We have shown that 21st Century climate change associated with a middle-of-the-road projection of increasing greenhouse gases raises average temperature in the middle Rio Grande region well beyond the envelope of historical variability by the latter decades of this century. It is important to keep in mind that the projections in Figs. 3 and 4 contain large uncertainties; the true future climate change could be significantly more or less rapid than the 3–4°C/century trends shown in Fig. 3. However an overwhelming consensus of climate scientists agrees that the radiative forcing associated with increasing greenhouse gases will generate some rate of warming this century. There is effectively no scientific debate arguing against the likelihood of continued warming, but considerable debate remains over how much warming and how fast it will occur. The evidence in support of model-based projections of long-term reductions in winter precipitation is considerable, but less conclusive, and there is no consensus at all concerning future trends in summer precipitation.

These conclusions will be carefully re-examined using new climate model projections now in progress, in anticipation of the next major IPCC assessment of climate change science due to be published in 2013. New, more detailed assessments of streamflow changes affecting the borderlands regions (e.g., U.S. Bureau of Reclamation 2011) are ongoing and represent a significant source of future guidance for policymakers.

Increasing vulnerability to water shortages is recognized as a primary effect of projected climate change in the border region in both the U.S. (Karl et al. 2009) and Mexico (Ibarrarán et al. 2010). Regardless of possible long-term climate change, the border region is already recognized as vulnerable to water conflicts due to stresses that already exist within the context of current climatic availability. The challenges to sustainability posed by ongoing and projected climate change in the middle Rio Grande borderlands must be considered in conjunction with non-climatic factors. By itself, the prospect of diminished surface water flows associated with warmer temperatures would be much more easily managed if groundwater supplies were not already severely depleted by 20th Century agricultural and municipal withdrawals. Explosive population growth over the past 50 years, during a period of relatively abundant precipitation after the principal drought episode of the 20th Century, has greatly exacerbated demand for potable water. Projected climate change merely adds to the overall water demand stress created by other factors.

The international border presents special challenges for reducing vulnerability and enhancing resilience to climate variability and change. As reflected in the results presented in this paper, the quantity of research-quality climate information is much greater on the U.S. side of the border. Many operational data sets and spatial analyses for climate monitoring prepared by U.S. governmental agencies simply stop at the border, despite the obvious fact that the climate system does not recognize political boundaries. Similarly, climate monitoring in Mexico tends to analyze Mexican territory. There have been some very successful recent efforts to synthesize information across the border, notably the North American Drought Monitor analysis (available online at http://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/) which has depicted drought conditions in the United States, Canada and Mexico on a single North American map since 2003. Similar efforts to promote cross-border analysis would be tremendously beneficial.

At present there is little or no consensus among policymakers and the public with regard to explicit consideration of climate change for water management or other aspects of planning. Despite a large and growing scientific consensus that the current observed warming trend in the region will very likely continue in the 21st Century, impediments still exist to formal adoption of climate change as an integral factor in policymaking to enhance resilience.

One impediment is simply the long time horizon for unambiguous detection and attribution of observed climate change on the regional scale. The time scale of projected change, barring an unpredicted surprise, is beyond the range of many policy and planning efforts, despite the potentially profound effects that could occur within a century's time. Furthermore, there are large quantitative uncertainties regarding how rapidly the climate is expected to change, making it difficult to present solid and credible projections of the sort that policymakers and the public seek. This uncertainty is a function of both limited modeling capability, which will improve with time, and our inability to accurately project future concentrations of greenhouse gases. The latter prediction depends on energy policy choices made worldwide over the next several decades that are economically and politically extremely contentious, and on poorly constrained projections of the global carbon cycle that determine how much carbon dioxide and methane are taken up by the global oceans and terrestrial biosphere (IPCC 2007).

Continuing research on climate model improvements and carbon cycle models will reduce uncertainties somewhat, but it is quite likely that model-based projections for the foreseeable future will continue to contain very significant quantitative uncertainties. The climate system is tremendously complex, highly nonlinear and chaotic, and depends on small scale processes (such as cloud physics) that will not be easily resolved even with larger and faster computers. Much more work needs to be done to improve communicate with policymakers and the public, based on syntheses of climate change information on the regional scale that preserve scientific credibility, maintain realistic uncertainties, and still provide useful input for public discussion.

Policymakers will need to develop strategies for resilience and sustainability in the face of large uncertainties concerning future climate change. A reasonable qualitative projection is that the borderlands will experience considerably higher temperatures and continued pronounced interannual-decadal variability in precipitation. Making this projection more certain and quantitative represents a large ongoing scientific challenge. Coping with a future drought—at least as severe as the 1950s drought in terms of magnitude and duration and possibly much more severe—superimposed on a changed climatology featuring warmer temperature and diminished streamflow, will be a daunting socioeconomic challenge.

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