CLIMATE CHANGE, DROUGHT AND POLICYMAKING IN THE U.S. SOUTHERN REGION

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Project Objectives

The availability of water to meet all the current and future needs for agriculture, industry, recreation, habitat preservation and human consumption is of great concern to scientists and policy makers. Increased demands on water resources from all categories of users and possible changes in climate that could increase drought are increasingly worrying scientists and policy makers.

Identifying and examining trends, improving predictions of the availability of water in the future and improving distribution of the use of water resources to maximize its benefits to all consumers is a huge task. Scientists and policy makers must work together to obtain the best scientific predictions of climate-related water resources, forecasting information must be communicated to stakeholders in useful and compelling ways, and policy makers must receive these predictions and use them to develop strategies that mitigate the potential negative consequences of water shortages.

This study is designed to investigate the factors affecting the drought-related beliefs, behaviors and policy choices of citizens and water managers in Texas and New Mexico. The study seeks to evaluate the information sources provided by the National Weather Service in these drought decision processes.

Methods

A research team led by the Institute for Science, Technology and Public Policy and including social scientists, economists and policy scientists, conducted the research. The project aggregates, synthesizes and evaluates the provision of scientific information on climate induced drought in Texas and New Mexico, conducts targeted research on public and water manager drought attitudes, beliefs and policy choices, examines the economics of water management and allocation regimes in times of scarcity, and relates all of these findings to the utility of information sources provided by the National Weather Service.

Significance

This interdisciplinary research project illustrates how scientific information on an important problem, climate induced drought, can be utilized by decision makers, water managers and the public to identify potential problem areas and evaluate policy options. The results of this study will help NWS better communicate its forecasts and other data and reports to relevant stakeholders, the public and policy makers.

Historical Context

In the Southern United States, as in most areas of the world, drought is driven by a combination of natural and man-made impacts on the water budget. There is a general perception that the region is facing an increased likelihood of future water shortages due to increases in population and water use combined with, for practical purposes, a limited water supply.

Future changes in precipitation and evaporation are possible with a changing global climate. The magnitude, and even the direction, of these changes at a regional and local scale are unknowable with current climate prediction capabilities. However, the response of society and policymakers to recent climate variations tells us something about the likely response to future climate variations.

As Figures 1 and 2 below indicate, this region has a history of severe and extreme droughts. While there are intermittent years with good rainfall counts, the 30 year trend is definitely toward more produced dry periods. Managing scarce water resources will be the norm for this region for the future and that means balancing the needs and demands of a variety of users.

Figure 1. New Mexico Palmer Drought Severity Index Yearly Average, 1980-2009

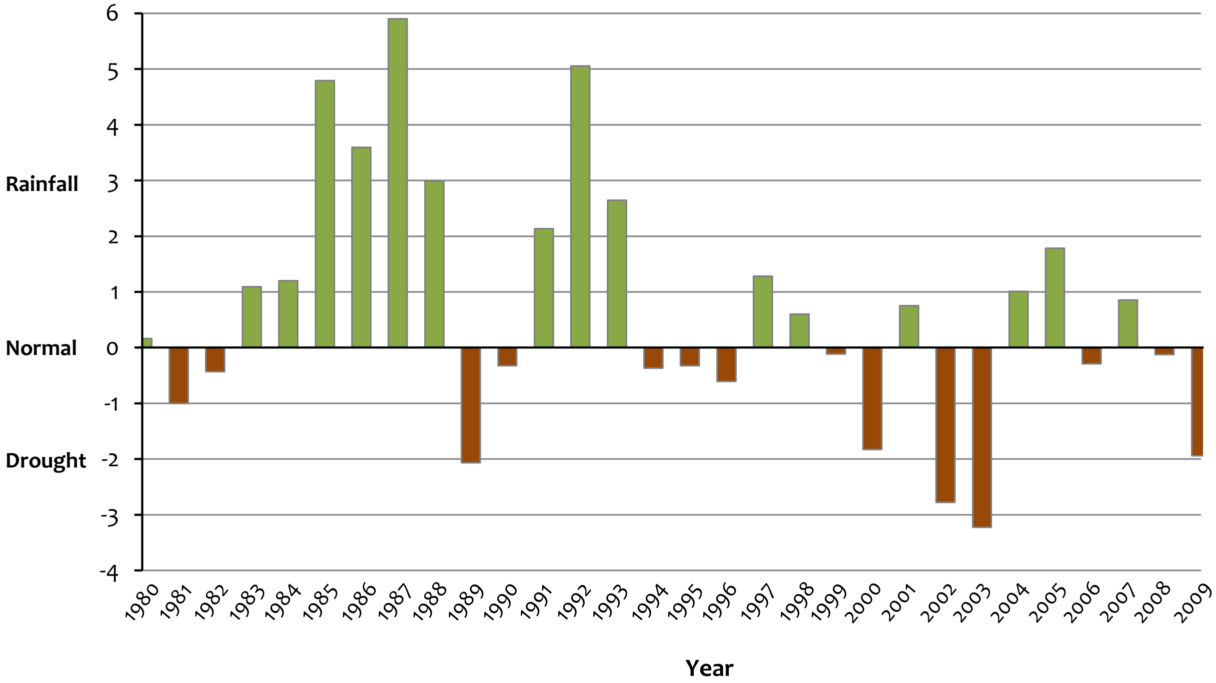
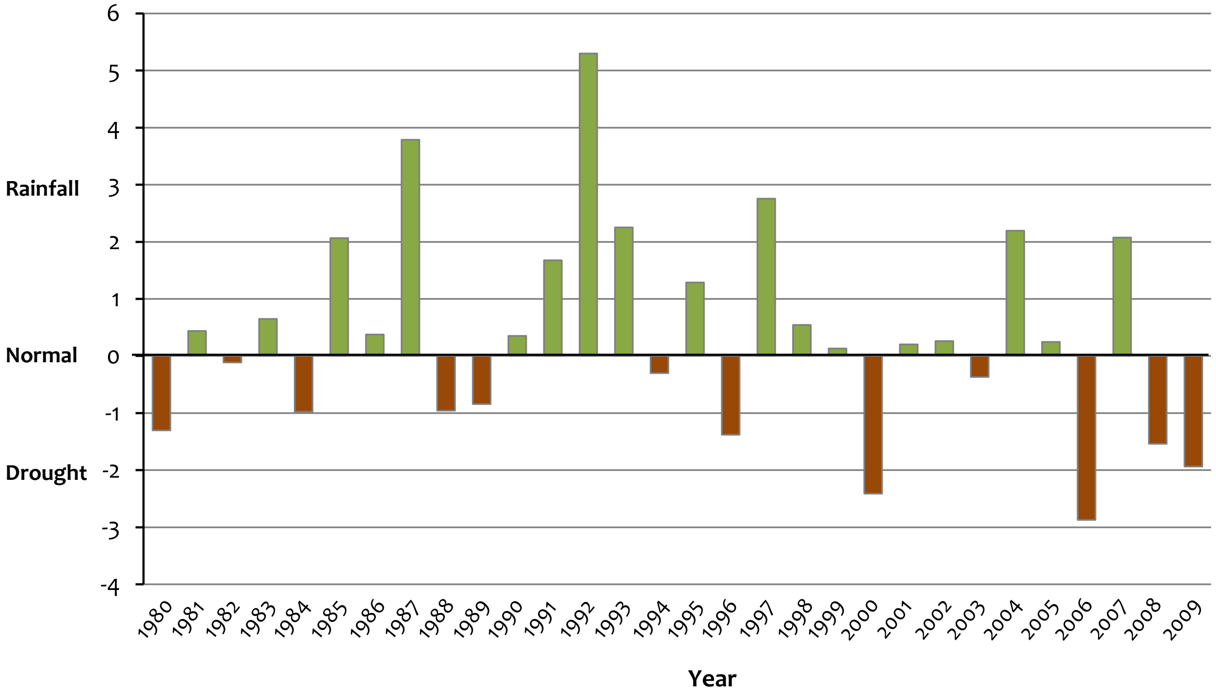


Figure 2. Texas Palmer Drought Severity Index Yearly Average, 1980-2009



In the last decade, we have witnessed the publication of numerous books, scholarly articles, and research reports that note difficulties in efficient and amicable management of water supplies—difficulties exacerbated by the vagaries of drought (Giordano, 2003; Gleik, 2003; Yoffe & Wolf, 1999; Wolf, 1998). This literature notes the potential for conflict among various stakeholders over water supply, suggesting the need for better *anticipation, adaptation, and resolution* of such conflicts before and when they arise.

Results from targeted research on drought probabilities and economic analyses of the costs and benefits of various strategies to mitigate and adapt to climate-induced drought will inform a multi-pronged investigation of the micro sources of potential conflict. This study does not deal with water-based conflicts per se, but rather examines the context within which future conflicts may arise and the potential methods that might resolve them. Potential micro sources of water conflict exist among: 1) individual water users and 2) water managers within and across agencies and districts responsible for efficient and equitable allocation of water resources.

Managing potential water conflicts among individual water users requires understanding of the demographic profiles, risk dispositions, values and attitudes that motivate water use and conservation behaviors; how water users assimilate and use information on drought and water shortages; how water users valuate, rank and prioritize types of water use in conditions of relative abundance and scarcity; the willingness of water users to support policy reforms that insulate water users from the adverse effects of climate-induced drought; and the thresholds of information type, as well as risk and uncertainty trigger points that result in policy support and behavior change. Theories of collective action and institutional rational choice on natural resource management will be used to predict variability in water user willingness to engage in costly behaviors that adapt to and mitigate problems of natural resource depletion and pollution (Lubell, Zahran, Vedlitz, & Alston, 2005).

Managing potential water conflicts among water managers within and across agencies and districts requires investigation of how water managers monitor local conditions and consumer use, how they use forecasting and trend information, how they prepare for water shortages of varying severity, the criteria or allocation formulas managers use to balance and prioritize competing water demands in both conditions of relative abundance and scarcity, how often local managers communicate with and coordinate managerial efforts with state, regional, and federal agencies for expeditious responses to water shortages, how water managers promote conservation efforts, and the willingness of managers to support various policy instruments and managerial regimes along with their ability to implement them. Theories of collective action and interagency cooperation inform the investigation.

Recent studies and reports on drought also stress the significance of institutions in drought policy either from the perspective that there are too many or that they are not coordinated (National Research Council 2001, 2004). Another institutional issue relates to the problem of institutions defining drought in different ways with a subsequent difficulty in developing comprehensive drought policy in the United States. Multiple definitions of drought result in stakeholders accepting and adopting different triggering factors and decision thresholds in response to drought conditions. The Western Governors' Association (2004) and the National Drought Policy Commission (2000) have called for increased attention to institutions and decision processes. That is the purpose of this project, where we focus on identification of drought problems, sources of information, and policy choices for the public and water managers in Texas and New Mexico. We pay special attention to the role of the National Weather Service's information in this analysis.

Survey of the General Public: A Comparison of Texas and New Mexico

One of this project's research tasks was to identify stakeholder interests and potential sources of water conflict in the Southern region. The region has experienced enormous population growth in conjunction with periods of severe drought, and water scarcity poses a genuine threat to maintaining the viability of the region's natural resources, health, and economic development.

To ascertain the views of the general public on issues surrounding drought and water scarcity, we conducted a survey of residents in Texas and New Mexico from January 17 to March 12, 2008. The survey included a total of 1,200 completes; 600 completes obtained through a random sample of Texas residents and 600 completes through a random sample of New Mexico residents. Survey questions covered water availability issues in the respondent's region, including evaluation of water uses, risk perception and potential hazards associated with drought, information sources about drought, use of National Weather Service products, and perceptions of policy options for dealing with drought situations. The survey was conducted by the Public Policy Research Institute of Texas A&M University. Following American Association for Public Opinion Research (AAPOR) conventions and algorithms, the survey response rate was 11.0%, the cooperation rate was 21.6% and the completion rate was 78.7%.

Public Perceptions of Drought

We first asked respondents to rank their level of concern regarding drought compared to other specific environmental issues, such as pollution, climate change, and genetically modified foods; the results are shown in Figure 3. Drought ranks fourth as an issue of concern on this list, behind pollution, overuse of natural resources, and the loss of plant and animal species. New Mexico respondents show slightly higher levels of concern about drought than respondents in Texas. One reason for this may be that New Mexico is a more arid state overall, and some of the respondents from Texas may reside in the eastern part of the state, which generally receives more rainfall and has a lower perception of water scarcity.

As seen in Figure 4, a majority of respondents in both states reported being worried about severe drought. While roughly a quarter of Texans surveyed and just over 10% of New Mexicans said they were not at all worried about drought, over half of Texas respondents and 50% of the New Mexicans surveyed described themselves as "somewhat worried" about drought. The remaining respondents were either "worried" or "very worried" about the issue.

When asked about whether they were currently more worried about severe drought than they were the previous year, just over half of the respondents reported the same level of concern. Respondents from New Mexico were slightly more concerned about severe drought compared to previous year than respondents from Texas. Responses to this question, "Are you more worried about severe drought now than you were last year?" are shown in Figure 5.

Figure 3. The Public's Concern about Environmental Issues

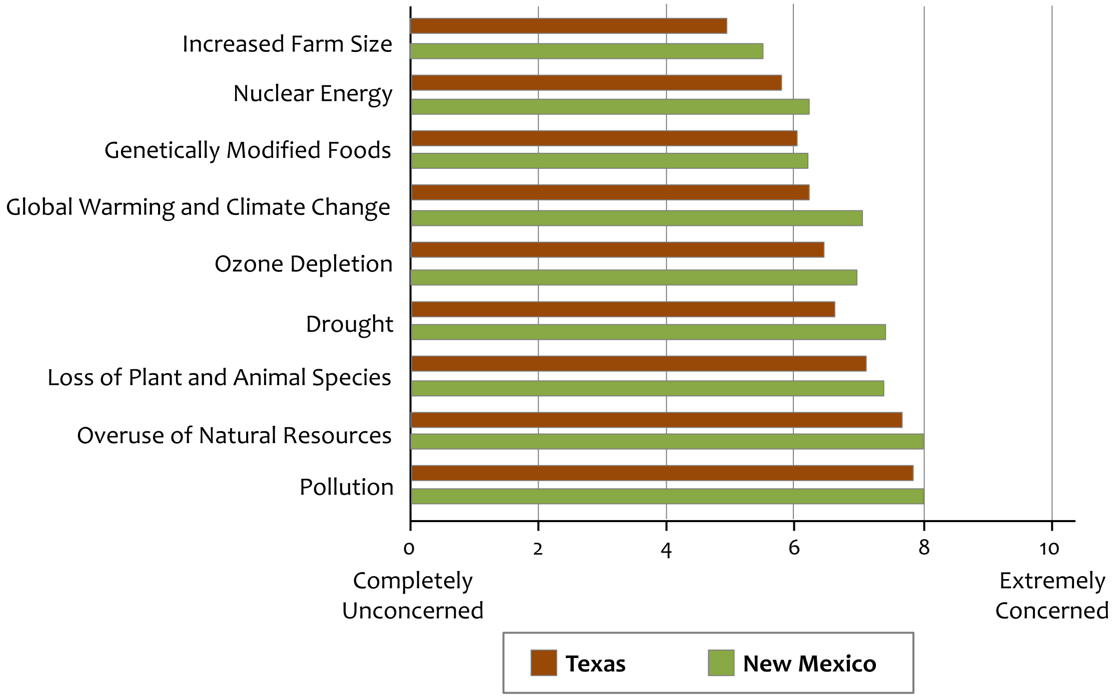


Figure 4. The Public's Concern about Severe Drought

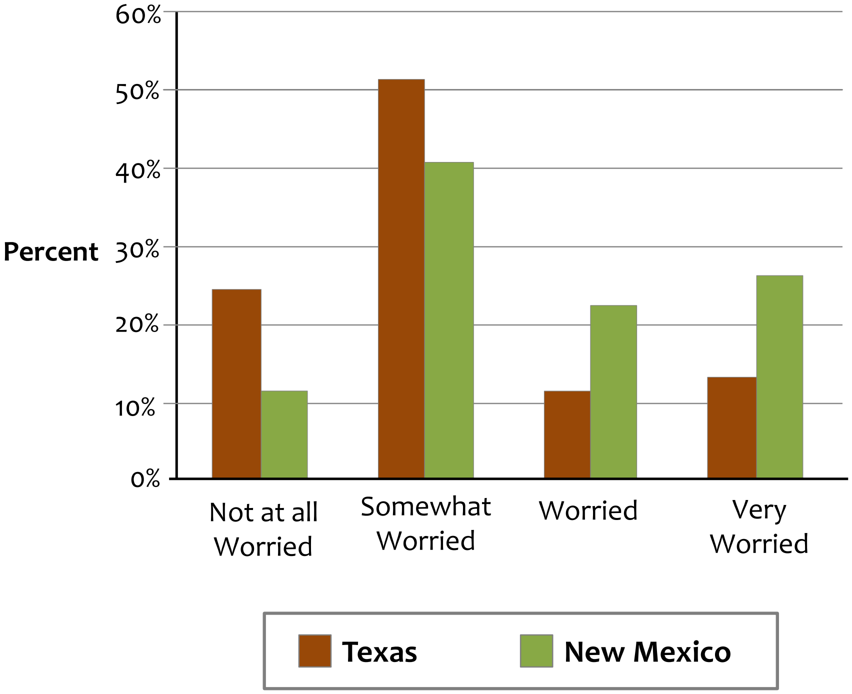
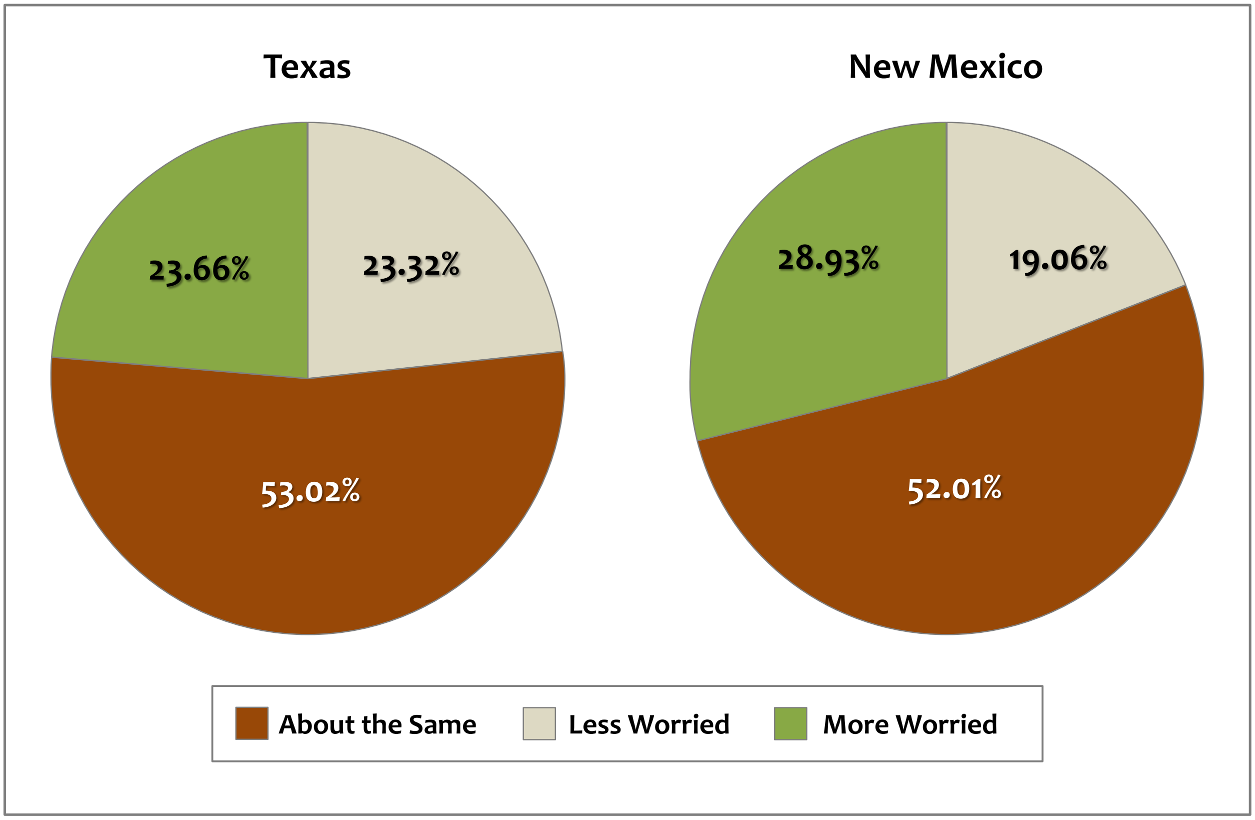


Figure 5. The Public's Concern about Severe Drought Compared to Previous Year



Overall, most respondents in both states perceive steady increases in drought frequency and severity over time. However, there are some differences between Texas and New Mexico respondents, as indicated in Tables 1 and 2. In Texas, over a third of the respondents believe that drought is actually becoming more common in their region, while in New Mexico the rate was nearly 45%. While most respondents in each state expressed the belief that the severity of drought in their region was not increasing, Table 2 shows that nearly 40% of the New Mexicans surveyed stated that they did believe that drought in their region was becoming more severe. Just under a third of the Texans surveyed thought that drought in their region was increasing in severity.

Table 1. The Public's Perceptions of Drought Frequency

Drought Frequency	**Texas**	**New Mexico**
Less common	5.67%	4.54%
Same rate	58.69%	50.79%
More common	35.64%	44.68%
Total	*100.00%*	*100.00%*

Table 2. The Public's Perceptions of Drought Severity

Drought Severity	Texas	New Mexico
Less severe	6.41%	4.06%
Same severity	65.66%	56.79%
More severe	27.94%	39.15%
Total	*100.00%*	*100.00%*

Thus, we see that the public in both Texas and New Mexico perceive severe drought as an increasingly common problem, continuing for the foreseeable future, although New Mexicans are slightly more concerned about the issue than Texans.

Sources of Information about Drought

Our survey next sought to discover where respondents get most of their information regarding drought. We asked respondents to provide their first and second most used sources of information; these findings are presented in Table 3. Newspapers ranked first as a source of information on drought, cited by nearly half of respondents in both states, followed by television news. "Other" sources of information included the radio, scientific research reports, interpersonal relations, and environmental interest groups.

Table 3. The Public's Sources of Information on Drought

Information Source	Texas	New Mexico
Newspapers	47.45%	45.47%
Television News	35.03%	29.19%
Internet	5.95%	6.54%
Personal Experience and Observation	1.53%	3.52%
National Weather Service	***2.55%***	***2.85%***
Other	7.49%	12.43%

Although it was not cited as one of most respondents' top two sources of information on drought, the National Weather Service is considered a useful source. As shown in Figure 6, the NWS products most frequently used by survey respondents are weather advisories, temperature and precipitation outlooks, and fire weather forecasts. Figure 7 illustrates the relative usefulness of NWS information on drought according to our respondents. A clear majority in each state responded that NWS drought information was either useful or somewhat useful.

Figure 6. Types of NWS Products Used by the Public

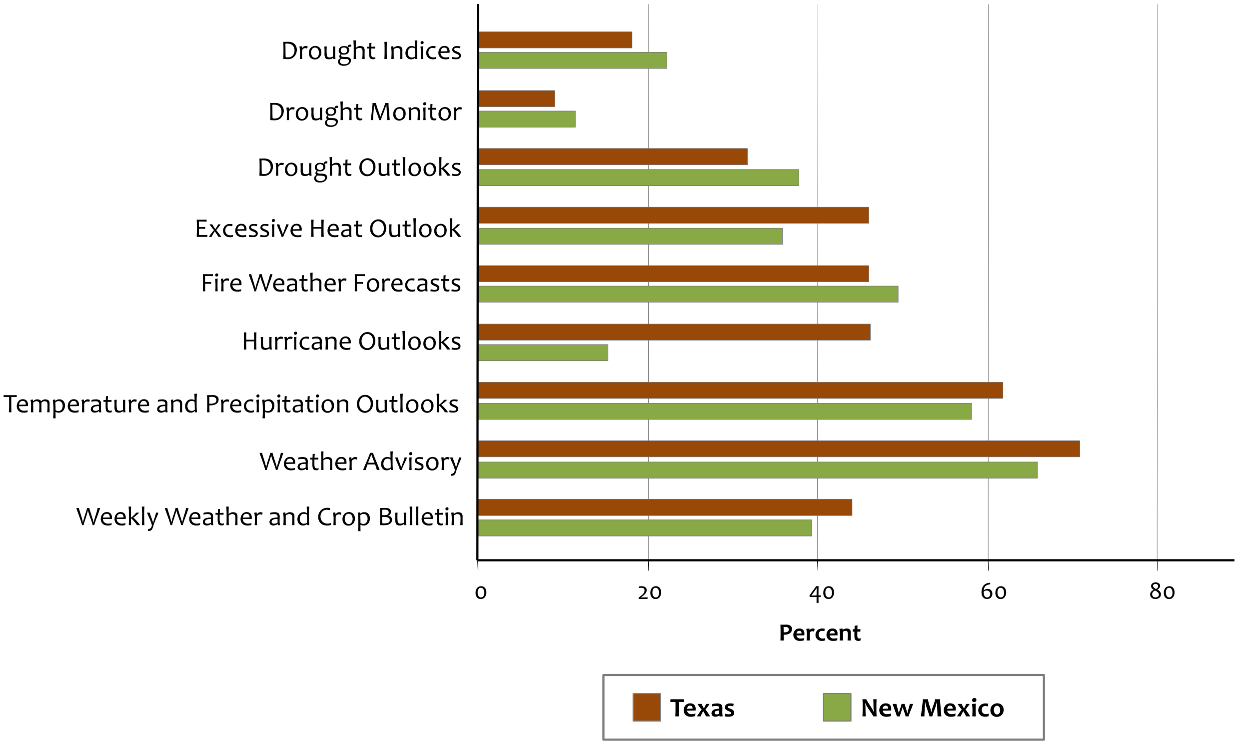
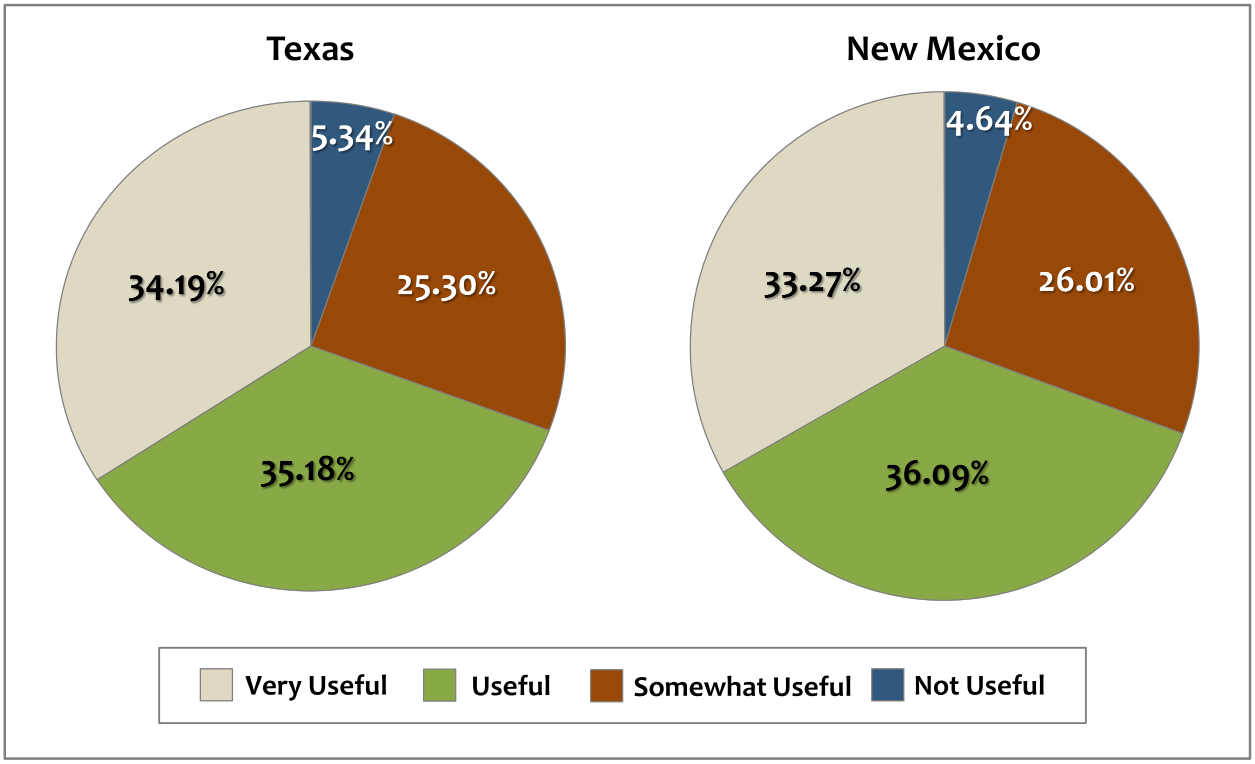


Figure 7. Usefulness of NWS Drought Information



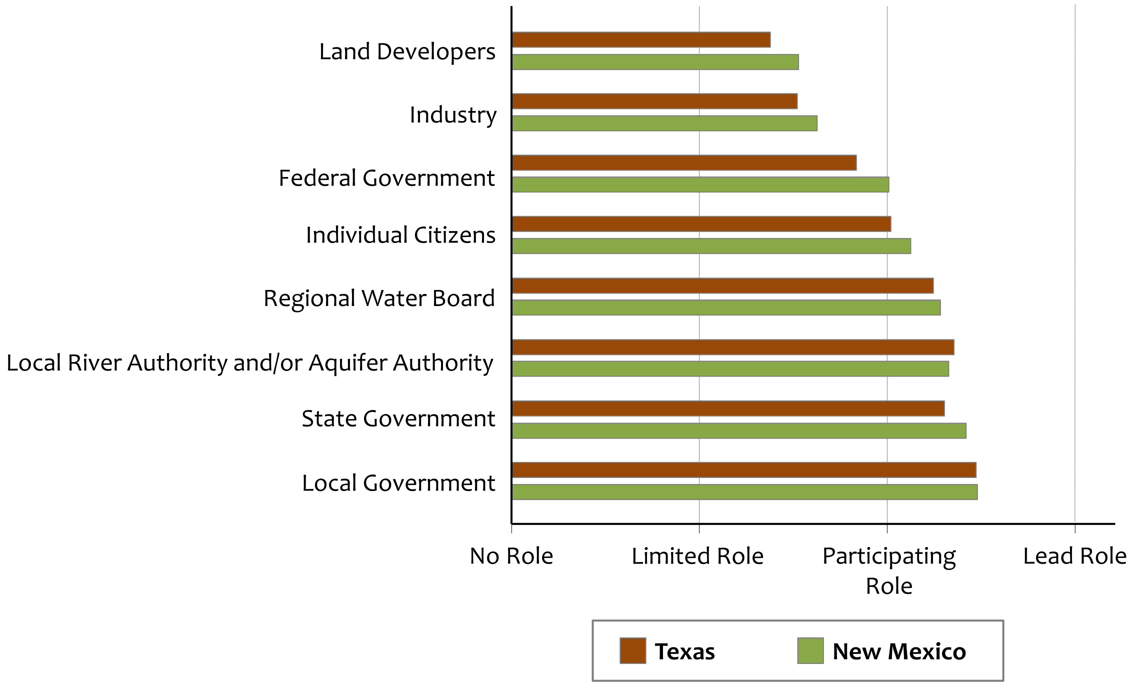
Addressing the Issue of Drought

This section of the report focuses on three particular aspects of addressing water scarcity and drought explored in the public survey. First, we surveyed respondents on which institutions should deal with drought issues, and we asked people about their confidence in each of these actors to manage water resources. Second, we asked respondents about their preferred policy options for addressing water scarcity and drought. Third, we sought to ascertain the public's level of willingness to conserve water.

Institutional Actors to Manage Water Resources

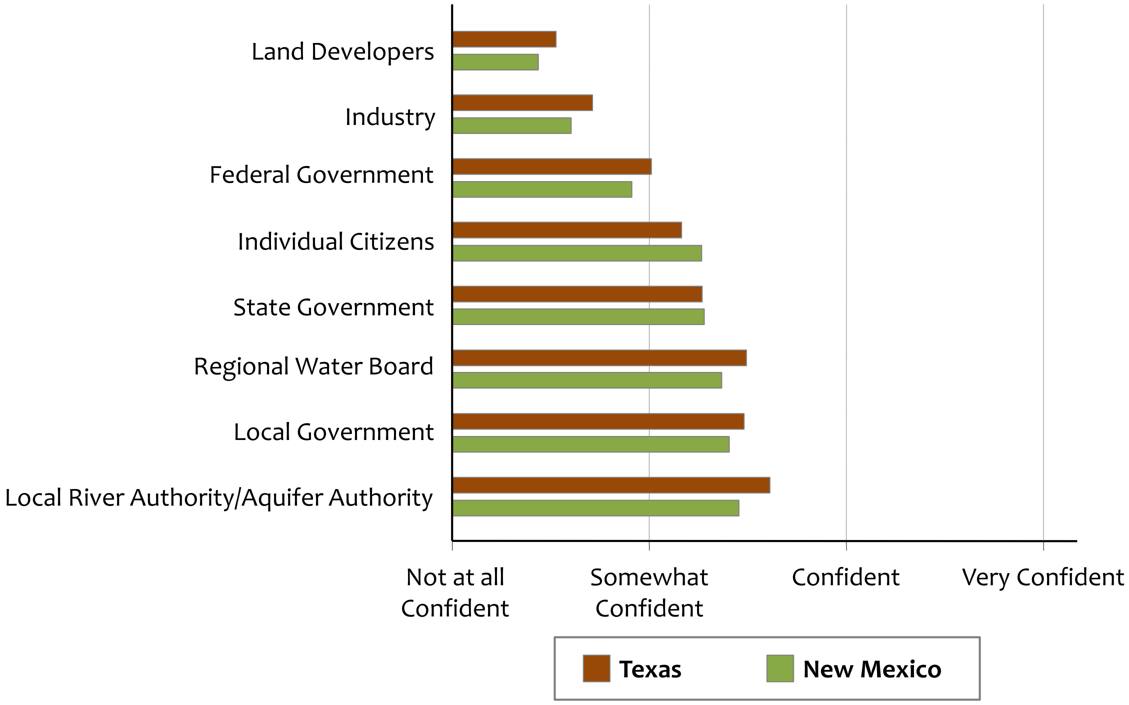
To ascertain the public's views on which actors should play a role in directing responses to water scarcity, respondents were asked, "What role should each of the following play in managing drought: leading role, participating role, limited role, or no role?" As indicated in Figure 8, respondents believe that water resource management and drought responses should be focused at the local level, with local and state governments and water authorities taking the lead. According to the responses given, private industry, including land developers, should be given the least amount of authority to address water resource management.

Figure 8. Role of Institutions in Drought Management



We next asked how confident respondents are with those institutional choices to manage water resources. Overall, the confidence in each of the entities listed is low. As illustrated in Figure 9, none of the institutions which we surveyed the public about received a ranking of "confident." While respondents expressed the highest level of confidence in local water authorities to manage water resources, their total score fell only halfway between "somewhat confident" and "confident." The federal government, industry, and land developers all ranked lowest in terms of confidence to manage water resources. These responses are consistent with the findings shown in Figure 8: the institutions that the public has the most confidence in to manage water resources are also those that the public believes should play a leading role in managing drought.

Figure 9. Confidence in Institutions to Manage Water Resources



Policy Options to Address Water Scarcity

Survey respondents were asked about a range of policy options to address the issue of drought and were asked to indicate whether they would strongly support, support, oppose, or strongly oppose each policy. The responses to this question are outlined in Table 4. Not surprisingly, the idea of voluntary water conservation received the most support while mandatory water rationing was the least favored policy option. Since voluntary conservation was the most popular policy option, we will explore this option further.

Table 4. Support/Strong Support for Selected Drought Management Policies

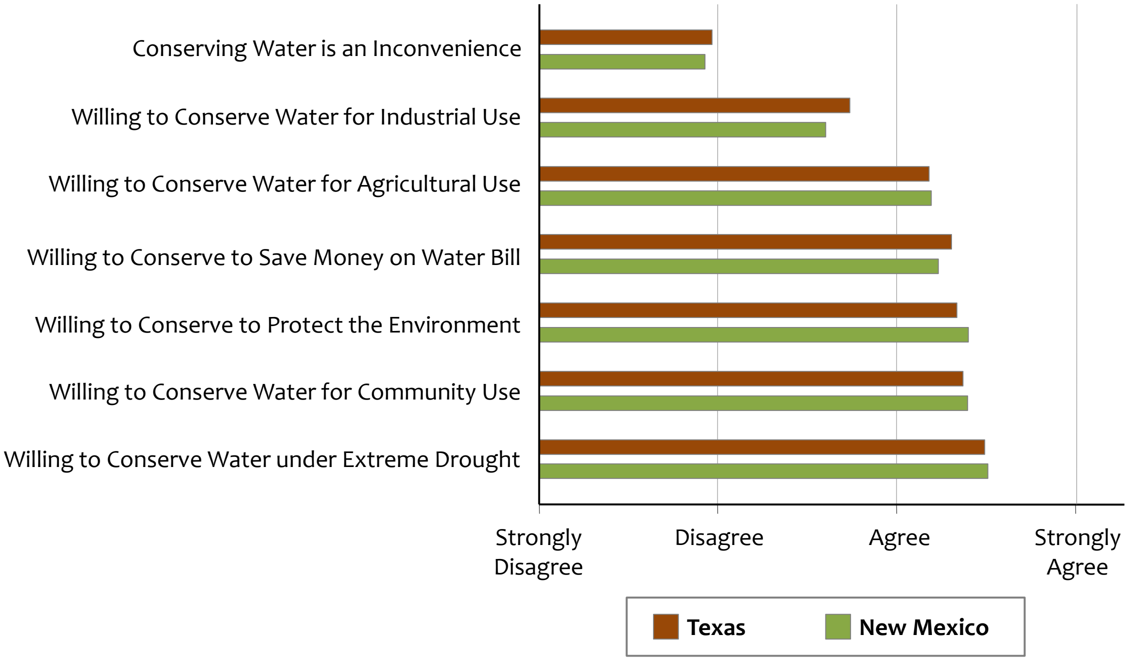
Policy Options	**Percent Supporting**	
	Texas	**New Mexico**
Campaigns for Voluntary Conservation	94.6	94.8
Build Infrastructure	92.5	81.1
Tax Incentive for Water-Saving Equipment	81.7	87.2
Impact Fees on Developers	83.6	86.6
Low-Interest Loan for Water-Saving Equipment	83.1	85.6
Mandatory Rationing	81.7	75.5

Willingness to Conserve Water

Respondents were asked about their willingness to conserve water under various scenarios, ranging from extreme drought to conserving water so that more would be available for industrial uses. The question was phrased, "I am willing to conserve water…" and respondents were asked whether they strongly agree, agree, disagree, or strongly disagree with the statement. The responses are graphed in Figure 10.

Most people agreed that they would be willing to conserve water under conditions of extreme drought, for essential community uses (such as drinking water, waste disposal, and fire control), and to protect the environment. Most respondents disagreed with the statement that the effort to conserve water posed an inconvenience. Responses from both Texas and New Mexico were extremely similar, the only real difference being that Texans seem slightly more willing than New Mexicans to conserve water to benefit industrial uses.

Figure 10. Willingness to Conserve Water



Survey of Water Managers in New Mexico and Texas

In this section of the report, we discuss the results of our survey of water resource managers in New Mexico and Texas. These two states were chosen for the sampling frame as they are most representative of the differing styles of water management in the U.S. Southern Region. In Texas, the Texas Water Development Board oversees the activities of 16 regional water planning areas. Within these areas, there are a variety of utilities and districts responsible for water management functions.

New Mexico waters are governed through the Office of the State Engineer and the Interstate Stream Commission. The State Engineer in New Mexico has jurisdiction over all surface and groundwater in the state, as well as streams and rivers crossing the state's borders. The New Mexico State Engineer also serves as Secretary of the Interstate Stream Commission and oversees its staff. The federal Bureau of Reclamation has jurisdiction over water used by the irrigation and conservancy districts in that portion of the Upper Colorado River Basin located in the northwestern corner of the state.

Survey Sampling and Methodology

The sampling frame for Texas was compiled from the comprehensive water utility database (WUD) which is maintained by the Texas Commission on Environmental Quality (TCEQ). This database provided contact information for the state's public drinking water systems, water and sewer utilities, and other water districts. To round out our sampling frame, we added entities such as groundwater conservation districts and soil and water conservation boards. This information was provided by the Texas Water Development Board and the Texas State Soil and Water Conservation Board, respectively. The full sample frame for Texas included 3,913 water management entities; from this frame we drew a random sample of 1,000 contacts for our survey.

In New Mexico, our sampling frame consisted of all 1,435 water management entities in the state. Since this number was so close to our desired sample of 1,000, we decided to survey the entire sample frame. A database maintained by the Drinking Water Bureau of the New Mexico Environment Department provides contact information on all of the state's public water systems and served as our major source of contact data. This database includes all community water systems, non-community water systems, and non-transient non-community water systems in the state. Other contact data sources included the New Mexico State Engineer's Office, the Interstate Stream Commission, the U.S. Bureau of Reclamation, the USDA Natural Resources Conservation Service, and the Office of the State Auditor.

Questions for the survey of water managers are based on theories of collective action, institutional rational choice, planned behavior, and natural resource management risk. The survey was designed to address the following: 1) respondents overall concern regarding drought; 2) attitudes about NWS drought information and the use of NWS drought information; 3) attitudes toward drought policies, particularly mitigation and adaption; 4) institutional roles in water resource management; and, 5) the respondents' assessment of individual willingness to conserve water.

The water managers' survey was multi-modal – mail, telephone, and online – with the majority of respondents choosing to take the survey online. The survey was conducted from August 2008 through January 2009. We received a total of 512 responses; 245 from Texas and 267 from New Mexico. The water managers surveyed had an average of 16 years of experience, with several respondents reporting that they had been in the field for over forty years. According to the AAOPR standard, the response rate for this survey is 28%, the cooperation rate is 76%, and the completion rate is 75%.

Overall Concern about Drought

We first sought to get some idea about water managers overall concern regarding drought. To that end, we asked respondents, "how worried are you about moderate and severe drought in your region?" We based our definitions of moderate drought and severe drought conditions on the definitions used by the *Drought Monitor*. These definitions, provided in the survey, were:

- Moderate drought conditions - some damage to crops and pastures; streams, reservoirs, and wells low; some water shortages developing or imminent.
- Severe drought conditions - crop or pasture losses likely; water shortages common; water restrictions imposed.

The majority of respondents from both states reported some degree of worry about moderate or severe drought occurring in their region. In both Texas and New Mexico, 47% of the water managers surveyed stated they were "somewhat worried" about moderate drought; while about 39% in both states were somewhat worried about severe drought. Regarding severe drought, 45% of New Mexico water managers and 38% of Texas water managers surveyed reported being "worried" or "very worried." Table 5 outlines the complete responses to this question.

Table 5. Water Managers - Concern about Drought

Level of Concern	Moderate Drought		Severe Drought	
	Texas	New Mexico	Texas	New Mexico
Not at all Worried	21.19%	16.86%	22.22%	16.60%
Somewhat Worried	47.03%	47.45%	39.74%	38.34%
Worried	23.73%	22.75%	18.38%	24.51%
Very Worried	8.05%	12.94%	19.66%	20.55%

We followed up our query about overall concern regarding drought with the question: "Are you more worried about moderate and severe drought now than you were last year?" Table 6 summarizes the responses to this question. Most respondents stated that their level of concern was "about the same" as in the previous year. This was true when asked about both moderate and severe drought conditions. Interestingly, about 20% of water managers surveyed in New Mexico reported that they were "less worried" about drought than in the previous year. More water managers in Texas reported that their level of concern about drought had increased from the previous year ("more worried") than their counterparts in New Mexico; this finding applied to both categories of drought.

Table 6. Water Managers - Concern about Drought Compared to Previous Year

Level of Concern Compared to Previous Year	Moderate Drought		Severe Drought	
	Texas	New Mexico	Texas	New Mexico
Less Worried	14.71%	20.47%	12.77%	22.40%
About the Same	57.14%	62.60%	60.00%	56.80%
More Worried	28.15%	16.93%	27.23%	20.80%

We next asked about frequency and severity of drought in the respondents' regions. Most respondents believe droughts will increase in frequency, with no change in severity over the foreseeable future. In answer to a question about the likelihood of drought occurring in their region in the next year, a majority of respondents think it is likely to happen. Most of these believed they would experience moderate drought conditions. Table 7 outlines the full range of responses to this question.

Most of the water managers surveyed believe that future droughts will occur in their region with the same frequency. About a third thinks droughts will occur in their region with greater frequency, while less than 4% believe drought will become less common. The responses to this survey question, "Do you think droughts in your region are becoming more common, less common, or will continue to occur at the same rate?" are summarized in Table 8.

As Table 9 describes, most survey respondents believe that droughts in their region will not change in level of severity. Only 5% believe drought conditions will become more severe. About a quarter of Texas respondents and a third of New Mexico water managers predicted that droughts would be less severe.

Table 7. Water Managers - Likely Occurrence of Drought in Current Year

Likely Drought in Current Year	**Moderate Drought**		**Severe Drought**	
	Texas	**New Mexico**	**Texas**	**New Mexico**
Not at all Likely	16.67%	17.83%	34.60%	34.25%
Somewhat Likely	44.58%	43.41%	41.35%	39.37%
Likely	26.67%	25.58%	18.14%	16.93%
Very Likely	12.08%	13.18%	5.91%	9.45%

Most perceive steady drought frequency and severity over time. When comparing frequency with severity, they perceive a little more frequency and same severity over time. However, the following tables show the differences between Texas and New Mexico respondents. In Texas, about 30% of the respondents believe that drought is actually becoming more common in their region while in New Mexico the percentage is as high as 37%. Regarding drought severity, Texas responses are close to New Mexico's.

Table 8. Water Managers - Perceptions about Drought Frequency

Drought Frequency	**Texas**	**New Mexico**
Less common	3.83%	3.11%
Same rate	65.96%	59.53%
More common	30.21%	37.35%
Total	*100.00%*	*100.00%*

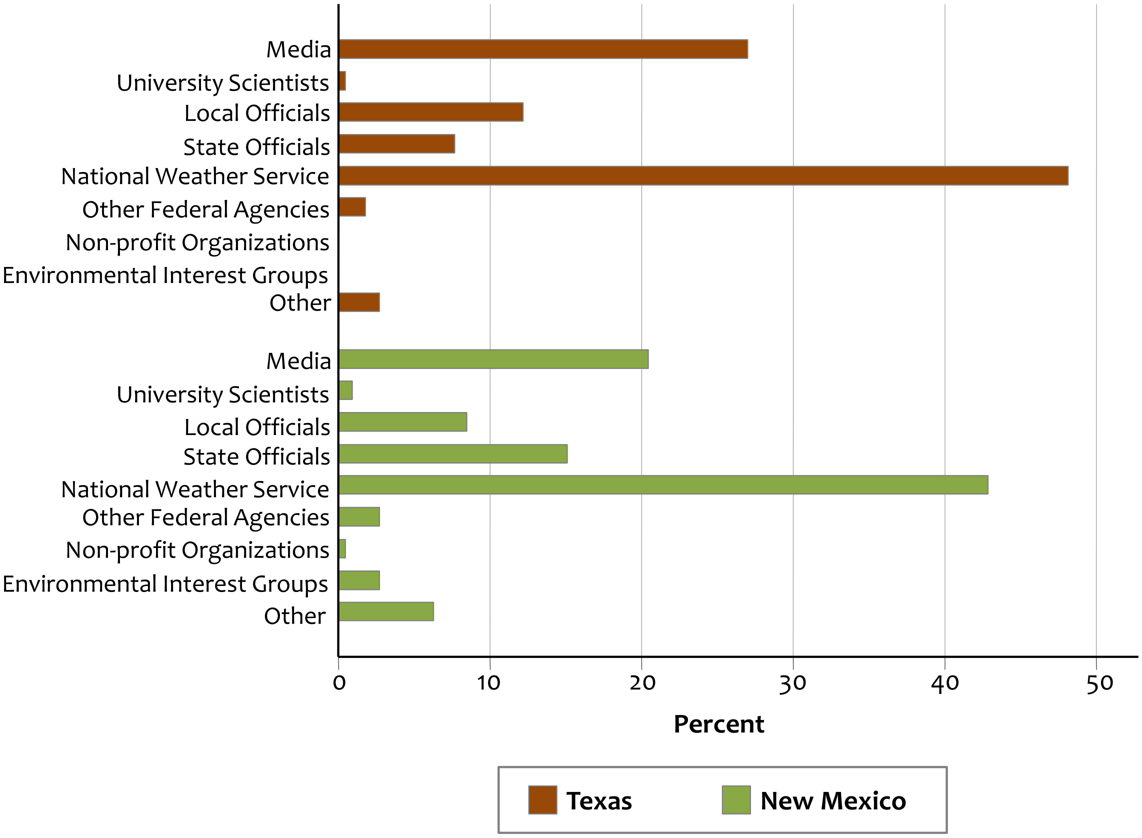
Table 9. Water Managers - Perceptions about Drought Severity

Drought Severity	Texas	New Mexico
Less severe	24.89%	31.64%
Same severity	69.53%	63.28%
More severe	5.08%	5.58%
Total	*100.00%*	*100.00%*

Sources of Information for Water Managers

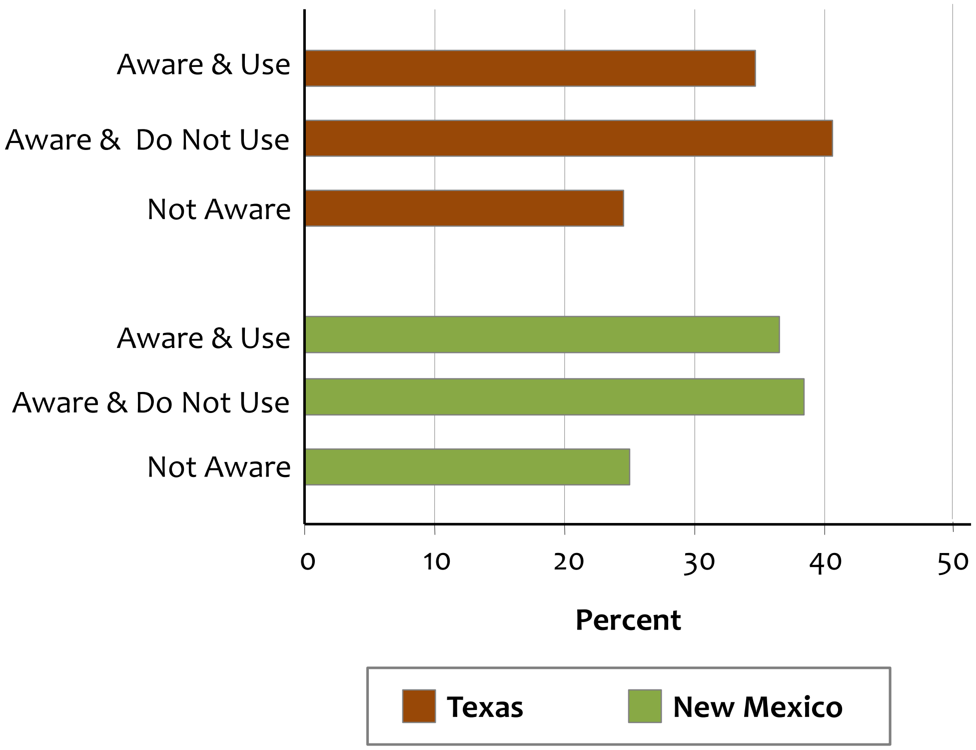
In this section, we examine the sources of information used by water managers in their role of administering water resources. We first asked respondents to list their most important source of meteorological forecast information. In both New Mexico and Texas, the National Weather Service (NWS) was by far the most important source for this information, cited by over 40% of respondents. In both states, the media ranked second as a source of information. Figure 11 illustrates the responses to this question.

Figure 11. Most Important Sources of Meteorological Forecast Information



We followed this question up by asking if the respondent's organization was aware of the availability of meteorological forecast information from the NWS, and if so, did the organization use NWS information. The results are graphed in Figure 12. About 35% of respondents stated that they were aware of, and used, NWS forecast information. This is somewhat less than the percentage who stated previously that NWS forecasts were their most important source of information. About 40% were aware of the existence of this information source, but did not use it, and about a quarter of the respondents were not aware of the NWS information.

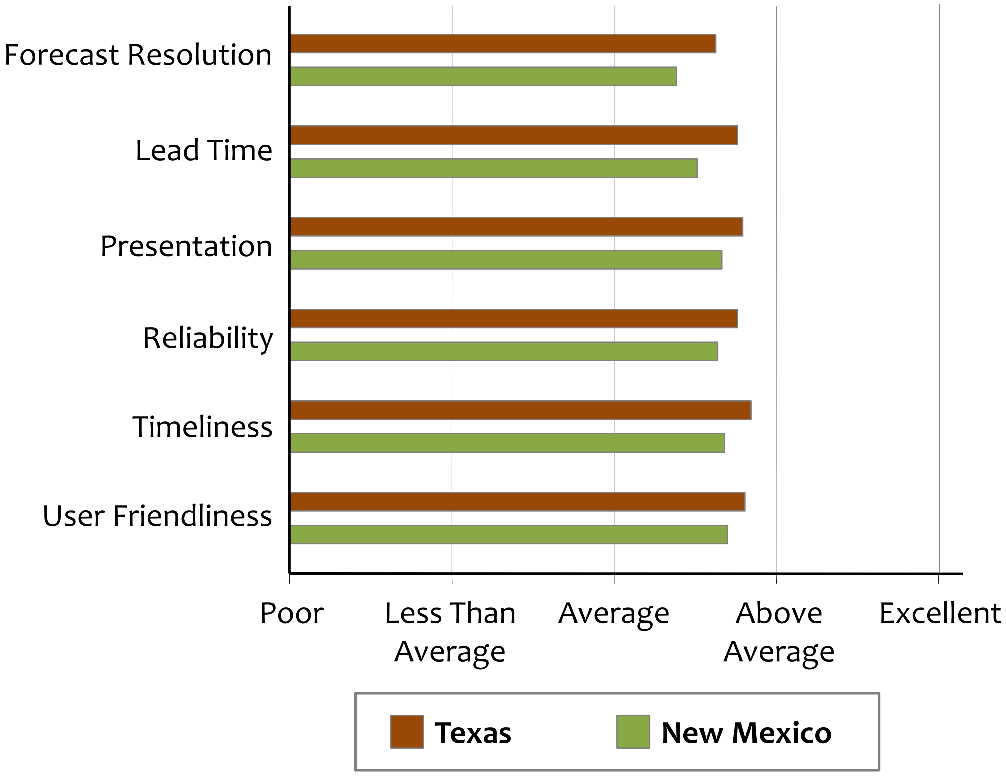
Figure 12. Awareness and Use of NWS Forecasts



Respondents who stated that they were aware of NWS forecast information, but did not use it were further queried as to why they did not use the resource. The most common reason was because the NWS forecast information was not necessary for the function of the respondent's organization.

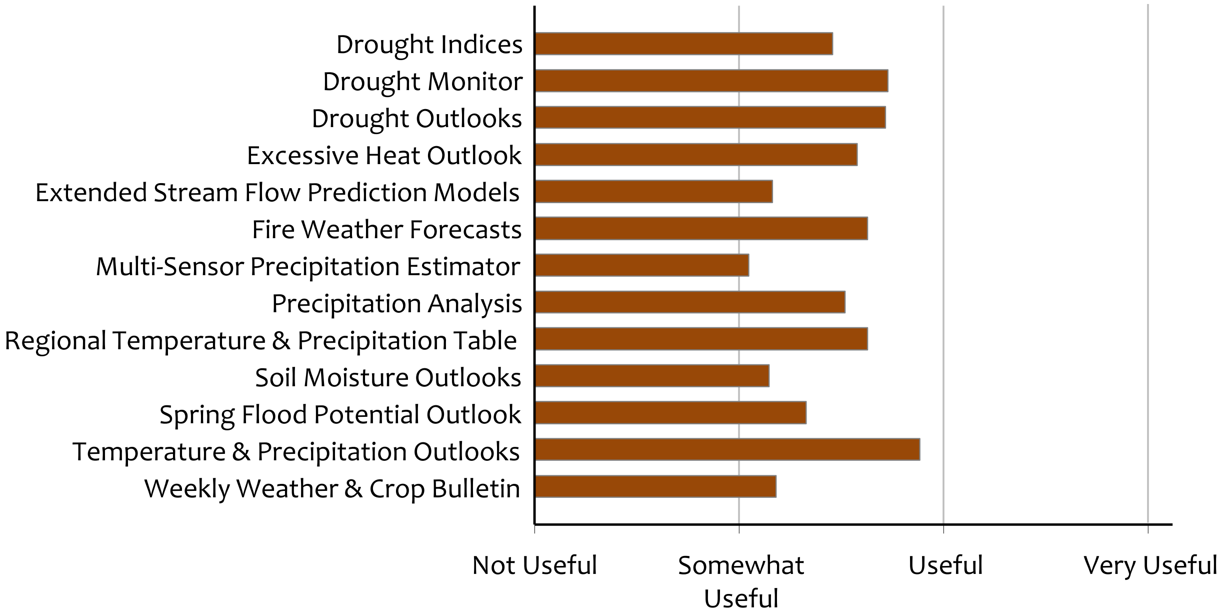
The water managers surveyed who stated that their organizations regularly used forecast information from the NWS were asked to rate the information in terms of reliability, timeliness, lead time, forecast resolution, presentation and user friendliness. As shown in Figure 13, the quality of NWS forecast information received ratings of average to nearly above average across the board. Texas respondents gave the NWS information slightly higher ratings than their New Mexico counterparts.

Figure 13. Water Managers Ratings of NWS Forecast Information



We also asked the NWS information users to rate how useful their organizations found various NWS products for making management decisions regarding drought. Figure 14 illustrates the responses to this question. Respondents found all the products listed to be useful for their work.

Figure 14. Usefulness of NWS Products for Management Decisions Regarding Drought



Finally, we asked the NWS information users to describe ways in which these NWS products could be improved. The majority of responses to this open-ended question fell into the following categories:

1. Make more localized information available
2. Greater accuracy of information.
3. Make the information available in a more timely fashion, more quickly.
4. Provide greater instruction on how to use the information provided.
5. Employ better dissemination techniques, e.g., coordinate better with media, direct/automatic emails, agency-targeted reports (like to MUDs) and expand website.

Role of Institutions to Address Drought

In this section of the report, we explore water managers' beliefs regarding the roles of various institutions and actors in managing drought. Respondents were asked to describe the role each of the listed groups should play in managing drought in their region. The roles were described as "leading role," "participating role," "limited role," and "no role." As with the survey of the general public, most of the water managers surveyed believed that decisions regarding drought should be made at the local and regional level. In both states, land developers, industry, and the federal government were the institutions which respondents stated should play the most limited role in water management at the regional level. Figure 15 charts the responses to this question.

After ascertaining what role the various institutions should play in managing drought in the respondent's region, we asked respondents to rate their level of confidence in these actors to manage water resources. Although the overall confidence levels for all groups are not very high, more confidence was placed in government at the local and regional level to manage water resources than at the federal level. As illustrated in Figure 16, local river/aquifer authorities had the highest rating of confidence, while land developers received very low confidence ratings.

Figure 15. Roles of Institutions in Drought Management

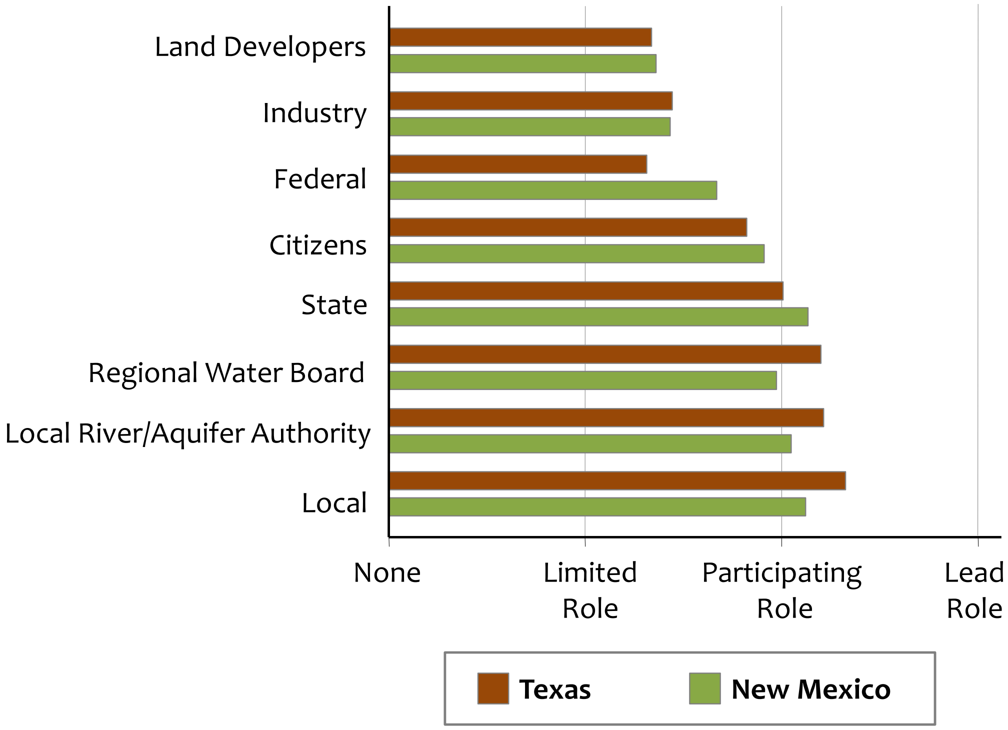
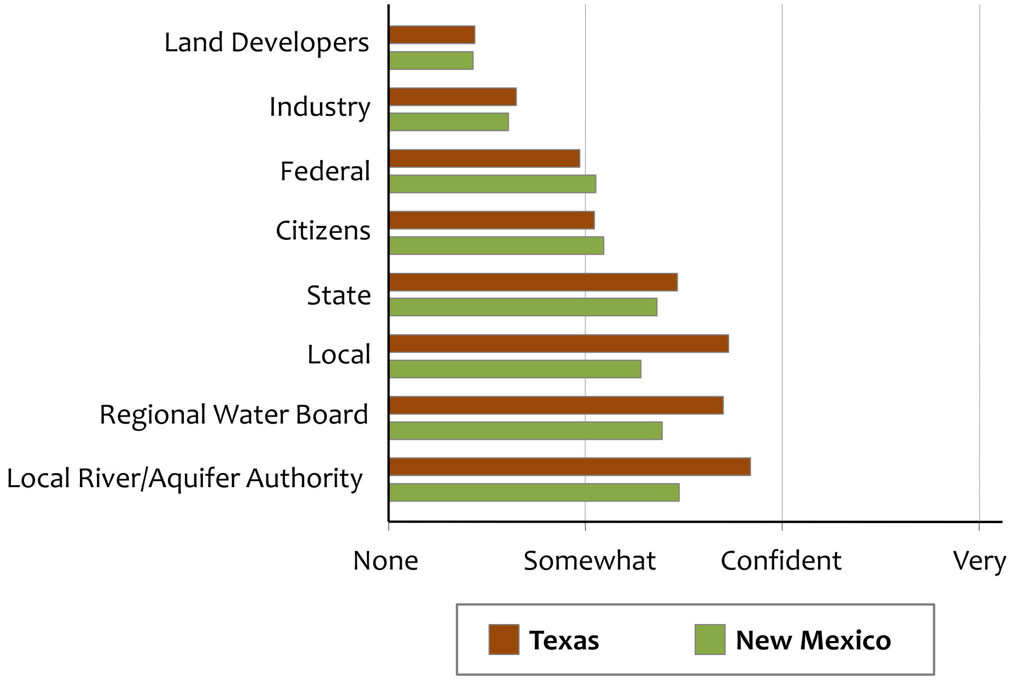


Figure 16. Level of Confidence in the Following to Manage Water Resources



Policy Options to Address Drought Conditions

We asked respondents to describe the kinds of policies adopted by their organizations. The majority of Texas respondents listed precautionary planning as the most used policy, followed by adaptation and early warning. In New Mexico, adaptation was the most frequently listed policy option, followed by precautionary planning and mitigation. Table 10 lists the policies about which respondents were queried.

Table 10. Policies Adopted by Water Managers' Organizations

Percent Adopting Specific Policy	Texas	New Mexico
Precautionary Planning	63.4%	38.5%
Early Warning	45.3%	23.8%
Mitigation	42.7%	27.0%
Adaptation	58.6%	40.9%
Rehabilitation	11.2%	17.1%
Other	5.2%	6.4%

Respondents were given a list of options and their opinion as to the most effective way to achieve water conservation. Respondents in both states believed that public awareness is the most important component of conservation. This is followed by realistic water pricing; that is, allowing the price of water to reflect the actual cost of obtaining and providing it to consumers. Table 11 details the responses to this question.

Table 11. Most Effective Way to Achieve Water Conservation

Methods to Achieve Water Conservation	**Texas**	**New Mexico**
Public Awareness	60.34%	62.75%
Realistic Water Prices	24.05%	16.08%
Water Rationing	11.39%	9.8%
Volumetric Delivery of Water to Farmers	0.84%	5.49%
Other	3.38%	5.88%
Total	*100.00%*	*100.00%*

Comparison of the Public and Water Managers Survey Findings

In this section, we compare some of the findings from the survey of water managers to the responses from the survey of the general public.

- Though the majority of both the public and water managers anticipated no change in drought frequency and severity, a much higher percentage of the public did believe that drought in their region would become more severe in the future.
- While the public listed the news media as their most important source of information about drought, professional water managers listed the National Weather Service as their number one source of drought information.
- When asked about the role of various institutions in dealing with drought, both the public and water managers believed that local governments should play the most important role, with private entities, such as land developers playing little, if any, role in responding to drought situations. In addition, both groups surveyed had higher levels of confidence in local governments to deal with drought, although none of the institutions listed received very high confidence ratings from either the general public or water managers.
- The importance of water conservation was recognized by both water managers and the public. Water managers stated that public awareness was necessary to achieve water conservation. Respondents to the public survey expressed a willingness to conserve water, and an understanding of the importance of water conservation.

Problem Definition, Institutions, Drought Triggers, and Drought Policy

To understand how drought information should be organized and framed to maximize its utility, we conducted two case studies consisting of open ended interviews with representatives of the drought policy network in the states of New Mexico and Texas. The organization and framing of drought within the two case study areas has been conceptualized as a case of agenda setting. Within the agenda setting perspective, the definition of a problem and its strategic linkage to alternative solutions represents a critical component of the analytic framework. The agenda setting framework focuses on how problems are defined, a significant issue within the drought research community, and how problems and solutions come to be taken seriously by the policy community, resulting in the formation and adoption of public policy. The agenda setting lens of the policy process is a longitudinal perspective in that it considers change, over time, in ideas, problems, solutions, participants and institutions. It also considers the flow over time of multiple streams of activity: the problem stream (where problems are debated and defined), the policy stream (where policy solutions and alternatives are advocated), and the politics stream (where problems and solutions are debated at the level of political decision making) (Kingdon, 1995). These three streams may converge if given a window of opportunity. Policy windows may present themselves as focusing events such as: 1) a natural disaster (drought) that can be causally linked to climate change or variability, or 2) a political opportunity such as the annual appropriations cycle or national elections.

From an agenda setting perspective, we will be interested in several threads of inquiry. Problem and solution definition are primary concerns: How are the problems of drought in the South and Southwest defined and by whom? Within the drought policy and planning community problems and solutions may be defined significantly differently among hydrologic, ecologic, urban or agricultural drought interests. Agenda setting is concerned with institutional change, evolution, or creation within policy communities in reaction to the focusing events or ideas associated with drought policy and planning. We are therefore interested in the implications of new climate science on drought decision making institutions at multiple levels of government in our study area.

Within the agenda setting perspective, the definition of a problem and its strategic linkage to alternative solutions represents a critical component of the framework. Four questions are of particular significance: 1) how is drought defined by various stakeholders, what threshold points and triggering factors are linked to these definitions, and for what purposes; 2) what is the significance of the linkage between climate change/variability and drought in regard to policy making; 3) what are the policy implications from multiple problem definitions in regard to the different threshold and triggering factors; and, 4) what are the appropriate roles for the multiple agencies and institutions involved in drought observation and prediction, particularly at the regional level?

The definition of an issue as a problem is a central component of the agenda setting framework. There are four questions that are of particular significance in determining the role of drought information in this process:

1) How is drought defined by various stakeholders, what threshold points and triggering factors are linked to these definitions, and for what purposes?
2) What is the significance of the linkage between climate change/variability and drought in regard to policymaking?
3) What are the policy implications from multiple problem definitions in regard to the different threshold and triggering factors?
4) What are the appropriate roles for the multiple agencies and institutions involved in drought observation and prediction, particularly at the regional level?

Research Methods

To answer the above four questions and to determine the role of drought information in the agenda setting process we conducted open-ended interviews with individuals involved in drought management in two case study areas of Texas and New Mexico.

Interview Sample

The central research program was to develop an account of drought decision making among key decision makers in the drought policy network. We sought key informants who were involved in drought policy within the case study areas. Interviewees represent a wide range of policy actors at the federal, state, regional and local levels of the Texas and New Mexico drought regime. Some interviewees belong to organizations that are mandated to deal directly with drought while others belong to organizations that deal with drought in the context of other water, ecosystem, or public safety issues. Interview subjects from the state and federal levels were identified through the networks of policy actors established in Texas and New Mexico who are embedded in the drought regimes of these states. Approximately 54 interview subjects were selected to capture representative policy-actors in Texas and New Mexico.

In May 2003, New Mexico Governor Bill Richardson appointed a 12 member Governor's Drought Task Force consisting of representatives of key agencies in the state charged with reducing the vulnerability of the state to the consequences of drought. In May 1999, the legislation enabling The State of Texas Drought Preparedness Council, a similar institution composed of representatives from fifteen state agencies, was passed by the Texas State Legislature. These two intergovernmental institutions formed the basis for identifying key informants at the state level.

We also chose to focus on specific regions within each state in order to capture an array of drought scenarios. In Texas, we interviewed representative water managers and other actors from facilities located in the Travis County and City of Austin area, while in New Mexico we focused our local level interviews on water managers in the Curry County and City of Clovis area, located in eastern New Mexico. These regions are relatively arid with both urban and agricultural areas. We also interviewed members of regional water planning entities, state and federal land managers, and members of a local water stakeholder group in the relatively water rich counties of East Texas. By interviewing an array of water users and managers, we were able to understand drought from the perspective of actors from different geographic regions and at different policy levels.

Discussion Guide

We developed a discussion guide based on the four general questions outlined previously. These questions were developed in an open-ended format to elicit as wide a range of responses as possible.

Drought Definitions and Drought Thresholds

We constructed a series of open ended questions to obtain formal and informal definitions of drought from our interview subjects, and to examine the policy implications of drought threshold definitions. These questions included:

- What constitutes a drought for your organization and how does your organization determine when their area of responsibility is under drought conditions?
- Where does your organization spell out their definition of drought?
- What constitutes a drought for you personally and how do you know when you are in drought conditions?
- What tools or decision tools do you use to measure drought?
- How do you identify concomitant thresholds and triggering points for taking action?
- What information do you use and apply in making these decisions?

One of the key points of this study was to determine not only how drought information was being used by the drought policy network, but to examine the specific role of National Weather Service products. We led with the above questions, but if National Weather Service products were not mentioned explicitly by the interview subject, we asked directly about their applicability.

Climate Change and Climate Variability

A second set of questions was developed to determine how the interview subjects understood the relationship between climate change or climate variability and drought in the policy context. These questions included:

- Have droughts been increasing, decreasing or staying constant and why?
- How have the institutions you are familiar with changed or evolved over time in response to the availability and interpretation of climate science?
- To what extent do you predict and plan for climate induced drought and water shortages?

Agency Roles

We created a third set of questions to address agency and stakeholder roles. We were interested in descriptions of current agency behavior and interagency interactions, as well as the institutional roles that govern agency and interagency interactions. These questions included the following:

- What role does your organization/employer take in regard to drought issues? Where does your organization spell out these roles and responsibilities?
- What or who do you think should take responsibility for a drought?
- What should the roles of these responsible parties be in regards to drought?
- How do/should water resources be managed during a drought?
- During a drought, how would or should allocation between beneficial uses change?
- How does/should a drought alter the water management procedures?
- To what extent do local water managers work regionally to solve demand and supply fluctuations in water supply?
- Describe the mitigation and adaptation efforts your organization takes in regard to drought? Refer to the concepts of economic, technological and behavioral impacts.
- How successful are these efforts?
- How have drought mitigation and/or adaptation changed over time from your perspective?
- What does the drought policy and planning network look like, in general? And who do you interact with on a regular basis for drought decision making?
- What institutions at the sub-national and national levels are involved with making drought policy and decisions?
- How have these institutions changed or evolved over time in response to the availability and interpretation of climate science?
- Can you characterize your interactions with stakeholders in regards to drought issues?
- What is the best way to deal with multiple stakeholders on drought issues?
- To what extent do you collaborate with multiple stakeholders on drought related problems (probe for attitudes towards individual stakeholders and towards collaboration)?

All of the above questions were reviewed and approved by the Institutional Review Board-Human Subjects in Research, Texas A&M University.

Interview Methods and Coding Scheme

Interviews were digitally tape recorded, with the exception of one interview subject who preferred us to take handwritten notes. Approximately one-third of the interviews were conducted in a face-to-face setting. The remainder was conducted by telephone. Transcription of the interviews was performed by an off-site service. Following receipt of the transcripts they were quality checked for accuracy of transcription.

Coding Scheme

Our analysis of the interviews began by developing a coding schedule based on the suggestion by Ritchie and Spenser who argue that qualitative policy analysis can best be performed if some research questions are pre-formulated prior to analysis (Ritchie and Spencer 2002). Our ultimate aim was to answer the four questions that identify the role of drought information in the drought agenda setting process. We constructed the following series of questions to guide our reading of the transcripts and to help us identify responses that are pertinent to the four research questions outlined previously:

- How do managers use forecasting and trend information, especially National Weather Service products?
- How do water managers define drought?
- How are water managers' definitions of drought linked to distinct approaches to triggering or threshold management mechanisms?
- How do water managers prepare for water shortages of varying severity?
- How do water managers allocate between competing water demands in positions of abundance and scarcity?
- How do managers monitor local conditions?
- How do managers monitor consumer use?
- How do local managers coordinate with state, regional and federal agencies for expeditious responses to water shortages?
- How do water managers promote conservation efforts?
- How do focusing events serve as policy windows?
- To what extent does climate change impact perceptions of drought and the management of drought?

An initial pass through the interviews used the above questions to break the interviews up into thematically oriented pieces more analytically suited for analysis. These segments were then used to address the above four principal questions.

Analysis

The overall analytic schema addresses the four questions that determine the manner in which drought is defined as a problem in the case study areas. We first ask how drought is defined and we examine how drought definitions are interlinked with the roles of agencies and stakeholder groups. We then address the significance of climate change/variability and climate prediction models on drought policy. Following this, we examine the definition of threshold and triggering factors, and the policy implications that arise from multiple definitions of these factors. We conclude with a discussion of the varied uses of drought products linked to the institutional character of the drought regime in the case study areas.

Defining Drought

Although many consider drought to be a rare, random event, it is actually a normally recurring part of climate which occurs in virtually all regions. The most basic definition of drought is "a deficiency of precipitation over an extended period of time, usually a season or more" (National Drought Mitigation Center [NDMC], 2006). However, the interaction between decreased precipitation and increased demand, due to human development, means that drought can have far-reaching impacts on society.

There are two main kinds of drought definitions: conceptual and operational (Wilhite & Glantz, 1985). Generally speaking, conceptual definitions of drought help people understand the concept. The NDMC (2006) offers this example of a conceptual definition: "Drought is a protracted period of deficient precipitation resulting in extensive damage to crops, resulting in loss of yield." Operational definitions help to identify the beginning and end of a drought, as well as the degree of severity. In order to determine the onset of drought, an operational definition will specify the degree of departure from some climatic norm; this is typically average precipitation over some period of time. This is usually accomplished by comparing the current situation to the historical average. The threshold set for the beginning of drought is usually arbitrary, for example, an area may be considered to be in a drought when precipitation is 75% of normal over a specified time.

Wilhite and Glantz (1985) describe four types of drought: meteorological, hydrological, agricultural, and socio-economic. Meteorological drought is usually expressed as a departure in the amount of precipitation over a given period of time. Hydrological drought is usually expressed as a deficiency in surface or subsurface water supply. Agricultural drought is typically expressed in terms of soil moisture needed for a particular crop at a particular time. Socio-economic drought usually associates drought with the supply of, and demand for, a particular economic good.

Drought definitions tend to be strategic. They are based on the immediate origins of the water in question, the demands placed on that source of water, and the institutional framework in which an agency is situated. In our interviews, we identified several distinct means of defining drought. Some definitions, as we expected from Wilhite and Glantz, were focused on the source of water, especially the source of water relevant to the research subject's area of responsibility. For example, an individual involved in the management of water supplied by an aquifer supplied an operative drought definition that corresponded to Wilhite and Glantz's hydrological category, whereas a manager who largely serviced dry land farmers defined drought in purely meteorological terms. Employees of the USDA Farm Service Administration informed us that drought was to be defined specifically in terms of economic impact on agricultural production, although they returned frequently to the availability of water in the region, more specifically to the relative abundance of rainwater which ultimately determined economic impact.

We encountered drought definitions that did not precisely fit the Wilhite and Glantz typology. This included the drought of record which is a term used by those involved directly with water supplies that involve some kind of catchments or groundwater source. Agencies such as groundwater and river authorities, as well as those who rely on water basins for water supplies, use a drought of record as a planning benchmark. For example, the Bureau of Reclamation uses the drought of record to define firm yields in reservoirs. Our respondent at the Bureau of Reclamation defined the appropriate firm yield as the amount of water that could be delivered through a drought of record without emptying the reservoir.

Another drought category that is relevant to some water utilities is capacity drought. This category refers to water shortages that result from water demand outstripping the capacity of a utility's ability to treat or move sufficient raw water. This is not a drought by most measures of the word; however it is the functional equivalent of a drought from the perspective of an end user.

We discovered that some agencies do not have a formal definition of drought. For example, the Bureau of Reclamation works with state and federal agencies which define drought conditions for the Bureau. The Bureau then provides funding and planning assistance to the agencies that deal directly with the drought.

Other agencies do not define drought because they are principally involved in water conservation efforts. For example, agricultural extension supports a number of water conservation programs designed to mitigate demands on water resources and to adapt water users to limited water availability. Their conservation efforts and those of other conservation oriented institutions were described as operating continuously, regardless of whether or not the area they service is under drought conditions.

Institutions that do define drought do so either based on criteria supplied from outside, or based on criteria associated with their actual source and use of water. We defined the term definitional authority to characterize whether or not an agency has the authority to define drought conditions. Within each state, definitional authority resided with some, but not all of the agencies involved in the drought task forces. Ultimately, drought definitions were given their authority at the state level through the interagency institution of the drought task forces which are set up so that contributing agencies define particular aspects of drought. In a sense, the two state drought task forces are drought definition clearing houses where distinct sub-components of drought definitions are defined by the appropriate bureaucracies and ultimately integrated into an overarching drought definition and drought statement for official policy purposes.

A number of interviewees expressed awareness of climate change scenarios, but they were either completely or at least somewhat unconvinced by anthropogenic climate change arguments. Many of those interviewed for this study defined drought as being cyclical in character, specifically as part of long natural cycles. Some respondents suggested that it would be difficult to distinguish between droughts that were increasingly severe and frequent due to anthropogenic climate changes and similar patterns that were the result of natural cyclical climate patterns. Many of also expressed the belief that such distinctions were unimportant for matters of drought adaptation. The cause does not matter as much as the adaptive responses.

Climate Change and Climate Prediction Models

In order to determine any linkage between climate change/variability, and drought in regard to policy making we queried our research subjects as to the impact and role of new climate science and climate prediction models on policy. If the respondent did not mention climate change in their answer, we then prompted them to also consider the role of climate change on drought policy. We found that climate prediction models and beliefs about climate change had limited impact on the practical policy world of drought management.

Among the actors we interviewed, responses to questions about whether or not climate was changing in some appreciable manner varied greatly. The greatest degree of concern over climate change was in New Mexico where the Office of the State Engineer has begun to formally question the kinds of impacts that climate change may have on the statewide water supply. This state-level response was unique to New Mexico; in Texas, there was no statewide initiative to address this issue, although some of the Texan respondents expressed concern about possible climate change impacts on the state. In spite of the concern expressed by some of our interview subjects about climate change, the actors we interviewed were unlikely to use climate models.

Beliefs about climate change were closely tied to the use of climate models; however, the linkages between use of climate models and belief in climate change were complex. Those individuals who did not believe in climate change did not use climate models, although some individuals who did not believe in climate change found more temporally bounded weather predictions to be of some practical applicability to their managerial needs. Institutional actors who either believed the climate was growing warmer, or who thought this was a distinct possibility, were often of the opinion that climate models would be useful to the management of drought. Nevertheless, many of them did not use climate models for a variety of technical and institutional reasons.

The principle reason given for not using climate models and climate prediction was the specificity of their predictions. Current climate predictions were not refined enough in their specificity of spatial scale to provide the level of detail needed to incorporate into local decision making. Another issue with the use of climate models is temporal specificity. Global climate change models provide information about long-term trends at a time scale much greater than that needed by most water managers.

We did find some evidence from interviews, mostly in New Mexico, that concerns about climate change might be having an impact on drought policy. For example, some respondents stated that some policies, particularly regarding wastewater treatment and recycling, could be attributed to concern about climate change's impact on the water supply. In addition, respondents reported that rather than a belief in climate change having an effect on planning for future drought, current changes in climate had directly impacted policy. For example, one interviewee reported that changes in climate had resulted in increased severity and frequency of droughts leading to more frequent and more severe wildfires, which in turn prompted an increase in funding and responsibility for his agency.

Drought Thresholds and Triggers

Some institutions do not have formal or informal tipping points or thresholds related to the declaration of a drought. Institutions that are primarily oriented towards conservation or general planning do not use these kinds of tools. For example, an extension agent usually focuses on teaching conservation methods such as using drought tolerant landscape plants or monitoring sprinkler systems to prevent runoff. These are techniques they try to institute regardless of drought conditions.

Institutions that do use drought thresholds are often oriented towards the distribution or supply of water resources. These include agencies such as water utilities, irrigation districts, and aquifer and river authorities. Institutions that deal with the consequences of drought, such as the USDA-FSA, also employ drought thresholds. In addition, agencies that deal with fire control and utilities that respond to shortages with a variety of mitigation efforts also use drought thresholds.

A number of our interview subjects indicated that they not only used formal tools based on models, indices, or calculations to determine drought thresholds, but also a range of informal observations such as the state of forage, or whether saplings appear to look good. An example of this approach includes wildlife managers who assessed the impact of a drought on deer by "eyeballing" the condition of food and water resources. These assessments of drought conditions are not based on measurements but on experience in the field.

Use of Drought Information Products

One of our research questions was to ascertain how managers in our case study use forecasting and trend information, especially National Weather Service products. Examples of the narrative and graphical climate monitoring drought products issued by the National Weather Service include the Palmer Drought Severity Index, the U.S. Drought Monitor, Water Supply Outlooks, Daily River and Lake Summaries, Hydrometeorological Discussions, and River Recreation Statements. Other drought measurement tools which may be used include the U.S. Forest Service's Keetch-Byram Index Map and National Fuel Moisture Database. The general tactic in our interviews was to wait to hear if individuals actually mentioned any tools, specifically in the question about information sources. If they were not mentioned, then the interviewer probed for their use.

Drought and climate tools were most often used by decision making entities. These may be institutions that make drought declarations, such as a river authority, or that change some aspect of their behavior in response to drought conditions. An example of the latter would be an irrigation district which may rely on a tool such as the Keetch-Bryram Drought Index.

We did find evidence of product use for non-decision making purposes. These may be monitoring groups, who gather the data and pass it along to a decision making entity. For example, extension agents may not make decisions regarding distribution of water resources, but instead use drought products to develop information products that will be used for decision making purposes by farmers and others who rely on the extension agent as an interpretive resource. Some respondents reported using tools such as the Palmer Index for reference only. Others described such products as useful for communicating with the public. An example would be a groundwater manager who based decisions on stream flow and the level of well water, but used the Drought Monitor and other indices for background information on overall drought conditions in the region.

We found that institutions primarily involved in preventative or risk reduction measures, such as water conservation, had less use for drought products, since they are not in the business of predicting or declaring drought. Their relationship with drought is mainly to prepare for such conditions by encouraging implementation of conservation methods, or introducing new water delivery systems or water access technologies.

An analysis of our data suggests three primary reasons that tools such as the Palmer Index or Drought Monitor are not used by many of our interviewees – scale, usability and timing.

Interviewees in east Texas repeatedly stated that drought is local and that one part of the watershed can be in drought while the other is wet. Several interviewees felt that current tools are not fine-scaled enough. For example, the data manager for a large river authority stated that the maps produced by NWS illustrating the Palmer Index do not have a fine enough resolution to be useful to him because drought varies significantly within one region and within a watershed. He therefore produces his own maps using a finer scale and tries to attach the Palmer Indexes to those maps. It would help him if the NWS produced information in a GIS mode that was not "black boxed." He needed to be able to modify the information to suit his organization's specific needs.

Similar commentary was provided by the drought extension agent who raised the concern that NWS tools were of limited applicability at the scale necessary for agricultural decision making. He preferred a set of drought indices developed by the Texas A&M University Spatial Sciences Laboratory which are scaled to a finer level than NWS products.

A water manager in a rural area who deals primarily with ground water supplies commented that small towns and rural water suppliers do not have the expertise or IT capabilities to deal with data as it is now presented. Data needs to be more user-friendly and the NWS should consider creating new data products more specific to the needs of rural users. Unlike the manager from a larger River Authority who wanted a "tweakable" product, this interviewee stated that he does not have the time, IT ability or expertise to tweak an information product. He feels that NOAA should work with rural users to design a suite of off-the-shelf information products that would be useful in an array of situations and at the appropriate scale. He was interested in concise graphs of historical weather patterns, stating that the historical information is now too difficult to understand. He stated that smaller, rural entities are more likely to be caught off-guard in a drought situation because they do not have adequate predictive and monitoring capabilities.

Another rural water manager expressed concern with the lack of local expertise needed to analyze and effectively utilize state groundwater models.

Texas state law requires that environmental flows must be considered when granting new water rights. A member of a regional water planning group commented on the difficulty in reconciling the groundwater supplies, surface water supplies, and environmental flows because they are based in different hydrological models. Tools are needed to provide a good accounting of both types of water supplies with environmental flows in order to adequately plan for drought.

Timing was also an issue for one resource manager who commented that by the time that these tools indicate the presence of drought conditions, it is too late because conditions are "already getting to the extreme." Another concern was that some indices were not sensitive to conditions that were drier than normal but not yet a drought. He would like to see an index relating precipitation in a watershed to flow into an estuary.

Media and Congressional Attention to Drought

As a baseline for understanding where drought as an issue resides in the minds of the public, we conducted a thorough assessment of drought as it is represented in the news media. Using the LexisNexis online research database, we conducted a search for drought and drought related articles from major newspapers in our study areas of Texas and New Mexico. We also included the *New York Times* as a national indicator of drought salience over a 30-year period. The newspaper data were complemented by a similar search and analysis of drought issues in Congressional hearings over time. These data provide a comprehensive view of drought as a national and regional issue

Climatic Conditions and Salience of Drought in the News Media and Congress

It has been demonstrated in policy agenda literature that issue salience has significant impacts on policymaking processes and policy outputs, as well as public attitudes (Erbring et al., 1980; MacKuen, 1981, 1984; Iyengar & Kinder, 1987; Baumgartner & Jones, 1993; Kingdon, 1995; Gilliam & Iyengar, 2000; Soroka, 2002; McGraw & Ling, 2003; Liu, Vedlitz, & Alston, 2008). In this section, we briefly trace the salience of the issue of drought in the national news, in local newspapers in the Southwest region, and at the federal level. We also explore the relationship between the salience of drought in these policy/agenda venues and the actual climatic conditions. Our findings indicate that the salience of the drought issue in the news media and governmental venues is sporadic and cyclical, with a seasonal characteristic in the regional news coverage; in addition, attention to drought is driven to some extent by actual climatic conditions.

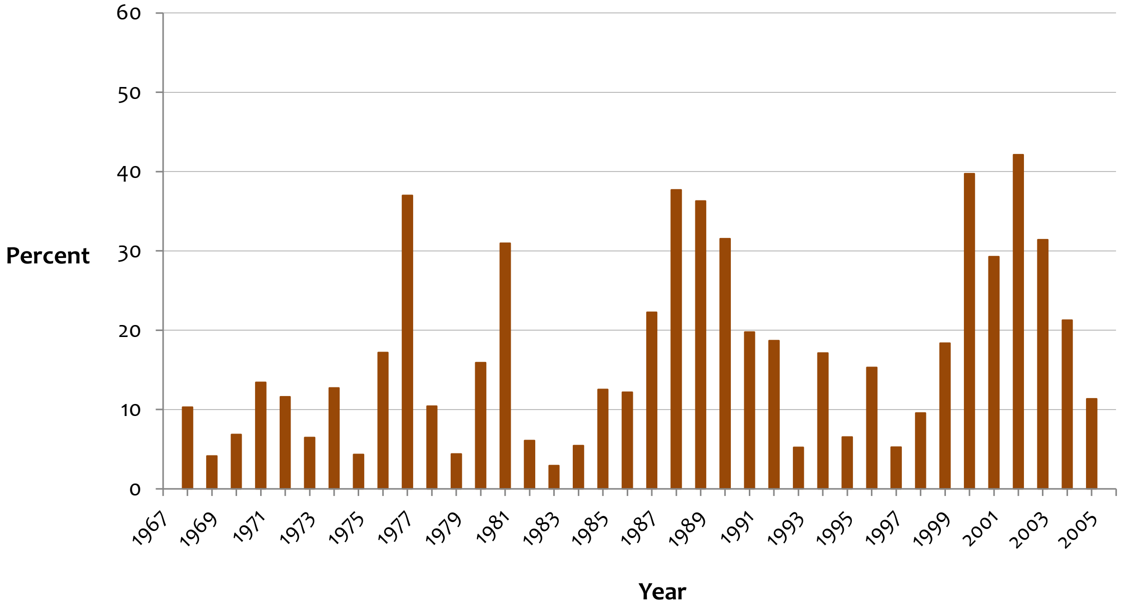
U.S. Drought Indicator and Issue Salience in National Media and Congress

One of the primary sources of the salience of a particular issue in the news media and on policy agendas is the objective indicators or conditions surrounding the issue (Baumgartner & Jones, 1993; Kingdon, 1995; Soroka, 2002). Before examining the salience of drought in national media and congressional agendas, we first traced the overall drought conditions in the United States from 1968 through 2005. During our research, three sources were identified for our data collections in this section: the National Climatic Data Center of NOAA for data on national drought conditions, the Vanderbilt Television News Archive for collecting data on national media's attention to drought, and the LexisNexis Congressional Publications for congressional hearings on drought. Since the Vanderbilt Television News Archive only included TV newscasts beginning in 1968, we restricted our data collection for all three data series shown in this section to the same time period.

Earlier in this report, we presented some drought statistics for our region of study. However, the news media and Congress take a much broader view and so we will include here some information on national drought conditions. In Figure 17, we used data from the National Climatic Data Center to graph drought conditions in the United States from 1968 to 2005. The bar graph represents the percent area of the United States in moderately to extremely dry conditions in each of these years. The average percent of the country affected by drought has generally increased in each of the last four decades: 12.45% in the 1970s, 18.23% in the 1980s, 14.74% in the 1990s, to 29.20% in the first six years of the 2000s.

With increased population and water consumption as well as the impacts of climate change, droughts, which are caused by various natural forces and human activities, have imposed great social, economic and environmental challenges to the United States. How much attention have the federal government and national news media paid to drought and water scarcity over the last several decades? Has the salience of the drought issue in the news media and policy venues evolved over time, responding to the changing drought conditions?

Figure 17. U.S. Drought Conditions: 1968-2005



To answer these questions, the Vanderbilt Television News Archive was used to retrieve the evening news stories on drought from five major television networks (ABC, CBS, CNN, FOX, and NBC), and the LexisNexis Congressional search tool was used to search all the congressional hearings on drought, water scarcity, and water shortage. As noted earlier, since the Vanderbilt data only went back to 1968, we used this as the starting point for all our data series; collecting data from 1968 through 2005. For the 38-year time span, 1,261 TV news stories and 60 congressional hearings were retrieved from these two sources. To trace how the salience of the drought issue has changed in the national news media and congress, we computed the annual number of drought news stories and annual number of congressional hearings and graphed the two data series in Figure 18 and Figure 19, respectively.

Both Figures 18 and 19 show that the salience of drought ebbs and flows in the media and governmental agendas over time, and the two times series seem to generally match each other (Pearson's correlation = .53, p<0.01). More importantly, when the two series are compared to the drought condition data shown in Figure 17, it appears that the ups and downs of the annual number of news stories as well as the annual number of congressional hearings generally correspond to the varying levels of drought severity over the 38-year time span under study. Bivariate correlation analysis reveals a strong positive relationship between the drought condition and news coverage (Pearson's correlation=.60, p<.01, n=38) and between the drought condition and congressional hearings (Pearson's correlation=.39, p<.05, n=38), suggesting that both the national newscasts and Congress have been monitoring drought-related problems and have been paying attention to the changing drought conditions in the last several decades.

Figure 18. Drought Coverage on TV Network News: 1968-2005

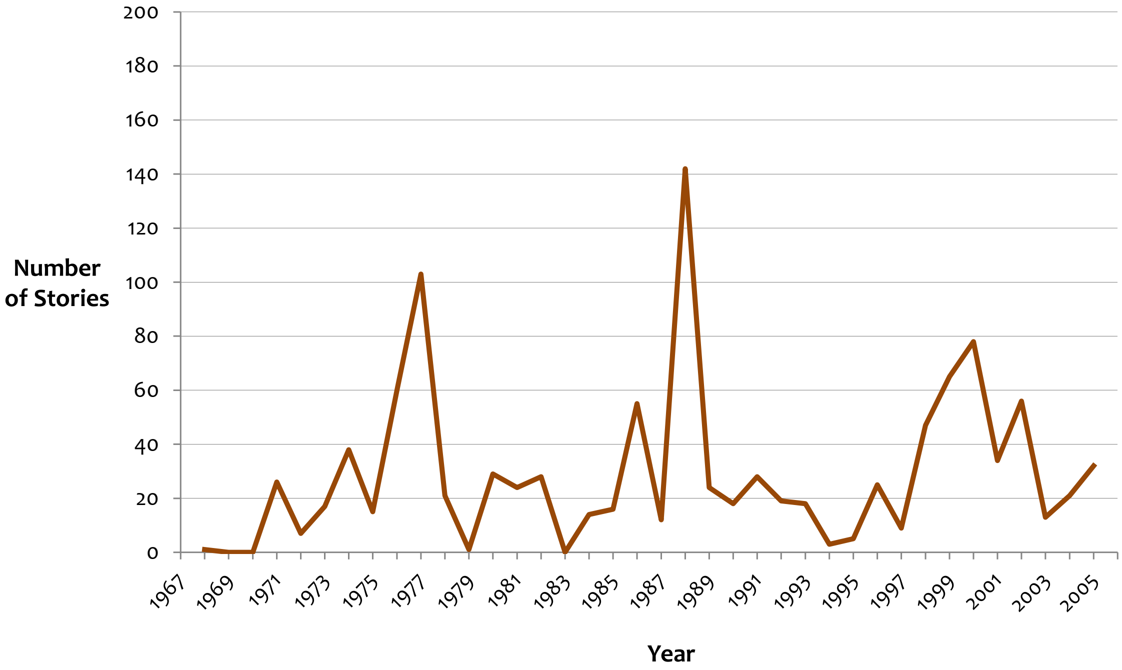
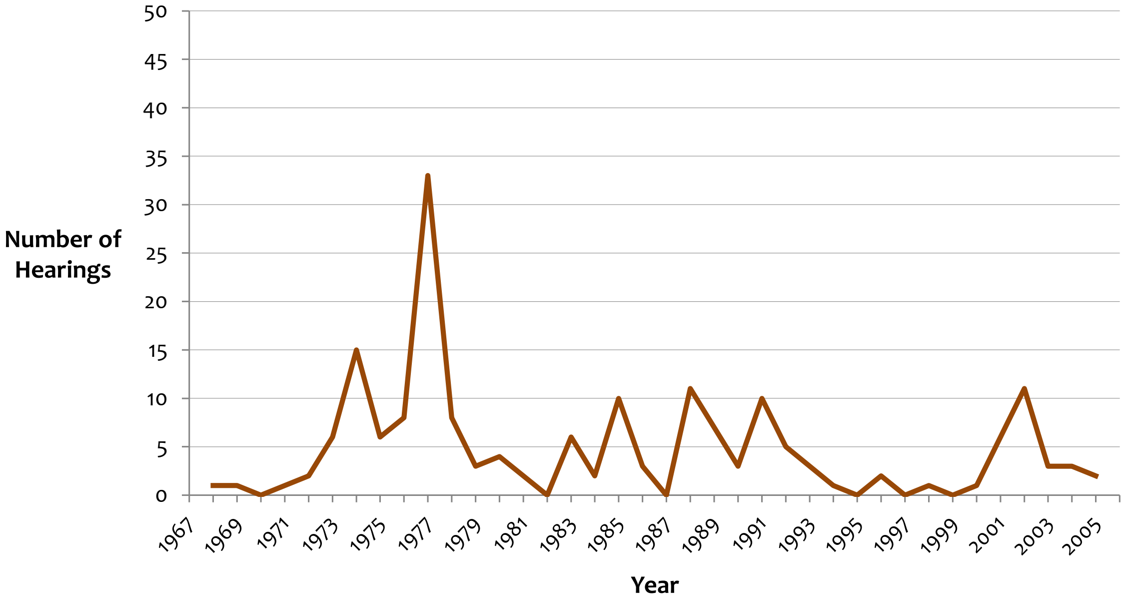


Figure 19. Congressional Attention to Drought: 1968-2005



However, it is worth noting that the salience of drought seems to have relatively weakened in recent years. While the data series in Figure 17 shows more frequent and severe droughts in the early 2000s, this is not matched by the news media coverage and congressional activity during this period. In comparison to the intense levels of media and congressional interest during the 1977 drought, both the numbers of media stories and congressional hearings in the early 2000s have declined relative to the rate of drought in the country.

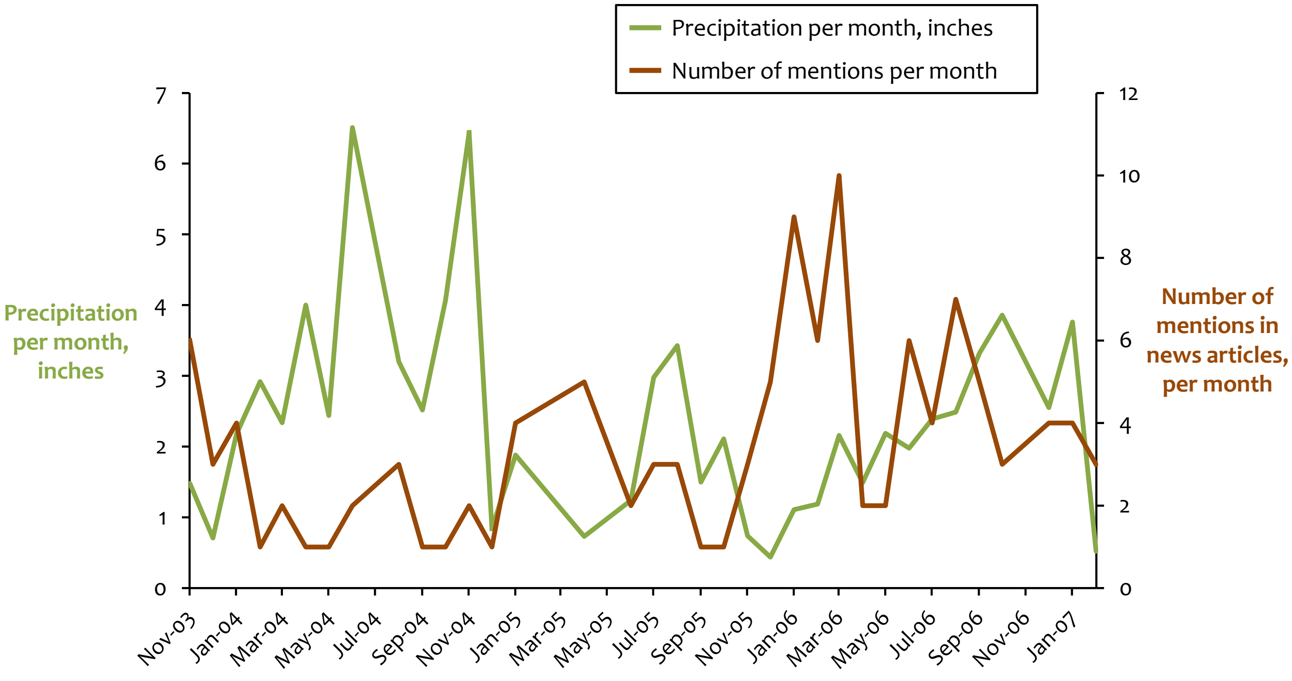
Salience of Drought in Local Newspaper and Regional Climate Conditions

At the regional level, we are also interested in how local news media in the Southwest regularly cover drought. The LexisNexis online newspaper archive was used to search for local newspaper coverage on "drought" (the key search term). Based on archival availability in LexisNexis, searches for drought articles were limited to one local newspaper – the *Austin American Statesman*, which is the newspaper of record in the Travis County/Austin area of Texas, and the coverage period ranged from November 2003 through February 2007. This corresponds to the most recent period of dry/wet cycle in the state.

Guided by the codebook developed by the research team, two well-trained coders independently reviewed and coded all the articles retrieved from LexisNexis. Since in the vernacular, the term "drought" can refer to various forms of dearth, irrelevant articles were excluded (for example, those referring to drought of victories for the local high school football team). We achieved a final dataset of 120 articles on drought. Formal inter-coder reliability tests showed good consistency between the coders with an overall average agreement rate of 0.96.

As drought is a perennial issue that we expected to shift in importance throughout the year, we chose to measure the salience of drought in the local newspaper by the number of articles on drought each month. The dotted line in Figure 20 shows the *Austin American Statesman*'s attention to drought during the period from November 2003 through February 2007. At the monthly scale, it demonstrates a seasonal pattern to the issue salience. Note that all the attention spikes in the graph occurred during either the winter or summer season, while the newspaper paid much less attention to drought during either spring or fall – times when there was typically more precipitation in the area.

Figure 20. Monthly Precipitation and Local Media Attention to Drought



As shown earlier in this section, the salience of drought as an issue in both the national media spotlight and U.S. Congress was in part driven by the actual nation-wide drought conditions. Was the local media's attention also tied to the actual climatic conditions in the region?

To explore this question we constructed a variable for monthly precipitation in the Austin, Texas region. This measurement – the monthly mean precipitation for Texas measured in inches – was derived from the *Climate at a Glance* data available from NOAA's National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html). This data series is graphed as the green line in Figure 20. Comparing the two data series, we see that the brown line – the monthly number of drought articles in the *Austin American Statesman* – approaches a mirror image of the monthly precipitation data. To determine the extent to which this visual comparison represents an actual relationship, we ran a correlation analysis between these two variables. The Pearson's correlation is (-).29 with a significance of 0.001, indicating that the less it rained, the more attention was paid to drought by the *Austin American Statesman*.

Economic Analysis of Drought: Risk and Ambiguity

Water management is a critical policy issue facing the American Southwest and Southeast. Demand for water continues to grow with growth in the economy, with the increased urbanization of population which has accompanied growth adding particular pressure to demand. In addition to increased municipal and industrial water demands, natural/environmental-based demands for water have found greater voice. The scope for supply responses to meet the expansion in demand appears to be quite limited. Viable water projects to establish new water supplies, such as building additional dams or reservoirs, are hard to come by. The value of water is rising with its scarcity. Against this backdrop of standard economic demand and supply fundamentals, we now add the potential impact of climate change.

The growing body of research and ongoing debate concerning climate change impacts beliefs about the current and future shape of the probability distribution for weather events, particularly for extreme events such as drought. The impacts can show up both in changes in the mean estimates of the event probabilities and in the variance in the estimated probability distributions. The decision problems for economic agents with returns that are highly weather sensitive are affected by the updated climate information. If the true probability of extreme events is increased, the decision environment becomes riskier. If the dispersion in estimates of the true probability distribution over weather events increases, the decision environment becomes less certain or more ambiguous. Models of the impact of changes in the climate information environment on agent decision-making should account for both of these information effects.

Agents have a variety of actions that they can take to manage drought risk. As one option, they can self-insure. For example, farmers can vary their choice of crop, vary aspects of their crop technology, or increase their holdings of water rights. As a second approach, they may be able to purchase crop insurance contracts. These contracts are offered by private carriers in the U.S., and are subsidized by the government. A third possible avenue is financial market hedging instruments. This third risk management tool is the subject of considerable current attention, and our research will consider the merits of newer capital market instruments as drought management tools.

With typical risk sharing arrangements, the optimal sharing of risk depends on the risk attitudes of the participants. The more risk averse a party is, the more that party is willing to pay to reduce risk and the more that party must be compensated to take on additional risk. The typical insurance arrangement involves a large, diversified, and therefore risk neutral insurer paired with a risk averse party facing risk. Because of its risk neutrality, the insurance company is willing to take on additional risk for less compensation than the risk averse party is willing to pay, and full exploitation of these gains from trade prescribe the risk averse party buying full insurance, that is, buying a policy that fully covers its potential losses.

The above argument relies on two assumptions about the seller side of the market. One is that the seller is risk neutral. The other is that the seller is able to compute actuarially fair values. On the demand side of the market, the assumption is that the agents have a well-defined willingness to pay based upon a well-defined belief as to the probability distribution over gains and losses that she faces. More problematic, and more germane to the weather event distribution that is the focus of this research project, is what happens when the probability distribution of the risk variable is not well-defined. One implication of climate change is that past data can only imperfectly (or more imperfectly, perhaps) inform parties about their exposure to weather risk.

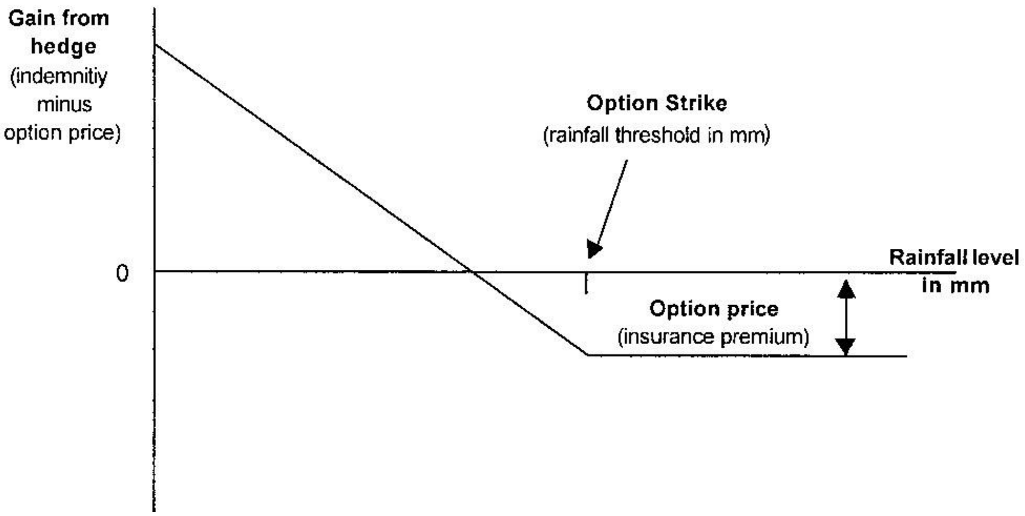
Economists and psychologists describe a setting in which decision makers do not know the probability distribution over payoffs as a situation of ambiguity, and decision makers are typically averse to ambiguity. This is a major point of departure in our research on economic behavior in an environment of changing information about the likelihood of drought events.

In our research on this project, we considered three different, but related questions about economic behaviors with respect to drought risk management in the presence of both risk and ambiguity in regard to extreme weather events. First, we identified some features of weather derivatives relative to crop insurance as instruments for managing drought risk within a traditional risk analysis setting. Second, we approached the viability of weather derivative markets in an environment of both risk and ambiguity averse agents. Third, we considered issues in the economic valuation of climatic information under ambiguity.

Weather Derivatives or Insurance: A Risk Analysis

Weather derivatives are contracts that specify payments from the seller to the buyer based on the value of an index of weather variables (Jewson & Brix, 2005; Vedenov & Barnett, 2004). For example, the contract designed to protect the buyer from losses caused by drought would specify payments based on amounts of rainfall, with lower precipitation levels leading to higher payments. While these derivatives are openly traded, they can still be thought of as risk sharing arrangements, with the seller sharing some or all of the risk faced by the buyer. A simple structure for a put option contract is shown in Figure 21. The option would pay out if cumulative rainfall is below a strike value, Z. Here the payout is proportional to the number of inches the rainfall is in the money, i.e. is increasing in the severity of the drought. This particular weather derivative design was used in a World Bank project in Morocco (Stoppa & Hess, 2003).

Figure 21. Payoff Structure for a European Put Option on Rainfall



Source: Stoppa & Hess (2003)/Turvey (2001, modified)

We constructed a model which allows farms to protect against adverse weather conditions by taking a costly action, and also to insure through either traditional insurance or financial instruments, specifically weather derivatives. To distinguish the self-protective activity from insurance, we construct the model so that engaging in the activity makes adverse consequences from weather events less likely, rather than making adverse consequences less severe.

We find two key differences between insurance and weather derivatives. First, full coverage through traditional insurance completely removes weather-related risk, but full coverage through weather derivatives does not. Second, and because of this continued risk, crop insurance provides less incentive to engage in the self-protective activity than weather derivatives do, and these incentive effects, until now unexplored in the literature, provide an additional reason for encouraging insurance through financial instruments.

The size of the tradeoff between insurance coverage and moral hazard associated with the either or choice environment will depend upon the nature of the risk and upon the risk preferences of the farmers. Simulation analysis for particular risks and for particular specifications of risk preference functions would provide useful insights into the comparative advantages of weather derivatives and crop insurance as drought risk management instruments.

In our analysis, weather derivatives and crop insurance were "either/or" choices. Since we find that weather derivatives score higher on moral hazard mitigation, but crop insurance scores higher on insurance protection, an optimal risk management approach involve a combination of the two instruments. This is an important topic for future research.

Modeling Ambiguity

Our research is grounded in the models of ambiguity preferences developed by Gilboa (1987), Neilson (1993), and Klibanoff, Marinacci, and Mukerji (2005). Let X be a set of outcomes of a random variable, and let $p(x)$ be the probability that x occurs. The decision maker chooses action a from the set A. When the decision maker chooses a and the realization of the random variable is x, the decision maker's monetary payoff is $\pi(x,a)$. In a world without ambiguity the decision maker chooses a to solve the problem:

$$\max_{a\in A}\sum_{x\in X} p(x)u(\pi(x,a)), \tag{1}$$

where $u(\cdot)$ is the decision maker's utility function. The curvature of the utility function reflects risk attitudes, with a more concave utility function corresponding to a more risk averse decision maker.

To see the intuition behind the maximization program, suppose that x is the amount of rainfall, so that $p(x)$ is the probability of receiving x inches of rain. A farmer can take a costly action a that affects his payoff under drought conditions, so that the choice of a affects the monetary payoff in two ways, by mitigating the effects of low rainfall and through the direct cost of implementing the action. The farmer computes the expected utility of every action in the set A and then chooses the action that generates the highest expected utility.

In situations of ambiguity the decision maker does not know the probability distribution $p(x)$. Following Gilboa (1987), Neilson (1993), and Klibanoff, Marinacci, and Mukerji (2005), the decision maker possesses a set P of potential probability distributions, with $P = \{p_1,\ldots, p_n\}$, where $p_i(x)$ is the probability that distribution p_i assigns to the outcome x. In Gilboa's model, the decision maker chooses a to solve the problem

$$\max_{a\in A}\min_{p_i\in P}\sum_{x\in X} p_i(x)u(\pi(x,a)). \tag{2}$$

Here the decision maker does not know the true probability distribution, so evaluates each action according to the worst possible probability distribution for that action, where "worst possible" means the distribution that generates the lowest expected utility for that action. The decision maker then chooses the action that generates the highest worst-possible expected utility. Because the decision maker chooses the maximal minimum expected utility, Gilboa's model is referred to as the maxmin expected utility model.

Neilson (1993) and Klibanoff, Marinacci, and Mukerji (2005) impose additional structure on the model to get less pessimistic behavior. They propose that decision makers formulate a subjective probability distribution q that assigns probability q_i to each probability distribution p_i in P. The decision maker then chooses a to solve the problem

$$\max_{a\in A}\sum_{i=1}^{n} q_i v\left(\sum_{x\in X} p_i(x)u(\pi(x,a))\right), \tag{3}$$

where v is a second utility function. The curvature of v reflects the decision maker's degree of ambiguity aversion, with more ambiguity averse decision makers having more concave v functions.

In this model the decision maker computes the expected utility for every risk in the set P using the utility function u to capture risk preferences. He or she then computes a subjective expected utility of these utility values using q as the probability distribution and v to capture ambiguity values. Because the decision maker bases choices on the subjective expected utility of expected utility values, Neilson (1993) calls this the SEU^2 model.

Note that the maxmin expected utility and SEU^2 coincide when the subjective probability distribution q assigns probability one to the probability distribution that yields the lowest expected utility. Thus, maxmin expected utility is an extremely pessimistic version of SEU^2, as the former places all of the weight on the worst possible probability distribution while the latter places weight on other probability distributions as well. Also, SEU^2 is consistent with ambiguity neutrality when $q_i = 1/n$ for all i and the function v is linear.

Ambiguity Aversion and the Market for Weather Derivatives

When ambiguity aversion is modeled using Gilboa and Schmeidler's model above, sellers are risk neutral but ambiguity averse, and buyers (farmers) are risk averse and ambiguity averse, financial markets are competitive on the seller's side, and buyers purchase fully-covering weather derivatives. Consequently, buyers are able to hedge fully against both risk and ambiguity. Essentially, with weather derivatives sellers do poorly in climate states in which the weather is bad, but so do farmers because the adverse weather causes their profits from agricultural activities to fall. So, in weather derivative markets the states of nature are aligned for the two parties, and mutually beneficial trade can occur.

This is an encouraging result for the scope of weather derivatives as an alternative to traditional crop insurance. Climate change may well make weather event probabilities more ambiguous, but this does not preclude weather derivatives markets from operating, and doing so efficiently.

Whether or not these results carry over to the case of SEU^2 model of ambiguity aversion is a subject for future research.

Ambiguity and the Value of Climate Change Information

To economists, the value of information is measured by what individuals are willing to pay for the information. A very nice discussion of the value of information in an earth science information context is found in a recent *Resources for the Future* discussion paper by Macauley (2005). As she notes, information has the most value when decision makers operate in a highly uncertain environment and when they have available a set of actions they can take to best respond to the uncertainty. Information allows the farmer to update or revise her assessment of the probability of weather events. In the extreme, the information might replace uncertainty about the rainfall for the season with certainty—a perfect forecast. Having such forecast information would definitely be interesting to the farmer, but it only has economic value if she can and will make different management choices with the information than without. The number and type of actions available for managing weather risks, and thus available for revision in the face of new information about weather risks, are thus critical to the potential value of information generated from new climate research.

In the traditional value of information approach as summarized in Macauley, the value of the information is grounded in the decision maker's ability to obtain new information about the probabilities associated with the true probability distribution over weather events. The point of departure in our research has been to identify a second source of uncertainty---ambiguity as to the true probability distribution. With this second source of uncertainty, there is a second type of information. If climate research were to reduce the dispersion in the estimates of the probability of drought conditions, with the attendant probability distribution over rainfall levels, this could reduce ambiguity. Such information would also have an economic value.

In the context of the weather derivatives market model discussed above, improved climate forecasting, interpreted as a narrowing of the set of priors over the distribution of weather event probability distributions, can reduce the price of weather derivatives, making hedgers such as farmers better off. The price effect provides the basis for generating monetary measures of the value of the climate information that generates the price change.

More generally, a willingness to pay measure of the value of information that reduces ambiguity can be determined as that amount of certain payment that makes the expected utility with the information about the distribution of rainfall distributions equal to the expected utility without that information. This is the same basic concept of willingness to pay that is commonly used to value updated information about the probabilities for events in cases where there is a single relevant probability distribution over events.

We can demonstrate the potential application of the willingness to pay concept for valuing ambiguity related information within our framework by adapting the classic Quirk (1976) information problem that Macauley uses to illustrate the standard value of information approach. Suppose a farmer can either fertilize or not fertilize his crop. Fertilizing is a costly activity. Assume that there are two potential weather outcomes, low or high rainfall. If rainfall is high, fertilization increases the crop harvest relative to no fertilization. If rainfall is low, the crop harvest is not affected by fertilization. The net profits associated with each of the four possible action/rainfall combinations in this scenario are shown in the payoff matrix in Table 12. Assume that the farmer is aware of three different estimates of the rainfall probability distribution. One expert assesses the probabilities of (low rainfall, high rainfall) as being (3/4, 1/4), a situation that we might refer to as the drought prediction. The second expert assesses the probabilities as being (2/3, 1/3), and the third expert predicts (1/4, 3/4). Suppose the farmer believes that the probability that the first pessimistic or drought state probability distribution forecast is correct is 1/6, that the intermediate forecast is correct is with probability 1/3, and that the probability is 1/2 that the most optimistic probability distribution is correct. For simplicity, we will assume that the farmer is risk neutral, but ambiguity averse, with a v function of the form v= $\{ \cdot \}^{1/2}$. Under these assumptions, if the farmer maximizes his subjective expected utility of expected utility values (the SEU^2 model of equation (3) above), he will choose to fertilize and his expected utility will be 174.5 (as opposed to 164.7 if he doesn't fertilize).

Table 12. Fertilization Payoff Matrix

	High Rainfall	Low Rainfall
Fertilize	$50,000	$10,000
Don't Fertilize	$30,000	$20,000

Now assume that new climate research can pin down with certainty which of the three probability distributions is the correct one. A priori the farmer expects the research to determine that the drought state probability distribution is the correct distribution with probability of 1/6, that the intermediate distribution is correct with probability 1/3, and that the chance that the optimistic distribution is correct is 1/2. Armed with the perfect information with respect to the correct probability distribution over rainfall, the farmer will choose not to fertilize if the drought state is revealed as correct, and will choose to fertilize under the other two realizations. The ability to tailor his fertilization decision to the rainfall state, and thus increase his returns in the drought situation by altering his actions, is valuable. In this case, he would be willing to pay $492 for the new information about rainfall distributions.

The value of the information depends upon: (1) the farmer's prior beliefs about the probability that each expert's prediction of the relevant rainfall probability distribution is correct; (2) differences in the rainfall probabilities across the expert's predictions; (3) the distribution of payoffs across the payoff matrix; (4) the risk preferences of the farmer; and (5) the ambiguity aversion preferences of the farmer. For example, in the above scenario, if the farmer believed that each of the three probability distributions were equally likely to be correct, then his willingness to pay for perfect information as to the correct distribution would increase to $934.

Conclusion

Our research contributes to the development of appropriate policy strategies for dealing with extreme climate events, such as drought. In particular, we have (a) identified some fundamental issues with respect to weather derivatives as a potential instrument for weather risk management (b) identified ambiguity as a fundamental modeling issue in modeling weather risk management behavior and (c) introduced a preliminary framework for valuing reductions in the dispersion of estimates of the probability distribution over weather events. The results are all preliminary in nature, but they provide a meaningful potential starting point for future discussion and for future basic research activity. The role of accurate information in assessing decision options is crucial.

Summary & Conclusions

Citizens and decision makers in the U.S. Southern Region states of Texas and New Mexico are aware of, and are concerned about, drought in their region. They have lived with water scarcity and expect it to get worse in the coming years. They are concerned about both water availability and distribution, and realize that a scarcer resource will create greater levels of competition among the array of users.

Information about drought presence and severity is almost certainly a major factor in framing, not only this awareness and concern, but potential solutions as well. Scholars have been looking more closely at the role of scientific and technical information in framing attitudes and policy choices on problems like climate change (see, for example, Kellstedt, Zahran, &Vedlitz, 2008; Malka, Krosnick, & Langer, 2009; Sabatier, Focht, Lubell, Trachtenberg, Vedlitz, & Matlock, 2005; Wood & Vedlitz, 2007)

Stakeholders in Texas and New Mexico differ in their sources of, and trust in, drought-related information. The public gets most of its drought-related information from the media and uses it to understand their environment and to assess likely stressors over both the short and long terms. Water managers get most of their information directly from the National Weather Service (NWS) and use it to gauge short-term and long-term problems and to frame planning and policy solutions. Everyone relates drought to quality of life issues and economic performance.

The National Weather Service plays a key role in providing the information environment within which drought awareness and decision making will take place. NWS provides, either directly or indirectly, the bulk of information utilized in drought awareness and decision making. The impact of NWS information is illustrated in Table 13.

Table 13. Mean Levels of Concern about Drought by Respondents' Assessment of National Weather Service Information

Levels of Concern about Drought	Mean Values of Concern		
		Useful/Very Useful	Not Useful/Somewhat Useful
General Public	National Weather Service	7.48	6.23
Water Managers	NWS Product-Drought Outlook	6.81	6.19
	NWS Product-Drought Indices	7.16	6.07
	NWS Products-Drought Monitor	6.96	5.97

For those in the public sample who thought the NWS products were useful, mean level of concern for drought is substantially higher than it is for those who did not find the NWS information useful. The distinction for water managers is even stronger. Here we look at levels of concern by the perceived usefulness of specific NWS products. Across the board, when water managers valued the NWS products, their mean scores on drought concern were substantially higher than those who did not value the NWS products. Whether those who are concerned are seeking more NWS information or whether those who use more NWS information become more concerned, it is clear that NWS information is an important framing factor in drought severity and policy discussions.

NWS materials, maps, indexes and forecasts are provided to local, regional and national media and are used as a principal source of stories and programs on the drought issue. These are filtered and managed by the press, and the NWS does not have control over their final form as it reaches the news consuming public. The public clearly appreciates and values the role the NWS plays in helping provide them this information.

The NWS also provides this information, and much more detailed products, directly to water managers. Our study indicates that water managers depend heavily on this information and use it consistently. However, we also identified that, especially at the local scale, managers would like more refined and locally detailed maps, forecasts, and past trends to help them.

This report shows that the role of NWS in providing drought-related information is significant and important. We do believe that NWS may have some avenues to pursue that could even make this role stronger and more relevant. For the public, it may be helpful and fruitful for the NWS to work closely with media organizations to design and produce products more visually oriented and user friendly to the public. Since the public depends so heavily on the media, the NWS has a ready audience for exercising a greater information and education role with the public through these new media-focused products.

For the water managers, it is clear that they would like to have forecasts and historical information more detailed and scaled to their local jurisdiction. The NWS and NOAA are clearly working to provide these more specific locally-focused products and, when ready for deployment, it is clear that local water managers will use them. Once they are deployed, it would be useful for NWS to monitor their utilization and effectiveness.

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Appendix A

Drought over the Past Century in Texas and New Mexico

Reducing Inhomogeneities in Long-Term Climate Records via Statistical Methods to Study Drought

Douglas Brent McRoberts

Drought over the Past Century in Texas and New Mexico

1. Introduction

The availability of water is a significant issue that will continue to grow in importance as both the public and private sectors have an increased demand for water. This growing demand will put stress on policy makers to make critical decisions for the allocation of water, especially when water resources are scarce. However, it is important to recognize patterns of precipitation that precede dry periods so that allotment and rationing of water resources can take place before the onset of droughts. Also, droughts can differ in severity and duration and it is important to know which areas are the most susceptible to the longest-lasting and most severe droughts. Therefore, it is important to study past droughts and learn from the precipitation patterns so that dry spells in the future can be accurately predicted.

Because New Mexico and Texas have a wide range of precipitation patterns and characteristics it is important to study precipitation in the 20th century using as many stations as possible. Of particular importance to drought are the extremes of precipitation distributions so each station needs a complete long-term dataset in order to accurately distinguish these extreme periods. For that reason, this research created datasets by using actual precipitation data and an interpolation process to fill in missing data within station records. The creation of datasets allowed for study of precipitation trends and drought in New Mexico and Texas over the entire 20th century.

The foundation of long-term climate studies in the United States is the National Weather Service Cooperative Observer Program (COOP) network (NCDC 2006), a spatially dense network of stations. However, the majority of stations in the COOP network do not have precipitation data throughout the entirety of the 20th century. A subset of the COOP data is the United States Historical Climate Network (USHCN) data set (Peterson et al. 1998), which contains only long-term stations with continuous precipitation records. This network has poor spatial coverage across Texas and New Mexico though, with only 24 stations in New Mexico and 44 in Texas.

The methodology of this project sought to find a process which best used the USHCN stations to interpolate the missing data for the COOP stations to create a spatially dense network of long-term stations. After an extensive literature review, the interpolation method chosen was the Inverse Weighting of the Square Difference method of Sun and Peterson (2005). The USHCN stations used in the interpolation process were 221 stations in New Mexico, Texas, and the surrounding states of Arizona, Arkansas, Colorado, Louisiana, Oklahoma, and Utah. This method is discussed in great detail in Section A of the supporting materials (at the end of this report), including modifications to the process that better suit the interests of this project.

Creation of a thorough quality-control check of the COOP data was necessary to ensure that rogue values did not disrupt the interpolation process of the several analyses related to drought that followed. Also, tests on the interpolated data found that the interpolation process created precipitation values with artificially low variances. This was adjusted for with the creation of a third time series, in addition to an actual time series and interpolated time series of values. At each station, the time series of interpolated values was transformed into a time series with an overall variance more characteristic of nearby long-term USHCN stations. This process is described in great detail in supporting materials section B. For each COOP station in this study, the time series of precipitation values includes actual precipitation data when available and variance-adjustment interpolated data otherwise.

Section I documents the precipitation trends in New Mexico and Texas throughout the 20th century, while Section II analyzes drought using the non parametric Mann-Whitney U statistic and resulting Z values. The Mann-Whitney statistics are described in further detail in Section C of the supporting materials. Though three separate time series of values exist at each station, all the datasets used to study precipitation trends and drought use actual data when available. The description of each dataset refers to the particular methodology used to create values when actual data at a particular station is not available.

Another characteristic of the COOP interpolated data used to fill the precipitation records of COOP stations is that the interpolations were done using only USHCN stations deemed homogeneous. A metadata study of USHCN stations summarizing the search for homogeneous stations is located in supporting materials section D, and was limited to Texas and New Mexico USHCN stations.

Additionally, analyses were conducted on the USHCN data itself. However, the analysis of the USHCN data was limited to the actual data unless a particular figure mentions otherwise.

Before going into further details of the analyses, it is important to describe the organization of the COOP datasets. The COOP data are subdivided into climate divisions, regions determined where climate or agriculture can be considered relatively uniform (Guttman and Quayle 1996). This study further grouped these climate divisions into three climate regions, namely New Mexico, East Texas, and West Texas (Fig. 1.1).

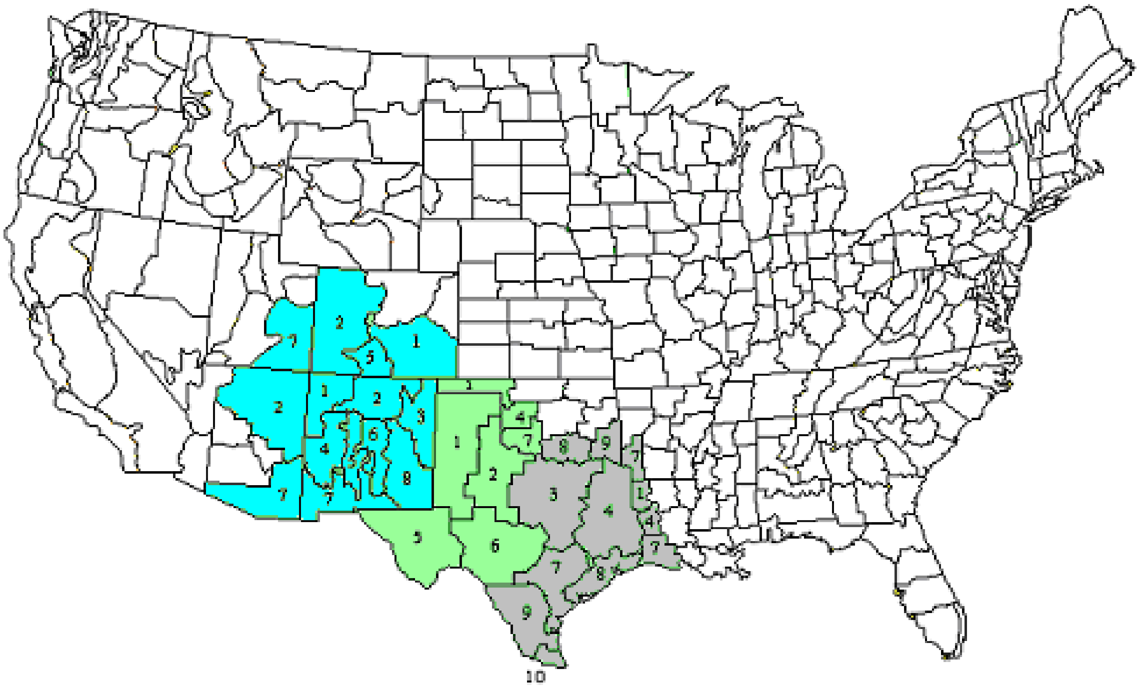


FIG A1.1. United States climate division map with divisions of interest shaded and numbered. The blue shaded climate divisions represent the New Mexico region, the green represent the West Texas region, and the gray represent the East Texas region in this study.

Climate division averages were created for each month through the 20th century using the available data at each station. For each month within a climate division, either the actual or variance-adjusted interpolated value was used at each station to create a monthly average. The analyses of precipitation trends and drought are based on running 12-month climate division averages. The three climate region averages are further averages of the climate division-averaged data. The precipitation data are organized into climate divisions and climate regions to condense the COOP data for analyses.

The homogeneous USHCN stations used in the interpolation process of the COOP dataset are those located in New Mexico and Texas. This data will be denoted by the abbreviation *CqY* and analyzes the variance-adjusted time series at stations using only the homogeneous interpolated data. It must be emphasized that an interpolated dataset refers strictly to the filling process of missing data and that each dataset uses actual monthly and 12-month running precipitation totals when available.

Analysis of strictly actual data from the long-term USHCN stations is denoted by the abbreviation *ULY*. Though the USHCN dataset was created to study long-term climate trends (Peterson et al. 1998), only 97 of the 221 stations in New Mexico, Texas, and surrounding states had continuous precipitation records through the entire 20th century.

2. Precipitation Trend Analysis

Two dot plot maps are included in the analysis of the USHCN data with the dots corresponding to the magnitude of the precipitation trend. Positive trends are denoted by blue dots and red dots denote negative precipitation trends.

The trend for a period of time is determined by fitting a least squares regression line to the time series data for a particular USHCN station time series or COOP climate division averaged time series. Since these analyses are focused on the entirety of the 20th century, the units will be denoted as inches of precipitation per century.

A. Dot Plots of USHCN Precipitation Trends

The first dot plot analysis includes USHCN stations with data dating back to the start of the 20th century. Ninety-six of the 221 USHCN stations fit this criterion and are labeled by boldface type in Section A of the supporting materials at the end of this report. Figure A2.1 contains a dot plot map of the ULY dataset station precipitation trends for the 20th century.

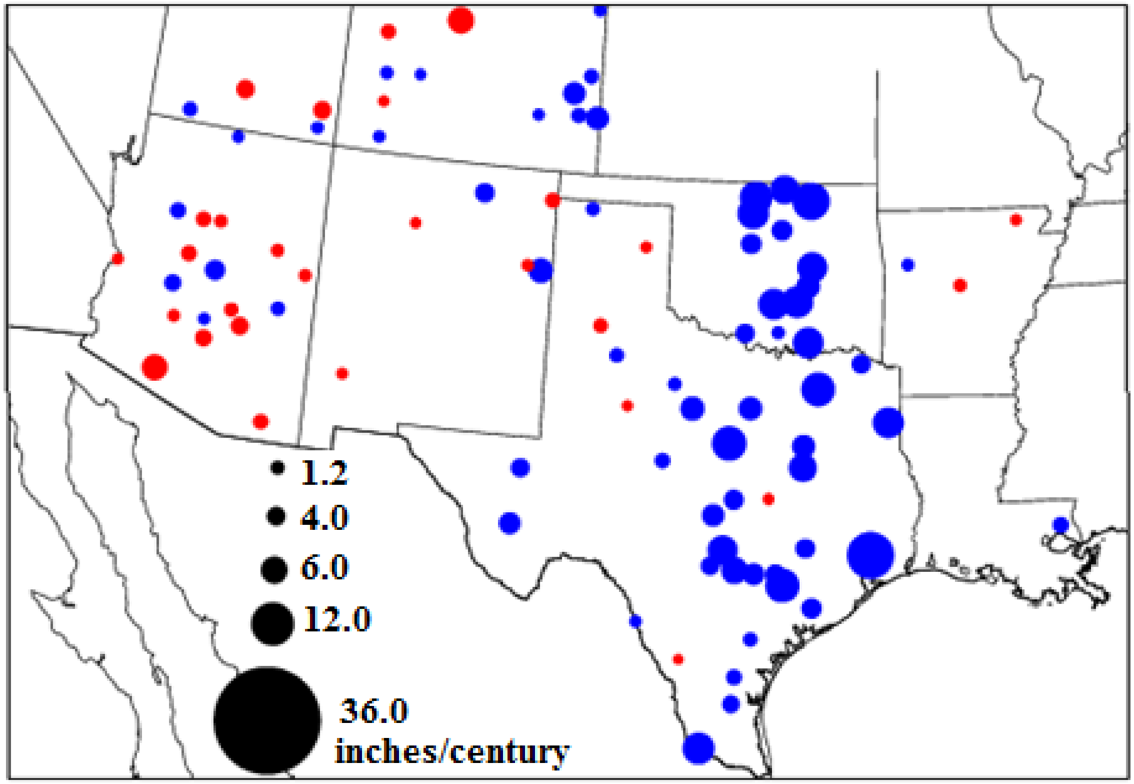


FIG A2.1. Dot plot map of precipitation trends over the 20th century using the interpolated dataset. The legend refers to the trend in inches per century.

This next analysis contains those from all 221 USHCN stations in our study and the interpolated data from each of these stations. The interpolated dataset is used in this analysis since several of the USHCN stations have shorter than century-long actual climate records. The 20th century dot plot map of the interpolated dataset station precipitation trends, denoted as *UIY*, is shown in Figure A2.2.

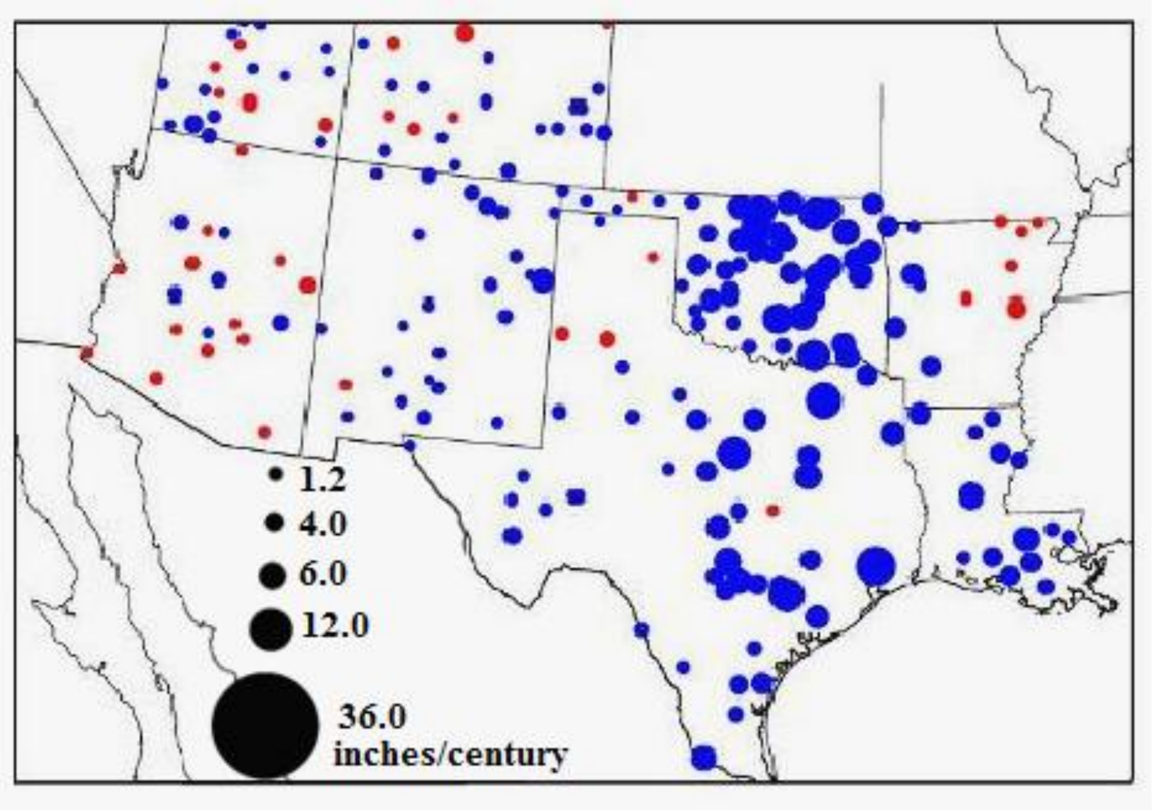


FIG A2.2. Dot plot map of precipitation trends over the 20th century using the UIY dataset. The legend refers to the trend in inches per century.

The same stations in the two dot plot maps (Figs. A2.1 and A2.2) show more increasing than decreasing trends. Fortunately, there is good agreement in both the sign and magnitude of the precipitation trends between the two datasets for stations in which data were available for both.

B. Time Series of COOP Climate Division Precipitation

Because of the spatial density of the COOP network it would be difficult to replicate the dot plot studies done for the three USHCN datasets. Following are analyses of the CqY COOP dataset in the form of time series graphs showing 12-month precipitation anomalies. The anomalies were originally calculated on a station-by-station basis, before being averaged across each climate division for every month. All the available data for each month in a given climate division were utilized. For the CqY dataset, the analyses contain precipitation trends over the entirety the 20th century, broken down into the regions denoted by Figure A1.1.

Each climate division time series includes the raw data of running 12-month anomalies. The raw data are useful for showing the extremes in each climate division's distribution and the general trends in precipitation across the 20th century. In each graph, the right-side vertical axis refers to the running 12-month averages over the entire region, either the East Texas region, the West Texas region, or the New Mexico region. The colored lines refer to the running 12-month climate division averages with the climate division label on the left-side vertical axis. The thick red line in each graph is the climate region smoothed 5-year centered-average of the 12-month running precipitation totals.

Figure A2.3 contains 12-month precipitation anomalies for East Texas, anomalies for West Texas are in Figure A2.4, and Figure A2.5 has the anomalies for all eight New Mexico climate division averages. This dataset is important because it is temporally complete, has had the variance of its time series adjusted to those characteristic of long-term USHCN stations, and uses high-quality USHCN stations in the interpolation process.

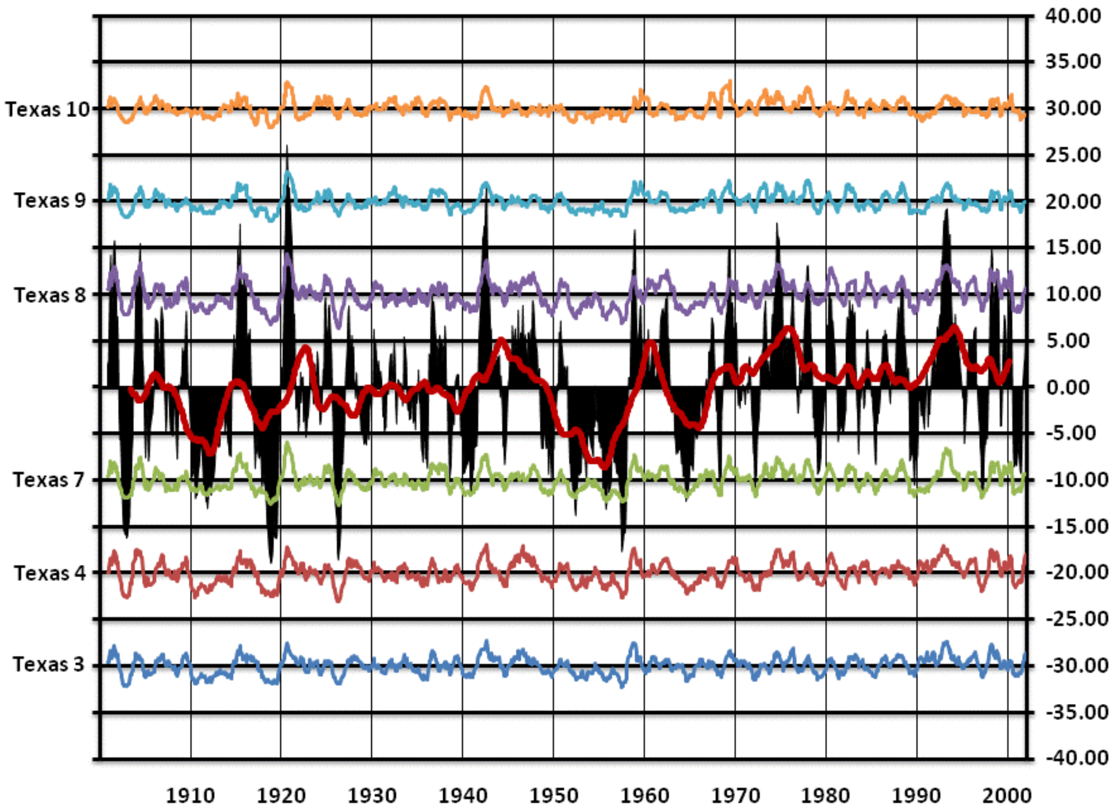


FIG A2.3. Time series climate division averages from the CqY dataset for all the climate divisions in the East Texas region on Figure A1, with a magnitude of 40" between horizontal lines for climate division data. The black indicates an anomaly for the climate region averages at a given time with the thick red line indicative of a 5-year centered-average.

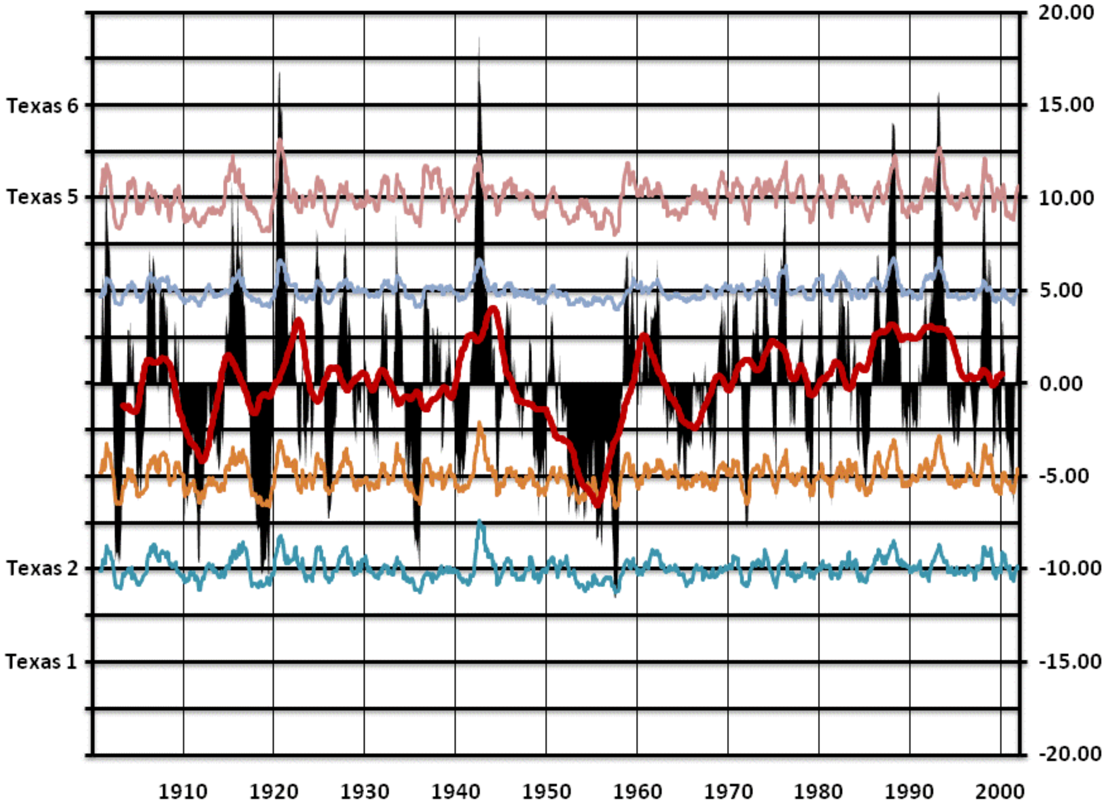


FIG A2.4. Time series climate division averages from the CqY dataset for all the climate divisions in the West Texas region on Figure A1, with a magnitude of 20" between horizontal lines for climate division data. The black indicates an anomaly for the climate region averages at a given time with the thick red line indicative of a 5-year centered-average.

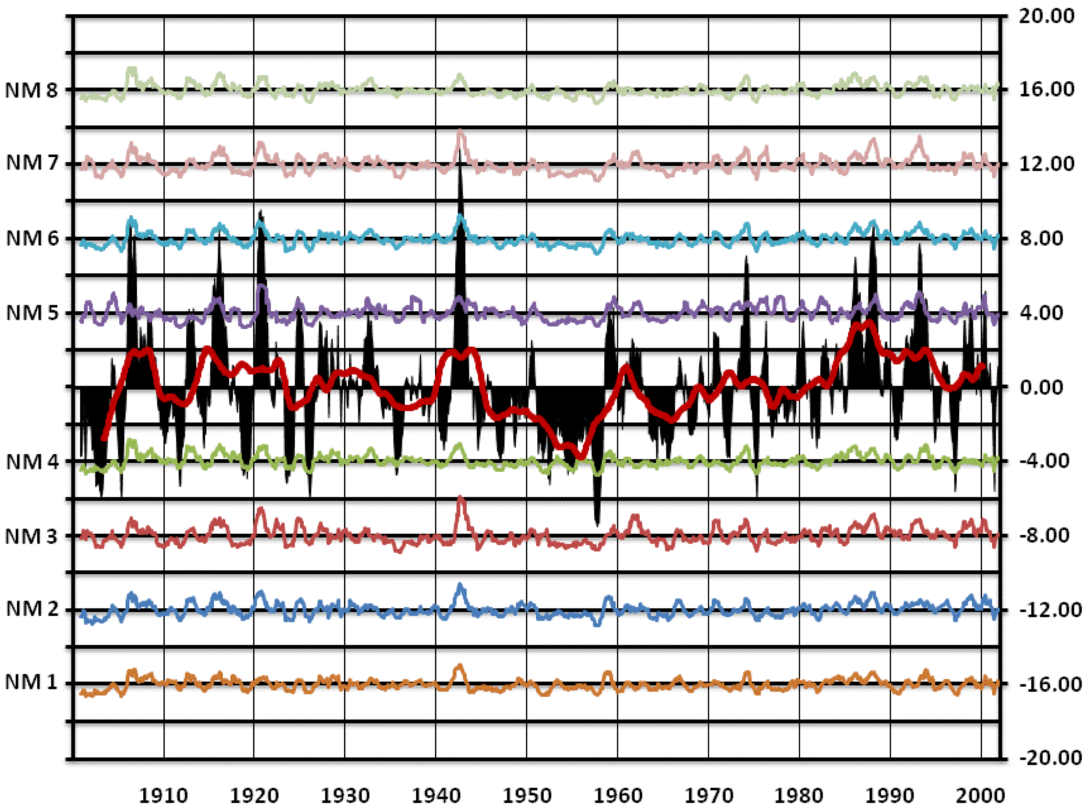


FIG A2.5. Time series climate division averages from the CqY dataset for all the climate divisions in the New Mexico region on Figure A1, with a magnitude of 20" between horizontal lines for climate division data. The black indicates an anomaly for the climate region averages at a given time with the thick red line indicative of a 5-year centered-average.

A great deal of information can be derived from the 20th century time series analyses for the four COOP datasets. The most apparent characteristic shared by all the time series plots (Figs. A2.3-A2.5) is the drought period in the 1950s. For the most part, there is a positive anomaly in precipitation toward the end of the 20th century. However, the New Mexico climate divisions and Texas climate divisions 9 and 10, both in the southern part of Texas, seem to show a decreasing trend in this time period. The decreasing trends in New Mexico are followed by relative maxima, a characteristic not in the time series for the two Texas climate divisions.

The time series plots suggest in all the figures that the driest stretches of 12-month precipitation occurred prior to the long-term drought of the 1950s. Following the drought of the 1950s through the end of the 20th century, there are few large magnitude and long-lasting dry periods. There is a signal in the three regions for a drought in the early 1960 which is strongest in the East Texas region. However, the longer-term trends in the individual climate divisions show this to be a small fluctuation in an overall increasing trend.

Most of the long-term individual climate division time series lines show a positive anomaly for most of the last quarter of the 20th century, with relative maxima in the late 1980s to early 1990s. The maxima in the New Mexico climate divisions occur in the late 1980s and in the early 1990s in the East Texas and West Texas climate divisions.

Taking a closer look at the 1910s shows the precipitation anomalies in the two Texas regions to show a major peak surrounded by two major relative minima. This anomaly pattern would show up as a minimum in the long-term signal for each climate division at the same time a peak is occurring in the 12-month data. This is a prime example of opposite signals being detected simultaneously on different time scales.

Mentioned earlier was the relative lack of drought strength and longevity in the latter half of the 20th century compared to the first half. Visual analysis of the time series plots shows the frequency of pluvial conditions in each of the three climate regions to be increasing. However, there does not appear to be any discernible differences in the magnitudes of these periods when compared to the pluvial periods in the early 20th century.

The magnitude of the smoothed curve for most of the climate divisions has a maximum in the late 20th century. The combination of these two observations would suggest an increase in the frequency of 12-month pluvial periods rather than an increase in the severity of these periods. Further analysis on drought and pluvial conditions will be conducted in Section 3.

C. Climate Division Century-Long Precipitation Trends

Because of the large number of COOP stations, the century-long precipitation trends for the COOP datasets will be displayed as climate division averaged trends in a tabular format following the time series analyses. The Table A2.1 will show the results for the CqY climate division averaged 20th century trends. Also included on Table A1.1 are the percentage changes in the expected rainfall total in 2001 compared to the beginning of the time series in 1900.

The overriding theme of Table A2.1 is an increase in mean precipitation for most of the climate divisions, regardless of the dataset. The only negative trend is for New Mexico climate division 4 in far western New Mexico with Texas climate division 1 showing the smallest positive trend for the remainder of the climate divisions.

TABLE A2.1. The 20th century precipitation trends for the 33 climate divisions in this study with the units as *inches of precipitation per century*. Also included is the percentage change in expected precipitation from 1901 to 2000.

	1900-2000 Precipitation Trend	1900-2000 Percentage Change
New Mexico 1	1.67	15.08
New Mexico 2	0.88	5.43
New Mexico 3	1.78	11.17
New Mexico 4	-0.43	-3.03
New Mexico 5	0.72	7.61
New Mexico 6	1.33	7.60
New Mexico 7	0.99	7.28
New Mexico 8	0.84	7.23
Texas 1	0.26	1.35
Texas 2	1.62	6.87
Texas 3	4.84	14.29
Texas 4	6.08	13.20
Texas 5	0.32	2.54
Texas 6	3.22	12.82
Texas 7	4.79	14.27
Texas 8	5.99	12.88
Texas 9	2.32	9.92
Texas 10	3.23	13.57

3. Precipitation Distribution Extremes and Drought

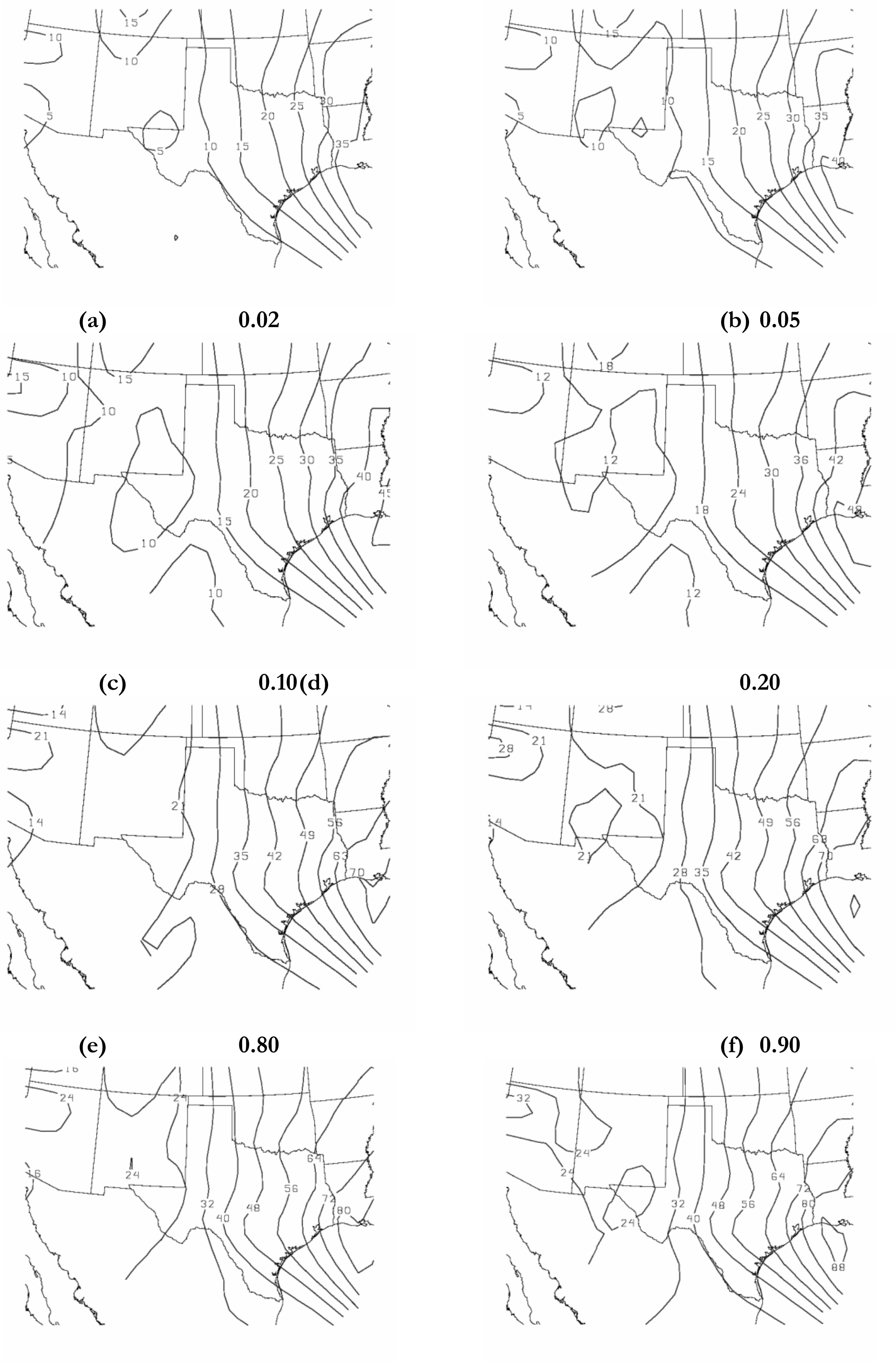
The extremes and long-term trends in the 12-month precipitation distributions will form the cornerstone of our drought analyses. Gibbs and Maher (1967) grouped monthly precipitation occurrences into deciles so that, by definition, "much lower than normal" weather cannot occur more often than 20% of the time. The classification of drought using this approach provides an accurate statistical measurement of precipitation given long climatic data records that are included in this study.

As for the precipitation distributions, the shape parameter remains relatively stable, but the scale parameter is variable spatially and temporally (Groisman et al., 1999). When the time period gets longer, the gamma distribution representing the precipitation distribution at a particular station approaches a normal distribution. Precipitation analyses will largely focus on the tail-ends of the gamma precipitation distributions and their effects on drought statistics. Karl and Knight (1998) found that across the United States, the total proportion of annual precipitation derived from extreme events has increased relative to moderate precipitation.

This implies that a shift in the mean precipitation will have the most influence on extreme precipitation totals. For each station, it is assumed the mean monthly precipitation is equal for the three different time series based on the interpolation process for the second dataset and gamma distribution fitting for the third dataset. However, it is the size and shape parameters of the gamma distribution that cause the three time series data variances to be unequal.

A. USHCN Gamma Distribution Extremes

Using the USHCN data, the gamma distributions were calculated for each of the three different time series at each station. One can determine precipitation totals equivalent to certain CDF values of precipitation and the spatial properties among the different types of precipitation time series. The following maps (Fig. A3.1) contain the USHCN precipitation totals from the ULY dataset representing CDF values of 0.02, 0.05, 0.10, 0.20, 0.80, 0.90, 0,95, and 0.98 for 12-month precipitation totals.



(a) **0.02** **(b) 0.05**

(c) **0.10(d)** **0.20**

(e) **0.80** **(f) 0.90**

(g) 0.95 **(h) 0.98**

FIG A3.1. Maps of 12-month precipitation CDF values for 0.02 (a), 0.05 (b), 0.10 (c), 0.20 (d), 0.80 (e), 0.90 (f), 0.95 (g), 0.98 (h) from the ULY dataset.

The spatial distribution of the contours for all eight maps in Figure A3.1. As one would expect, the magnitudes and spatial variances of the precipitation values for all the maps included on Figure A3.1 are larger in the Eastern half of our domain. An interesting finding with regards to drought is that the areas receiving the least amount of precipitation in a severe drought are outside of New Mexico (Figs A3.1a and Fig. A3.1b). This includes much of the Trans Pecos region (CD 5) in Texas and much of Northern Arizona and Southern Utah. These data would suggest that precipitation is more variable over West Texas than in the state of New Mexico with more frequent droughts.

B. COOP Gamma Distribution Extremes

From the COOP climate division distributions, we can create climate division cumulative distribution functions and determine the monthly precipitation values for the aforementioned extreme CDF values (Table A3.1).

TABLE A3.1. Table of extreme CDF values for New Mexico and Texas COOP climate division 12-month precipitation totals using the CqY dataset.

Climate Division	0.02	0.05	0.10	0.20	0.80	0.90	0.95	0.98
New Mexico 1	6.10	6.95	7.78	8.86	13.97	15.57	16.97	18.64
New Mexico 2	10.40	11.47	12.48	13.79	19.63	21.39	22.92	24.72
New Mexico 3	9.06	10.27	11.44	12.97	20.13	22.35	24.30	26.62
New Mexico 4	8.46	9.47	10.44	11.70	17.45	19.22	20.76	22.58
New Mexico 5	3.30	4.26	5.26	6.67	14.52	17.26	19.76	22.82
New Mexico 6	11.87	12.93	13.93	15.21	20.82	22.48	23.92	25.61
New Mexico 7	7.19	8.30	9.39	10.83	17.72	19.90	21.83	24.13
New Mexico 8	6.12	7.02	7.89	9.05	14.51	16.23	17.74	19.55
Texas 1	11.43	12.80	14.11	15.81	23.59	25.97	28.05	30.51
Texas 2	13.85	15.57	17.21	19.36	29.23	32.26	34.91	38.05
Texas 3	20.51	22.81	25.00	27.83	40.67	44.56	47.95	51.94
Texas 4	30.34	33.31	36.11	39.71	55.71	60.50	64.64	69.48
Texas 5	6.41	7.47	8.50	9.87	16.52	18.64	20.52	22.77
Texas 6	13.12	15.05	16.92	19.39	31.10	34.78	38.02	41.87
Texas 7	17.99	20.50	22.94	26.15	41.21	45.91	50.03	54.92
Texas 8	27.76	30.97	34.04	38.01	56.10	61.61	66.40	72.04
Texas 9	11.44	13.31	15.15	17.61	29.46	33.24	36.58	40.58
Texas 10	13.42	15.30	17.12	19.51	30.75	34.26	37.34	41.00

C. Measuring Drought: Mann-Whitney Z-Values

To compare trends between different USHCN stations and COOP climate divisions with different precipitation means and variances, it is important to create a dimensionless variable that can indicate extremes in precipitaiton trends. The Z-statistic normalizes the data within a station's time series based on its mean and variance. Higher magnitude Z-statistics that are negative are indicative of drought and higher magnitudes of positive Z-statistics indicate a positive anomaly of precipitation for a given time period. For precipitation, Z values were calculated using the Mann-Whitney method developed by Mann and Whitney (1947) and shown in section D of this report's supporting materials.

Figure A3.2 has running statewide MWZ values for New Mexico and Texas using 12-month period lengths. This analysis has statewide averaged 12-month precipitation totals from each of the available long-term USHCN actual values for each 12-month period. The time stamp for any accumulation period value indicates the last month of in that particular period. Included are values from this dataset in addition to the smoothed, 10-year center-averaged lines for both the Texas and New Mexico time series. The values for the Pacific Decadal Osciallation (PDO) and the El-Niño/Southern Oscillation (ENSO) indices are also includeed, two cycles for which relationships to precipitation are examined.

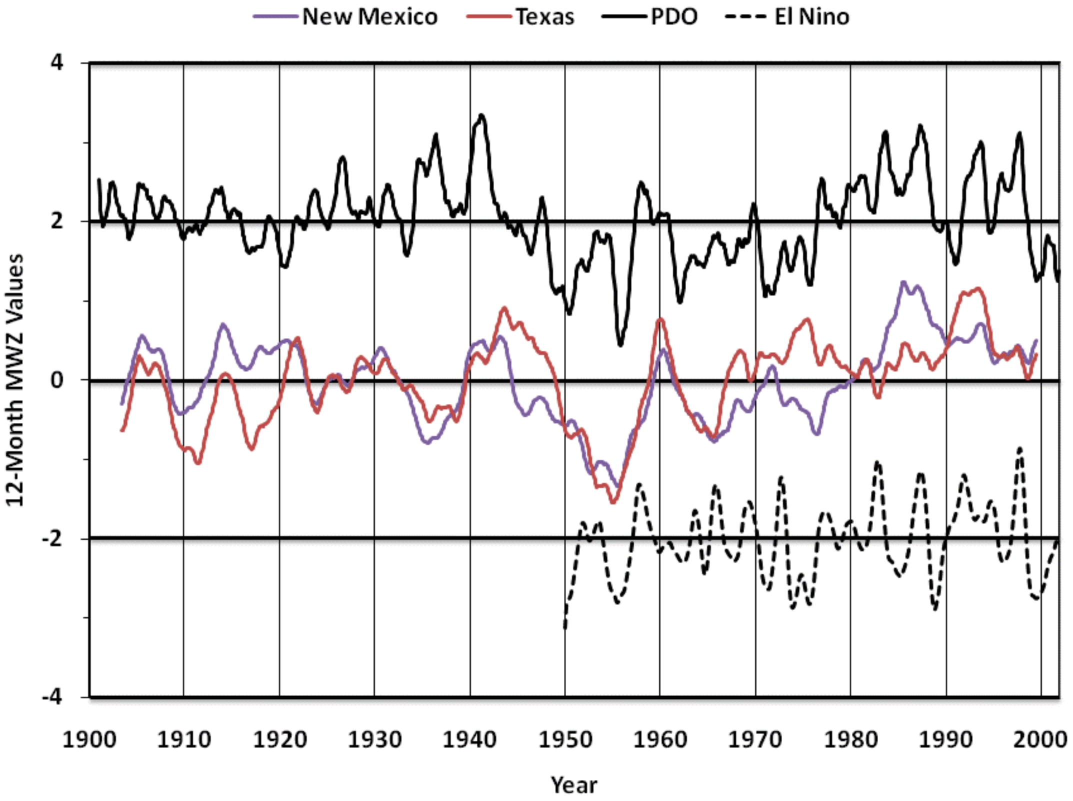


FIG A3.2. Time series of USHCN 12-month precipitation MWZ values for New Mexico (blue) and Texas (red) statewide averages using the ULY dataset. Also included are the values for the ENSO (solid black) and PDO (dotted black) indices, each with its own axis, separate from the central axis for the MWZ values.

The MWZ values for precipitation can show both trends over time and the spatial distribution of precipitation at specific points in time. Of most interest are months with high magnitudes of MWZ values, both positive and negative. Figure A3.2 shows that the long-term precipitation trend in the 20th century can be broken down into three parts. The most notable features are the minima for both New Mexico and Texas in the 1950s. This period of drought in both states is preceded by a noisy and overall indiscernible pattern of precipitation MWZ values in New Mexico and Texas through the first half of the 20th century. The drought of the 1950s is followed by increasing precipitation through the end of the 20th century in both New Mexico and Texas.

The long-term trend in precipitation appears to be leveling off at the end of the 20th century but that brings into question whether this is the beginning of a different long-term trend or a slight fluctuation in the increasing trend. The 12-month running averages of precipitation totals in New Mexico and Texas would suggest a downward trend, but a lack of long-term data beyond this period brings that conclusion into question.

The 12-month accumulation time series (Fig. A3.2) highlights separate peaks in precipitation toward the end of the 20th century for Texas and for New Mexico. The downward trend in statewide averages for New Mexico precipitation begins after a particularly wet period from 1986-1987, in which the El Niño-Southern Oscillation (ENSO) was in a positive phase, better known as an El Niño period. The peak in Texas occurred in the middle 1990s and also coincided with El Niño conditions.

Another cycle that has influence on global weather is the Pacific Decadal Oscillation (PDO), which deals with Pacific sea surface temperatures (SST) north of 20°N, whereas ENSO is an index dealing with SSTs near the Equator. Positive phases of both ENSO and PDO, typically though not always coinciding, generally spell wetter than normal conditions in New Mexico and Texas, whereas the negative phases are correlated with drier than normal conditions. Table A3.2 (Liles 2003) describes the differences in annual precipitation between positive and negative cycles of these two indices for New Mexico Climate divisions.

TABLE A3.2. Relationships between in phase ENSO/PDO episodes and Annual Precipitation for New Mexico climate divisions (Liles 2003).

	Div 1	**Div 2**	**Div 3**	**Div 4**	**Div 5**	**Div 6**	**Div 7**	**Div 8**
El Niño and PDO+	14.68	18.95	20.82	16.87	12.73	21.06	19.51	13.69
La Niña and PDO-	7.50	11.95	12.78	9.57	7.12	13.26	11.40	8.00

The time-series of MWZ shown in Figure A1.2 can be replicated for the individual climate divisions to show the spatial differences in precipitation trends over the past century. All the first graph (Fig. A3.3) includes the show the time series for the six East Texas region climate divisions in Texas, the second graph (Fig. A3.4) contains the remaining four Texas CDs in West Texas, and all eight climate divisions in New Mexico are displayed on the third time series plot (Fig. A3.5).

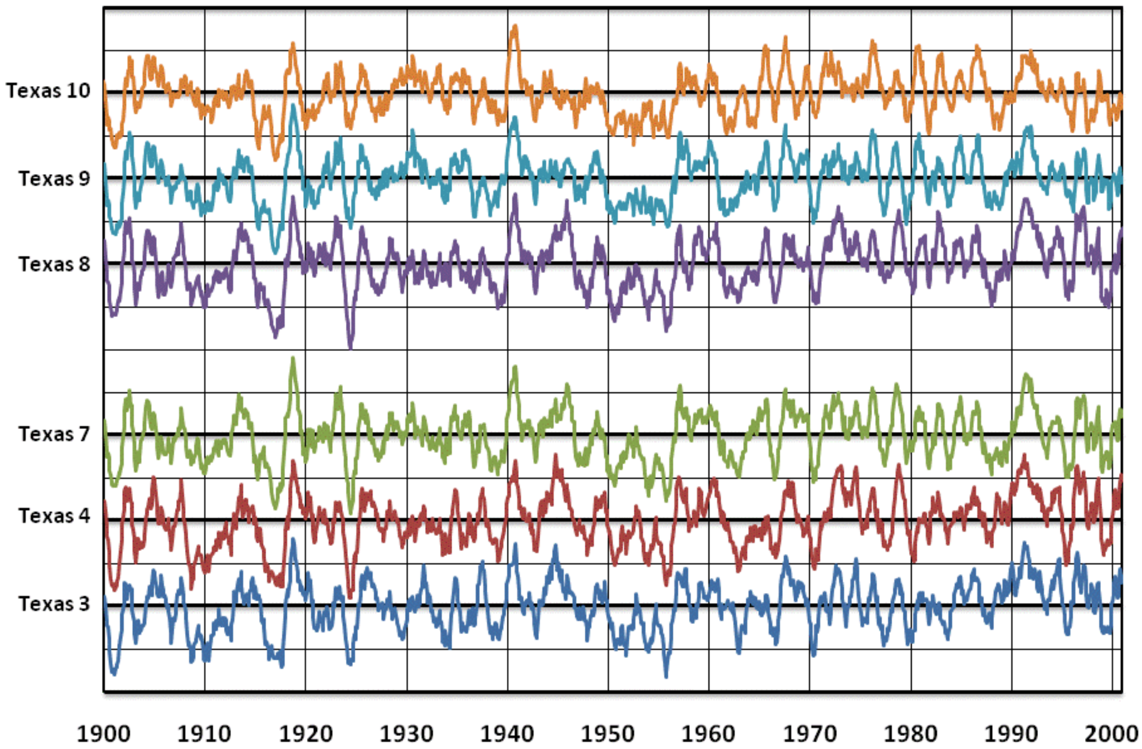


FIG A3.3. Time series of 12-month running precipitation MWZ values for the Texas climate divisions in the East Texas region using the CqY dataset, with each bold line representative of a climate division averaged MWZ value of zero and each horizontal line an increment of two.

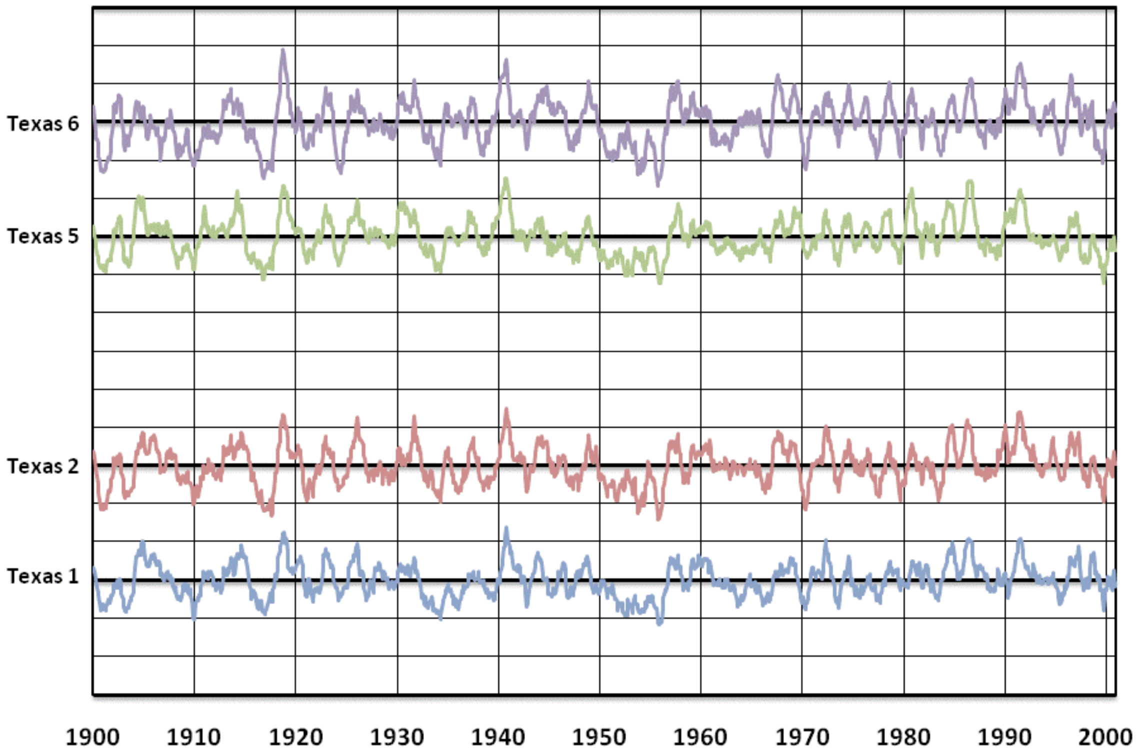


FIG A3.4. Time series of 12-month running precipitation MWZ values for the Texas climate divisions in the West Texas region using the CqY dataset, with each bold line representative of a climate division averaged MWZ value of zero and each horizontal line an increment of two.

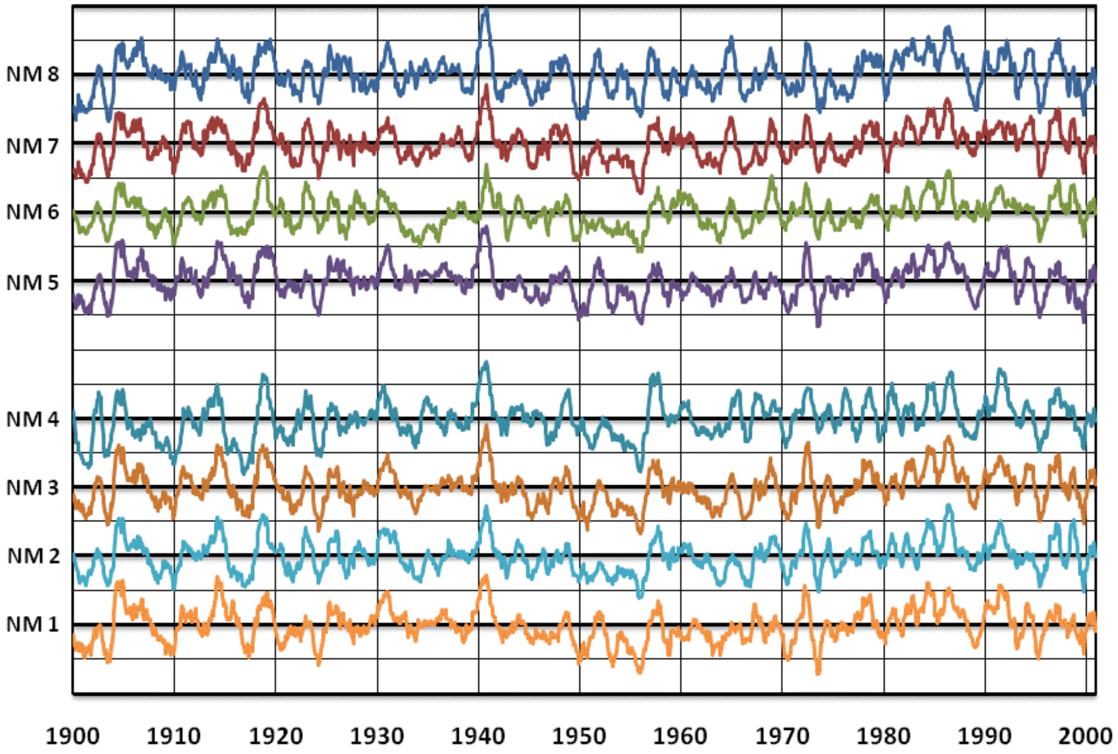


FIG A3.5. Time series of 12-month running precipitation MWZ values for the New Mexico climate divisions in the New Mexico region using the CqY dataset, with each bold line representative of a climate division averaged MWZ value of zero and each horizontal line an increment of two.

The figures in this section (Figs. A3.3-A3.5) all show roughly the same pattern when the short-term noise is eliminated. The basic pattern is a steady to slightly increasing trend in precipitation over the first half of the 20th century followed by a drastic decrease in precipitation in the 1950s. Following the long-term drought lasting through most of the 1950s, the latter half of the 20th century saw an increasing trend in precipitation.

However, there is some evidence of a downturn in MWZ precipitation values for the last few years in most of the individual climate division time series datasets. This signal is most prominent in West Texas and New Mexico (Figs. A3.4 and A3.5) and not in East Texas (Fig. A3.3). This result would be indicative of a shift towards drier conditions in areas already relatively dry and wetter conditions in areas already with relatively wet overall conditions. However, any conclusions implicating a long-term shift in precipitation trend need several more years of data to conclude that is not in fact just a short-term fluctuation in the overall precipitation pattern.

D. Drought on Decadal Time Scales

There are several ways to measure precipitation trends on decadal scales, with perhaps the simplest measure being the annual average precipitation by decade. Table A3.3 contains the decadal annual precipitation averages for each of the 18 New Mexico and Texas COOP climate divisions using the CqY dataset.

TABLE A3.3. Annual average precipitation by decade for division averaged precipitation using the CqY dataset.

	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s
New Mexico 1	12.73	12.69	11.59	11.66	10.83	11.20	11.48	11.78	14.60	12.94
New Mexico 2	16.54	18.40	16.85	15.70	16.85	15.00	15.54	15.38	18.45	18.22
New Mexico 3	15.54	17.60	16.88	13.52	17.39	14.80	15.21	15.58	18.66	18.50
New Mexico 4	14.76	16.60	14.45	14.62	12.83	12.78	13.10	13.46	15.94	14.48
New Mexico 5	11.50	12.72	10.27	12.75	11.60	9.44	10.16	14.40	12.20	12.03
New Mexico 6	16.22	19.33	17.30	17.74	17.85	15.69	16.61	17.57	20.74	18.77
New Mexico 7	13.55	14.90	13.87	13.11	14.35	11.65	12.24	14.35	15.81	15.18
New Mexico 8	12.41	13.79	11.78	12.19	10.91	10.37	11.47	11.93	14.50	13.34
Texas 1	18.64	20.32	19.92	16.23	21.03	16.84	17.69	18.65	20.47	20.14
Texas 2	22.92	24.14	23.50	22.72	24.67	21.07	23.25	24.24	25.42	25.22
Texas 3	31.44	33.30	32.49	33.31	35.74	31.04	33.51	33.59	36.15	37.82
Texas 4	44.63	44.82	44.80	45.27	48.94	43.67	42.90	47.78	48.23	51.54
Texas 5	14.99	13.19	13.34	13.03	13.54	10.51	11.74	14.44	15.04	12.63
Texas 6	22.46	25.61	24.40	26.37	25.84	22.72	24.29	27.68	26.21	27.41
Texas 7	31.34	32.76	32.37	33.30	33.71	31.56	33.17	37.21	32.84	37.52
Texas 8	45.95	46.10	44.64	45.89	49.82	42.73	44.21	50.77	47.51	53.68
Texas 9	22.16	23.12	22.58	23.29	24.22	21.78	23.17	26.81	23.24	24.27
Texas 10	-1.00	22.84	24.38	24.16	23.74	22.12	26.54	28.46	23.99	25.23

Another measure of precipitation was developed to track changes in extreme precipitation on decadal time scales. This methodology uses the climate division averaged COOP time series data and produces a statistic based on MWZ monthly precipitation values. For each decade, this statistic determines the percentage of MWZ values below the precipitation value representing a CDF of 0.10 in Table A3.4. Similarly, each climate division has a decadal percentage of MWZ values above the precipitation value representing a CDF of 0.90 (Table A3.5). These percentages for the 18 climate divisions in New Mexico and Texas are calculated using the CqY dataset.

TABLE A3.4. Percentage of MWZ precipitation values for the 18 New Mexico and Texas climate divisions below the CDF precipitation value of 0.10. Data are organized by decade and used the CqY dataset.

	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s
New Mexico 1	14.17	0.83	0.83	0.00	7.50	15.00	0.00	4.17	4.17	6.67
New Mexico 2	10.00	0.00	1.67	0.00	5.83	11.67	2.50	0.00	0.00	3.33
New Mexico 3	1.67	0.83	0.00	3.33	0.00	6.67	0.83	0.00	0.00	0.00
New Mexico 4	8.33	0.00	2.50	0.00	2.50	14.17	0.00	7.50	0.00	5.00
New Mexico 5	24.17	25.00	6.67	0.83	0.00	15.83	0.00	0.83	0.00	2.50
New Mexico 6	6.67	1.67	4.17	0.00	2.50	14.17	6.67	5.83	0.00	2.50
New Mexico 7	2.50	4.17	0.00	0.00	0.00	5.83	5.00	2.50	0.00	1.67
New Mexico 8	10.00	0.83	5.00	0.00	1.67	25.00	1.67	11.67	0.00	1.67
Texas 1	2.50	4.17	0.00	4.17	0.00	14.17	0.00	0.00	0.00	0.00
Texas 2	7.50	12.50	1.67	0.83	0.00	16.67	0.00	4.17	2.50	0.83
Texas 3	18.33	23.33	7.50	4.17	0.00	21.67	4.17	5.00	0.00	0.00
Texas 4	19.17	25.00	8.33	2.50	0.00	16.67	6.67	5.00	1.67	2.50
Texas 5	5.00	7.50	0.00	3.33	0.00	16.67	0.00	0.00	0.00	3.33
Texas 6	15.00	16.67	6.67	5.00	0.00	24.17	2.50	6.67	0.83	3.33
Texas 7	8.33	15.83	9.17	1.67	0.83	25.83	6.67	4.17	0.83	3.33
Texas 8	10.00	20.83	9.17	5.83	2.50	23.33	3.33	3.33	2.50	5.83
Texas 9	9.17	15.83	5.83	3.33	0.00	12.50	2.50	5.00	0.00	0.00
Texas 10	8.33	15.83	0.83	0.00	0.00	15.00	3.33	0.00	1.67	2.50

TABLE A3.5. Percentage of MWZ precipitation values for the 18 New Mexico and Texas climate divisions above the CDF precipitation value of 0.90. Data are organized by decade and used the CqY dataset.

	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s
New Mexico 1	7.50	6.67	0.83	2.50	10.83	0.00	3.33	2.50	15.00	4.17
New Mexico 2	5.83	9.17	0.00	0.00	9.17	0.00	0.00	0.83	12.50	2.50
New Mexico 3	1.67	8.33	1.67	0.00	5.00	0.00	2.50	0.83	11.67	0.83
New Mexico 4	9.17	13.33	0.00	3.33	11.67	0.00	0.00	4.17	11.67	6.67
New Mexico 5	0.83	9.17	0.00	2.50	12.50	10.00	0.83	7.50	15.00	11.67
New Mexico 6	7.50	15.00	0.00	1.67	10.83	0.00	0.83	5.00	16.67	5.00
New Mexico 7	7.50	12.50	0.83	0.00	9.17	0.83	0.00	1.67	15.83	8.33
New Mexico 8	9.17	9.17	0.00	5.83	10.83	0.00	0.00	6.67	17.50	6.67
Texas 1	3.33	7.50	3.33	0.00	6.67	0.00	0.00	1.67	10.00	5.00
Texas 2	0.83	7.50	4.17	2.50	5.83	0.00	1.67	3.33	13.33	10.00
Texas 3	1.67	6.67	0.83	5.83	16.67	1.67	5.00	6.67	2.50	20.83
Texas 4	6.67	6.67	0.00	0.00	20.00	3.33	8.33	19.17	0.83	28.33
Texas 5	7.50	10.83	1.67	3.33	9.17	1.67	0.00	0.00	15.83	8.33
Texas 6	0.00	9.17	2.50	1.67	13.33	5.00	9.17	2.50	6.67	15.00
Texas 7	4.17	10.00	5.00	0.00	15.00	2.50	2.50	11.67	0.83	16.67
Texas 8	5.83	8.33	5.83	0.00	16.67	1.67	1.67	15.83	5.00	29.17
Texas 9	5.00	7.50	1.67	1.67	10.83	3.33	7.50	5.83	5.83	8.33
Texas 10	3.33	4.17	0.00	0.83	10.00	0.00	9.17	6.67	11.67	6.67

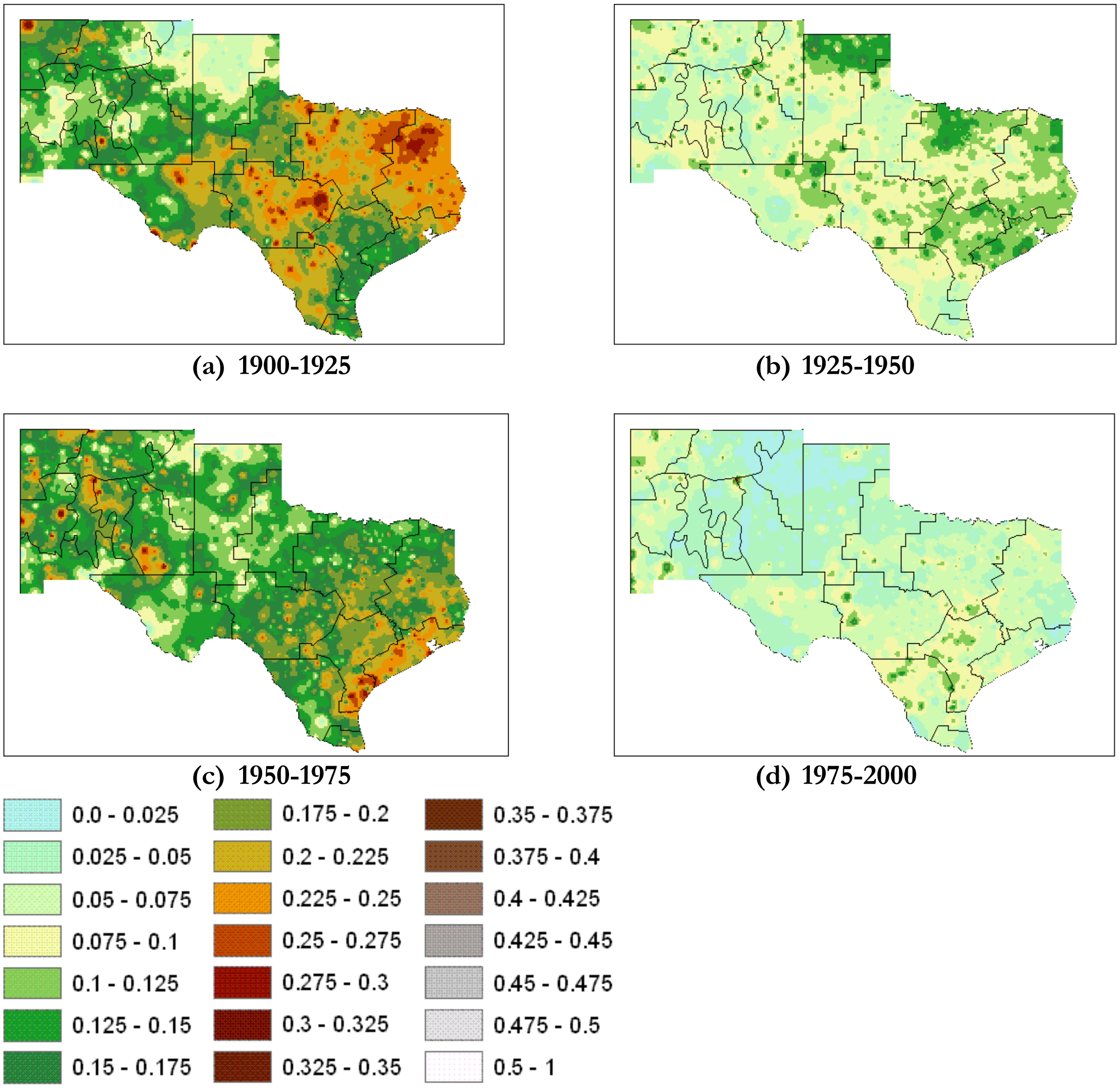
The analyses done on decadal averages and on the decadal distribution extremes back the other analyses in that the 1950s was the decade with the driest conditions and the 1990s were the driest decade overall. Nine of the ten climate divisions in Texas and six of the eight climate divisions in New Mexico (Table A3.4) had their driest decade from 1951-1960. Drought in this sense is loosely defined as having monthly precipitation totals below the 10th percentile of their climate division's distribution.

Table A3.5 provides overwhelming evidence that the largest number of months with extremely high precipitation occurred in the last two decades of the 20th century. Six of the ten Texas climate divisions count the period from 1991-2000 as its highest average from the ten decades in the 20th century. Seven of the eight climate divisions in New Mexico (Table A3.5) have their wettest decade from 1981-1990 with particularly high 12-month MWZ values (Fig. A3.2) in the period from 1986-1987.

E. Percentages of 12-Month Periods with Droughts for COOP Stations

Further drought analyses were done on the COOP stations in Texas and New Mexico for the entirety of the four 25-year periods and ten 10-year periods in the 20th century. The severity of drought is often thought of as an extension of an area's overall precipitation distribution. This study characterizes periods with precipitation totals below the 20th percentile of its given distribution as a moderate drought and months below its 2nd percentile as more exceptional droughts, following the guidelines of the United States Drought Monitor (Svoboda et al. 2002).

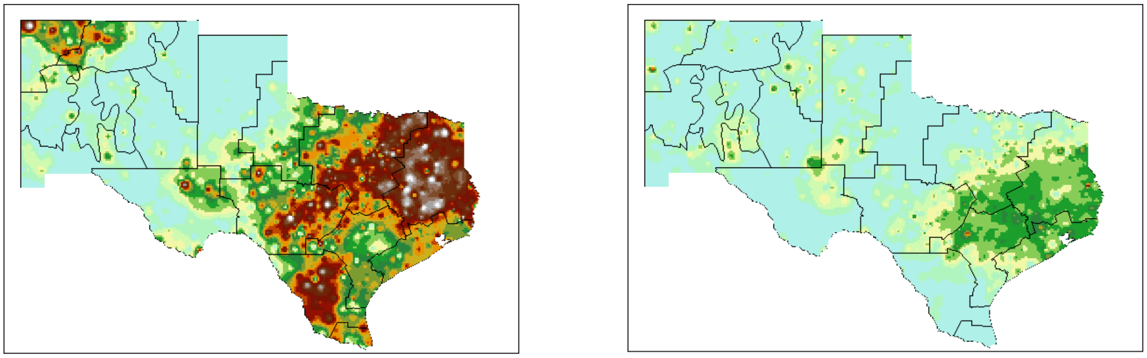
The following set of analyses focuses on the 20th and 2nd percentile of each COOP station's overall CqY distribution. Each analysis will be a map color-coded according to the percentage of months below each drought threshold. Figures A3.6 and A3.7 each contain four maps of the 25-year periods, the first pertaining to the 20th percentile (Fig. A3.6) and the second for the 2nd percentile (Fig. A3.7). Figures A2.8 (20th percentile) and A3.9 (2nd percentile) each contain maps of the 10-year periods in the 20th century.



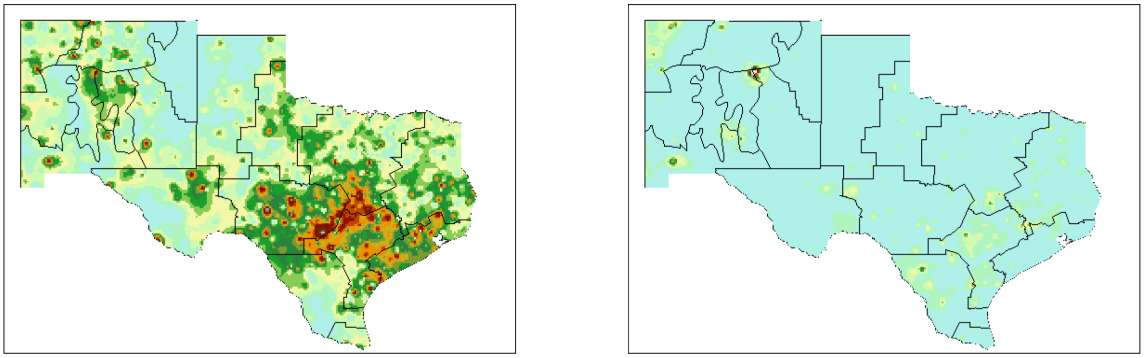
(a) 1900-1925 **(b) 1925-1950**

(c) 1950-1975 **(d) 1975-2000**

FIG A3.6. COOP climate division maps color-coded according to the percentage of months below the 20th percentile of its given distributions for the periods 1900-1925 (a), 1925-1950 (b), 1950-1975 (c), and 1975-2000 (d) using the CqY dataset. The legend denotes the fractional percentage for the colors on the maps.



(a) 1900-1925 (b) 1925-1950



(c) 1950-1975 (d) 1925-1950

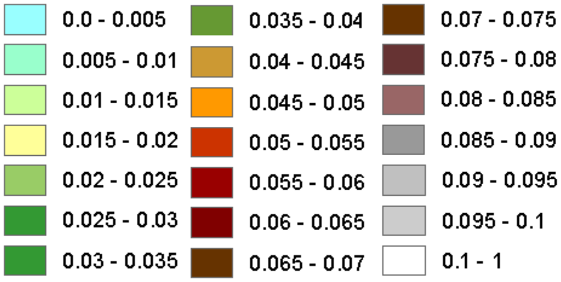
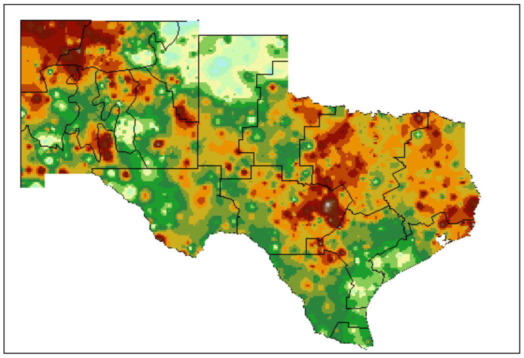
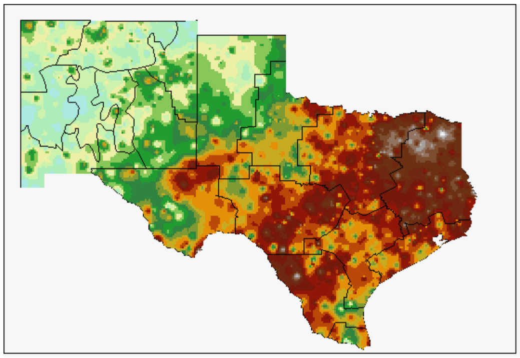


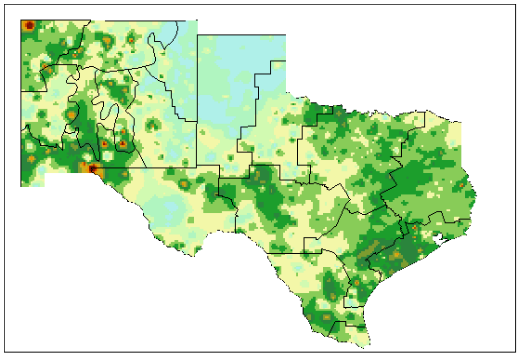
FIG A3.7. COOP climate division maps color-coded according to the percentage of months below the 2nd percentile of its given distributions for the periods 1900-1925 (a), 1925-1950 (b), 1950-1975 (c), and 1975-2000 (d) using the CqY dataset. The legend denotes the fractional percentage for the colors on the maps.



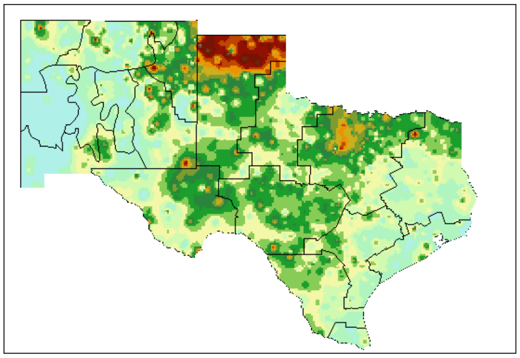
(a) 1900-1910



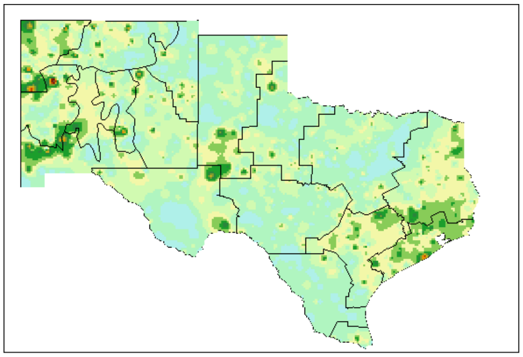
(b) 1910-1920



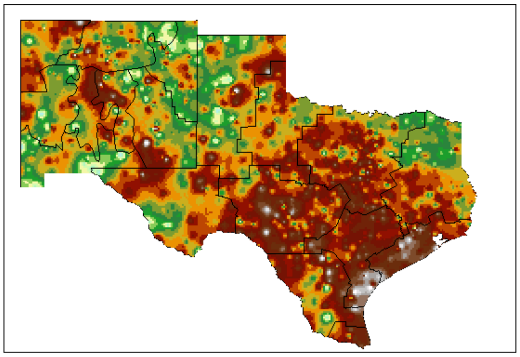
(c) 1920-1930



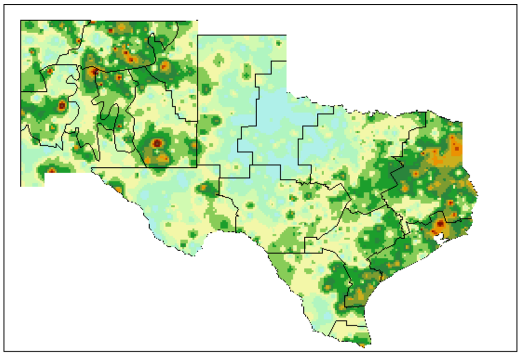
(d) 1930-1940



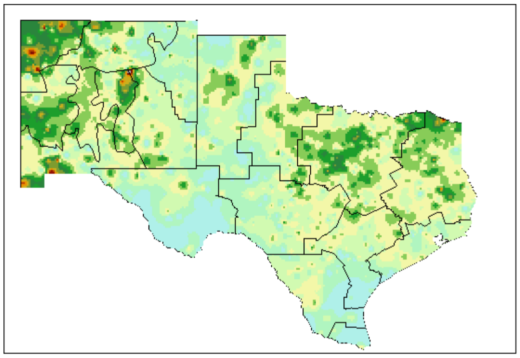
(e) 1940-1950



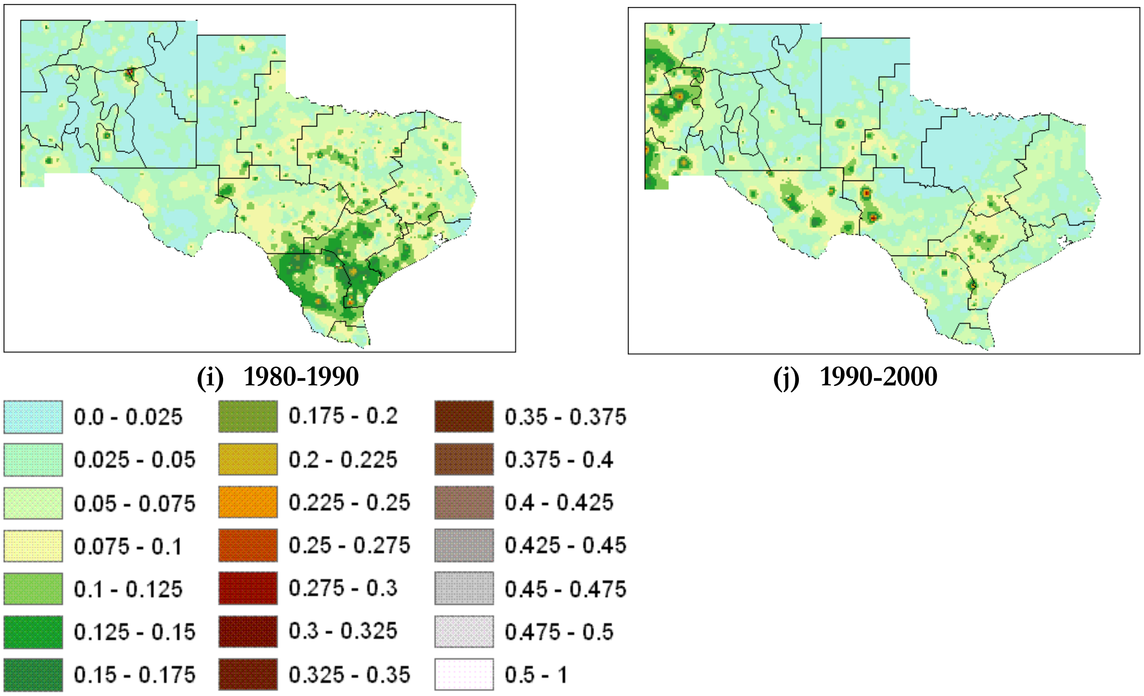
(f) 1950-1960



(g) 1960-1970

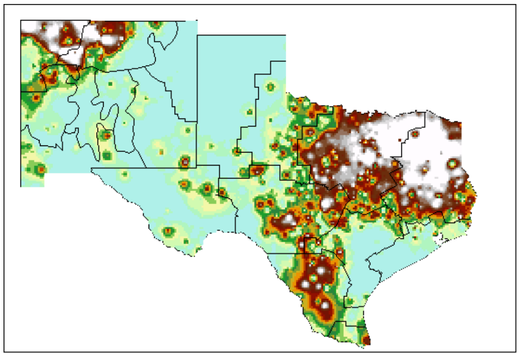


(h) 1970-1980

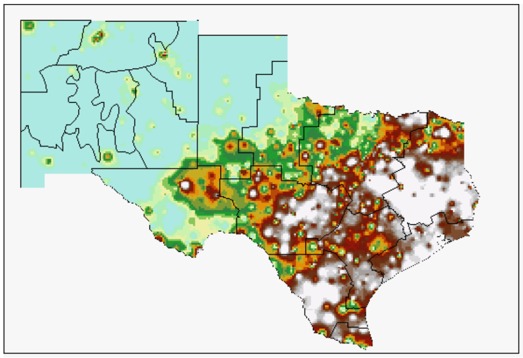


(i) 1980-1990 **(j) 1990-2000**

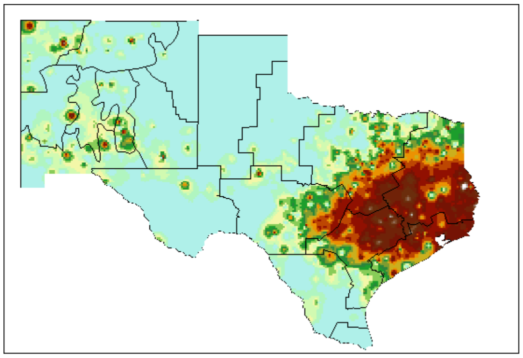
FIG A3.8. COOP climate division maps color-coded according to the percentage of months below the 20th percentile of its given distributions for the periods 1900-1910 (a), 1910-1920 (b), 1920-1930 (c), and 1930-1940 (d), 1940-1950 (e), 1950-1960 (f), 1960-1970 (g), and 1970-1980 (h), 1980-1990 (i), 1990-2000 (j) using the CqY dataset. The legend denotes the fractional percentage for the colors on the maps.



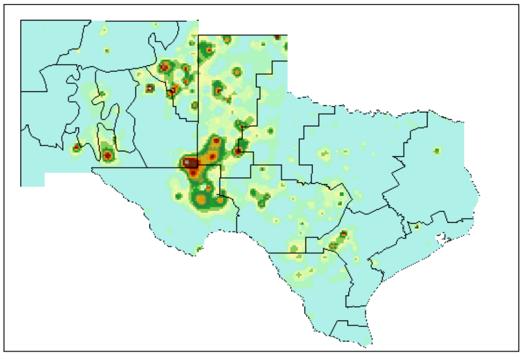
(a) 1900-1910



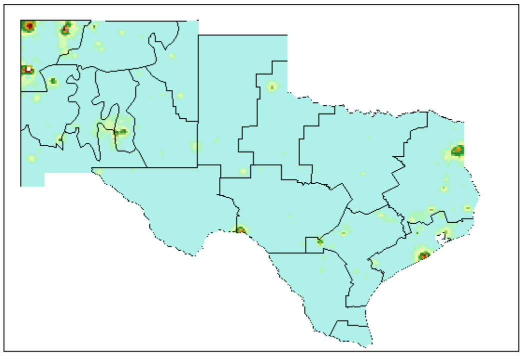
(b) 1910-1920



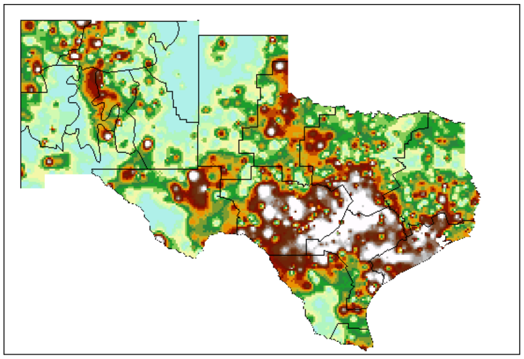
(c) 1920-1930



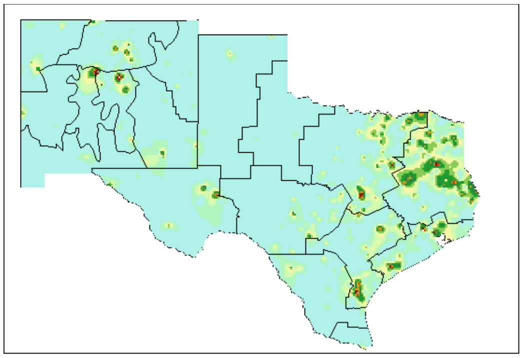
(d) 1930-1940



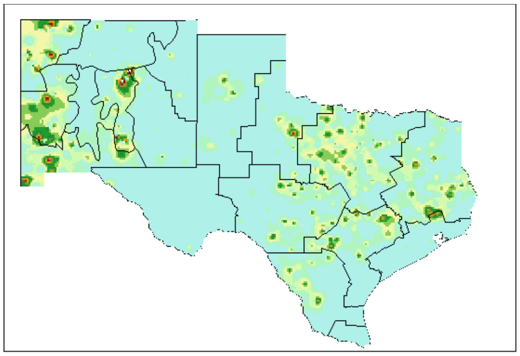
(e) 1940-1950



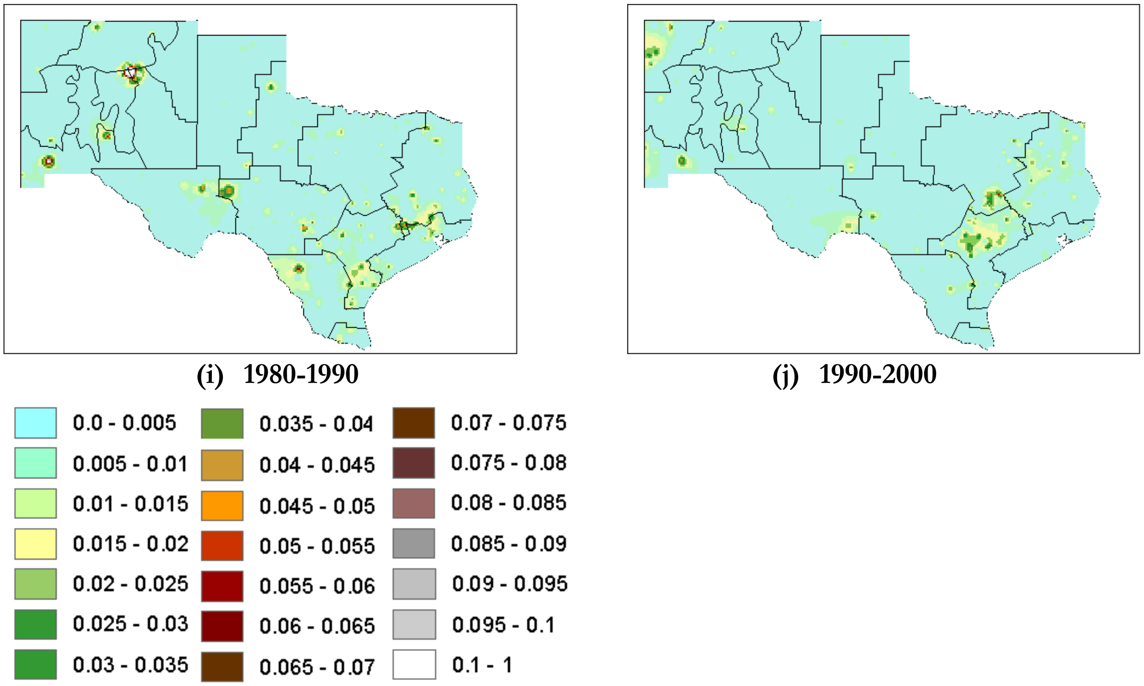
(f) 1950-1960



(g) 1960-1970



(h) 1970-1980



(i) 1980-1990 **(j) 1990-2000**

FIG A3.9. COOP climate division maps color-coded according to the percentage of months below the 2nd percentile of its given distributions for the periods 1900-1910 (a), 1910-1920 (b), 1920-1930 (c), and 1930-1940 (d), 1940-1950 (e), 1950-1960 (f), 1960-1970 (g), and 1970-1980 (h), 1980-1990 (i), 1990-2000 (j) using the CqY dataset. The legend denotes the fractional percentage for the colors on the maps.

Figures A3.6 through A3.9 provide an excellent visualization of the spatial differences in moderate (below 20th percentile) and exceptional (below 2nd percentile) droughts. Beginning with Figure A3.6, it is clear to see that the first and third 25-year periods of the 20th century contained the most months with conditions below the 20th percentile of each station's 12-month running time series.

The years 1900-1925 (Fig A3.6a) were most affected by drought in Northeast and Central Texas, with the rest of Texas and New Mexico experiencing more months with moderate drought in the 1950-1975 period. Judging by Figure A3.7, the most frequent exceptional droughts in New Mexico and Texas were in Northeast Texas toward the beginning of the 20th century. Figure A3.3 shows the largest magnitude negative values for Texas CDs 3 and 4 occurred in 1917.

The maps for percentage of moderate drought months by decade (Fig. A3.8) show the 10-year period of 1950-1960 to have the most drought months for each region in New Mexico and Texas with the exception of the panhandle of Texas and far East Texas (Fig. A3.8f). The time period from 1930-1940 was the driest in the panhandle region in association with the Dust Bowl that was prevalent across the Great Plains. The 1910-1920 time period was most responsible for the high percentage of droughts in the first quarter of the 20th century in East Texas.

According to Figs. A3.9a and A3.9b, the greatest frequency of exceptional droughts occurred in the first two decades of the 20th century and was prevalent over East Texas. The drought of the 1950s was most severe in the present-day 1-35 corridor from Austin to San Antonio. With the exception of the period 1950-1960, the number of severe droughts from 1930 through 2000 was extremely low when compared to the numbers from 1900-1930.

The next section deals with the more specific durations of drought, breaking down the exact time periods of climate-division drought for the four different drought thresholds of interest. The subsection following this next penultimate subsection adjust the USHCN state averaged and COOP climate division averaged variance-adjusted time series for the century-long trend. Would a changing mean of precipitation cause the inordinate amounts of moderate to severe droughts in the first part of the 20th century and a relatively low number toward the end of the 20th century? The maps shown for the decadal percentages of moderate and severe droughts will be recreated after adjusting the time series of variance-adjusted precipitation.

F. 20th Century Drought Durations and Intensities for COOP Climate Divisions

The figures associated with the previous section (Figs. A3.6-A3.9) depicting the percentage of months below the two drought threshold cannot tell the entire story of drought throughout the 20th century, nor can they tell the entire story for the shorter periods of time. The goal of this section is to provide a basic visualization of the specific period of droughts below each of our four drought thresholds.

For each of the four thresholds, there is a straight line that will have patches of color denoting the intensity of drought for certain periods. These patches will show up if a climate division averaged 12-month precipitation value from the CqY dataset was below the 20th percentile. The four 25-year quarters of the 20th century will be investigated (Figs. A3.10-A3.13) rather than the 20th century as a whole in order to get a better resolution of the different droughts and intensities of these droughts.

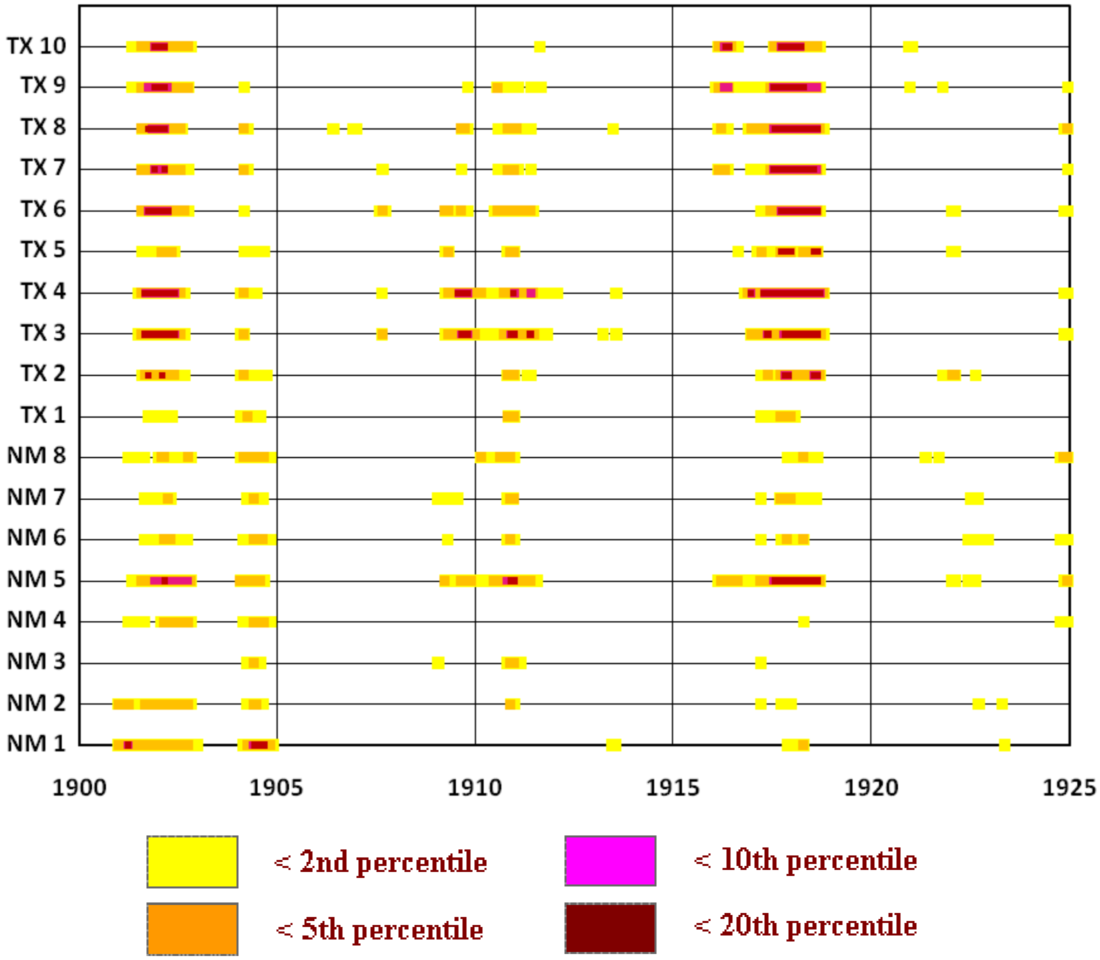


FIG A3.10. Periods in the time frame 1900-1925 when 12-month running climate division averaged values, from the CqY dataset were below the thresholds specified by the colors.

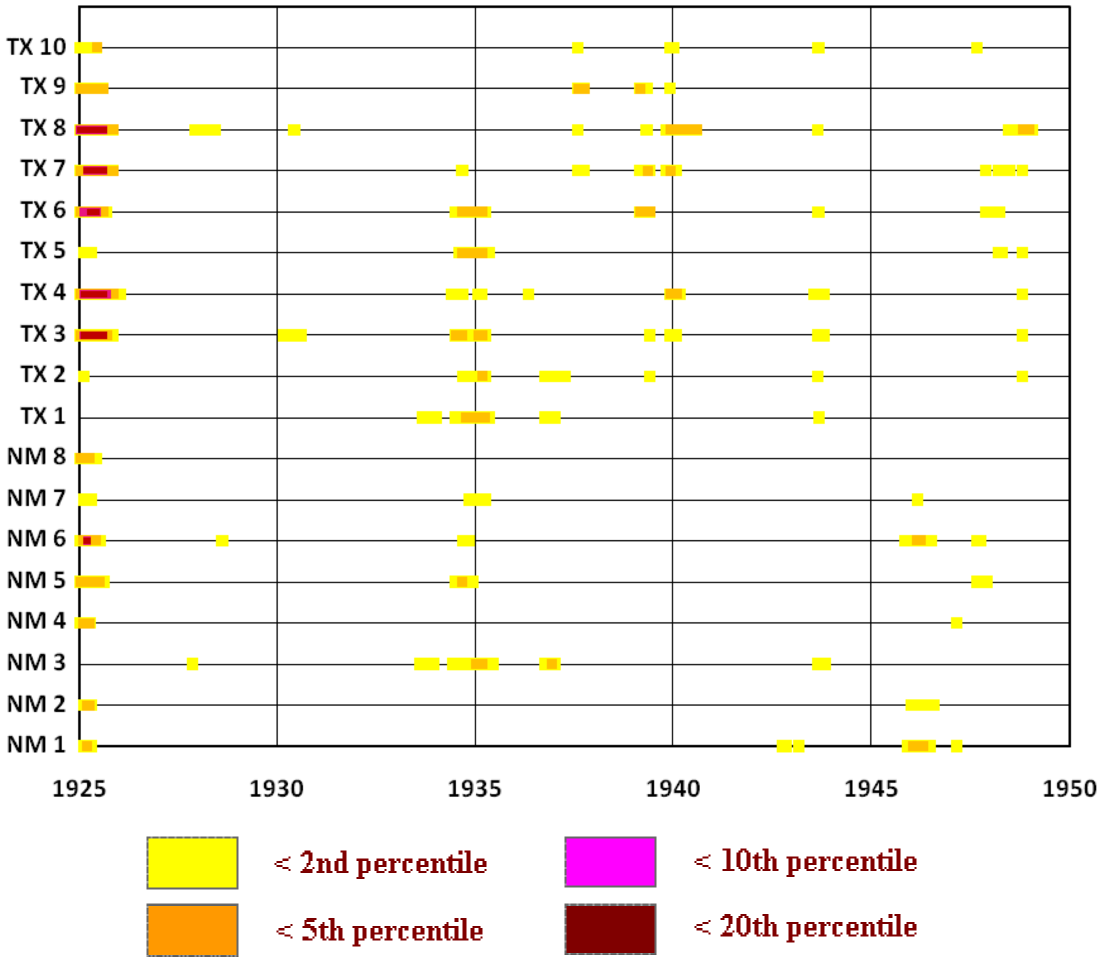


FIG A3.11. Periods in the time frame 1925-1950 when 12-month running climate division averaged values, from the CqY dataset were below the thresholds specified by the colors.

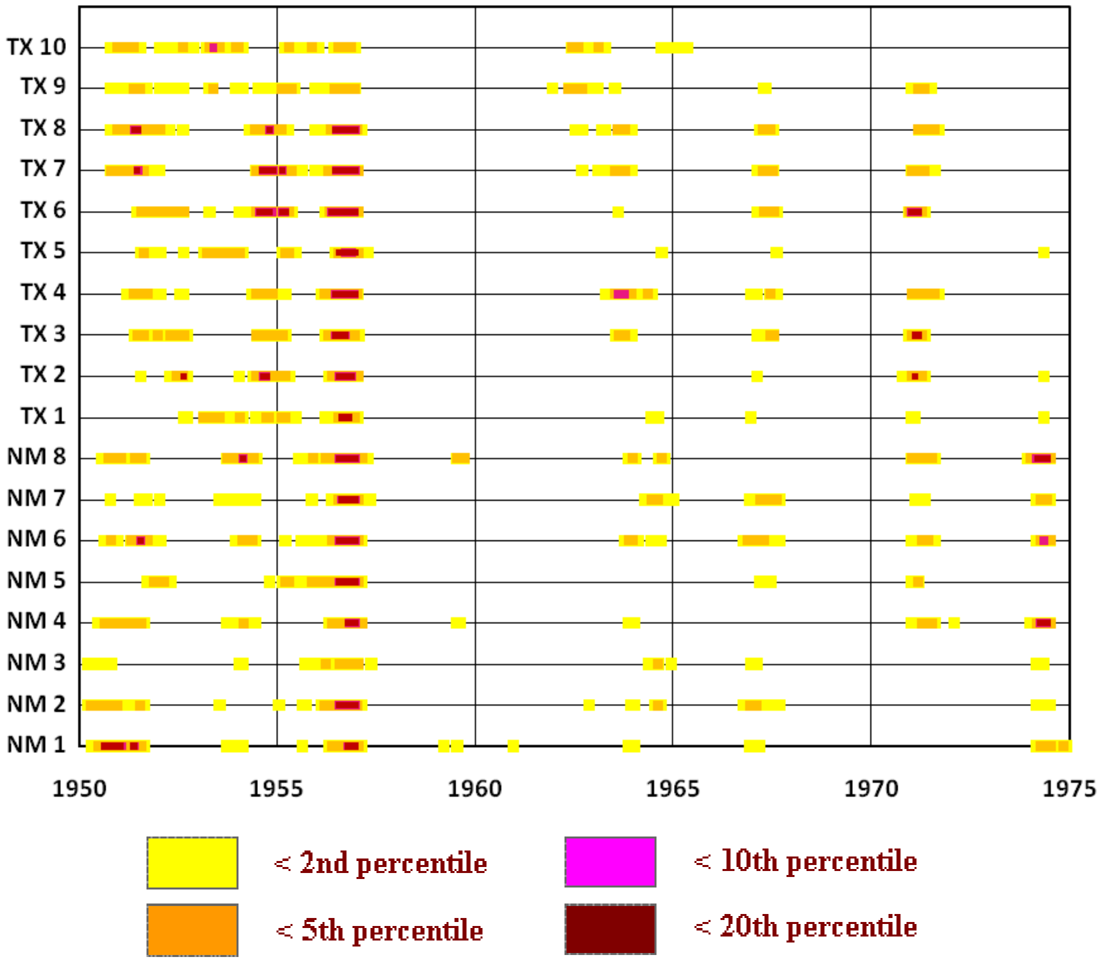


FIG A3.12. Periods in the time frame 1950-1975 when 12-month running climate division averaged values, from the CqY dataset were below the thresholds specified by the colors.

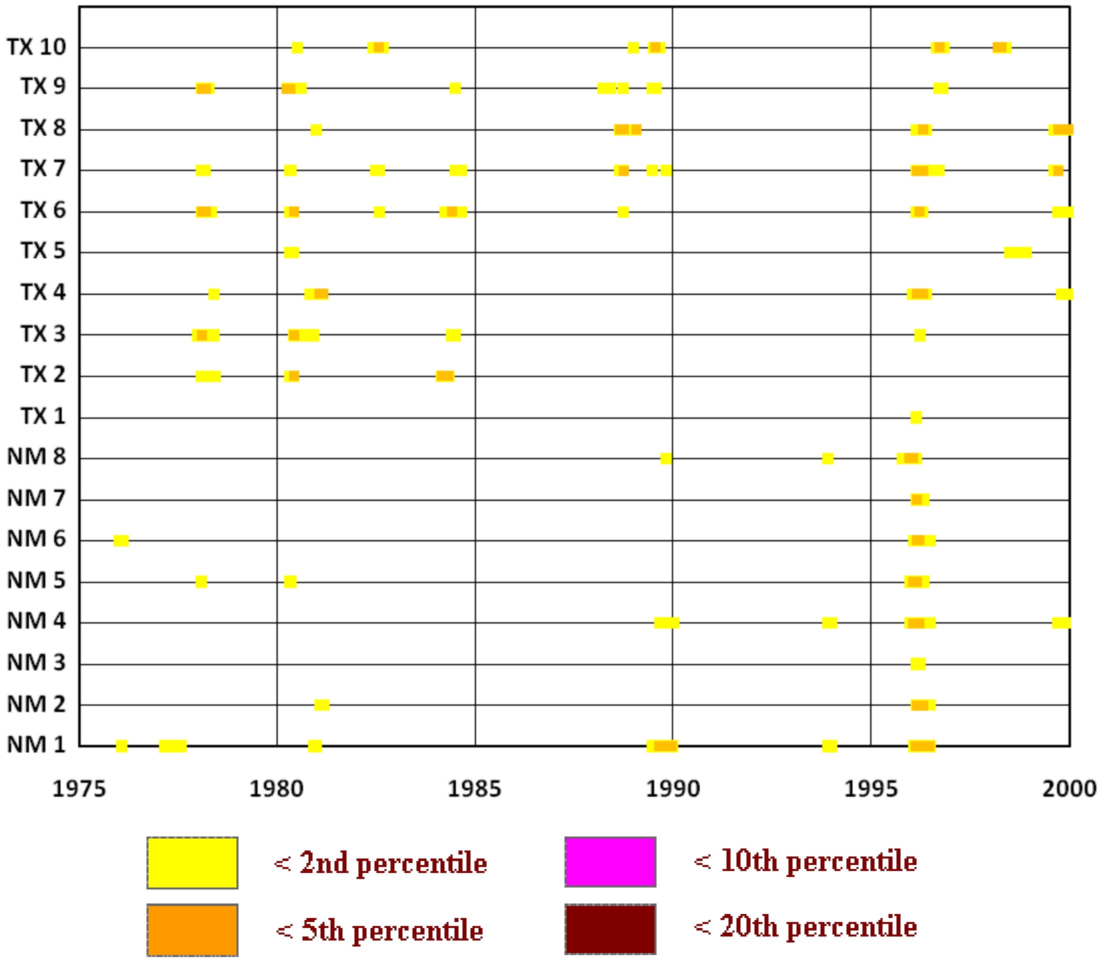


FIG A3.13. Periods in the time frame 1975-2000 when 12-month running climate division averaged values, from the CqY dataset were below the thresholds specified by the colors.

The analyses of drought duration for different thresholds based on 12-month running precipitation totals make it very clear when drought affects the different climate divisions. Every climate division in New Mexico and Texas experiences at least a moderate drought through most of the 1950s. These analyses also back up the previous conclusion that the 1980s were a wet decade throughout the entire state of New Mexico. The state of Texas, based on the drought definitions based on percentiles of distributions, had very few major drought episodes from the drought period of the 1950s through the end of the 20th century. Exceptional droughts were frequent from 1900-1930 across Texas but none of these periods were sustained as long as the drought in the 1950s.

The lengths of droughts appeared to be longest in the first 25-year period and during the long-term drought of the 1950s. Generally speaking, the periods of drought toward the end of the 20th century were much shorter in duration than those during the first half of the century. Also, the severity of droughts has lessened toward the end of the 20th century when compared to the earlier drought periods. There were only four short during the last 25-year period in which 12-month precipitation totals fell below the 5th percentile (red on Fig. A3.13) and at no time in any climate division was there a 12-month exceptional drought.

G. Adjusting Precipitation for Overall 20th Century Trends

The analyses of precipitation trend show that for the most part, precipitation is increasing on all time scales. The literature review on drought and precipitation trends suggests most of this occurs in extreme precipitation events. Whatever the case, mean precipitation is not a static quantity so it is useful to adjust the precipitation distribution to account for these changes over time. This last section will focus on analyses of precipitation time series using the trends in ULY station data (Fig. A2.1) and CqY climate division averaged data (Table A2.1), which formed the *UTY* dataset for the USHCN long-term stations and the *CTY* dataset based on modification of the CqY dataset.

The first analysis adjusts the 12-month precipitation totals according to the USHCN trends, creating a new time series plot for the statewide averages from Texas and New Mexico (Fig. A3.14). The second group of analyses (Figs. A3.15-A3.17) is similar to the MWZ analyses in Figures A2.2 through A2.5 and again, adjusts the 12-month MWZ values to adjust for the 20th century trends in precipitation for each COOP station.

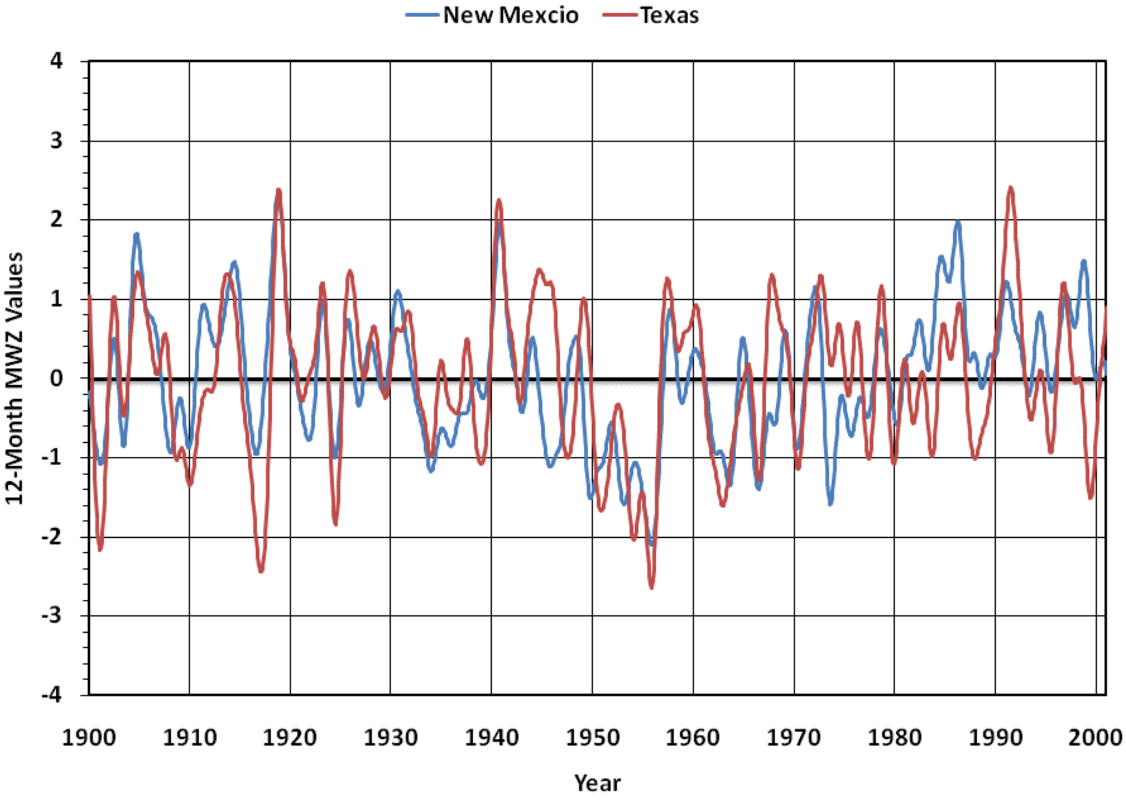


FIG A3.14. Time series of 12-month running precipitation MWZ values. These values are statewide averages for both New Mexico and Texas using actual the UTY dataset.

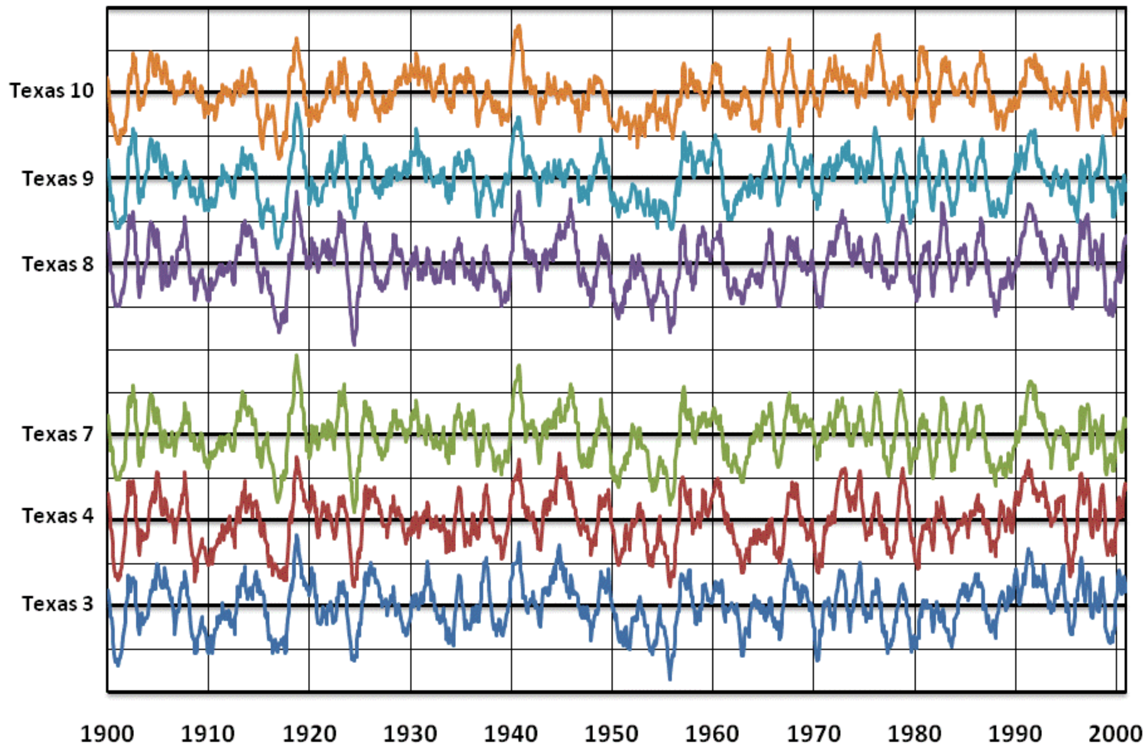


FIG A3.15. Time series of climate division averaged 12-month running precipitation MWZ values for the East Texas region using the CTY dataset, with each bold line representative of a climate division averaged MWZ value of zero and each horizontal line an increment of two.

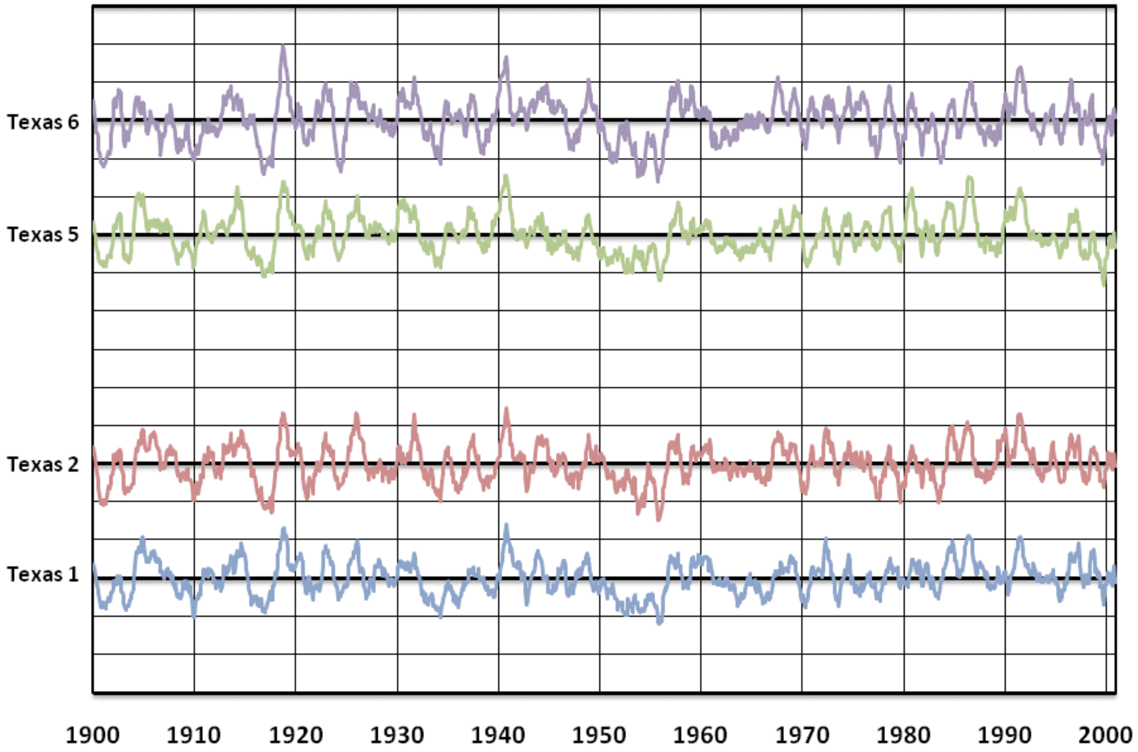


FIG A3.16. Time series of climate division averaged 12-month running precipitation MWZ values for the West Texas region using the CTY dataset, with each bold line representative of a climate division averaged MWZ value of zero and each horizontal line an increment of two.

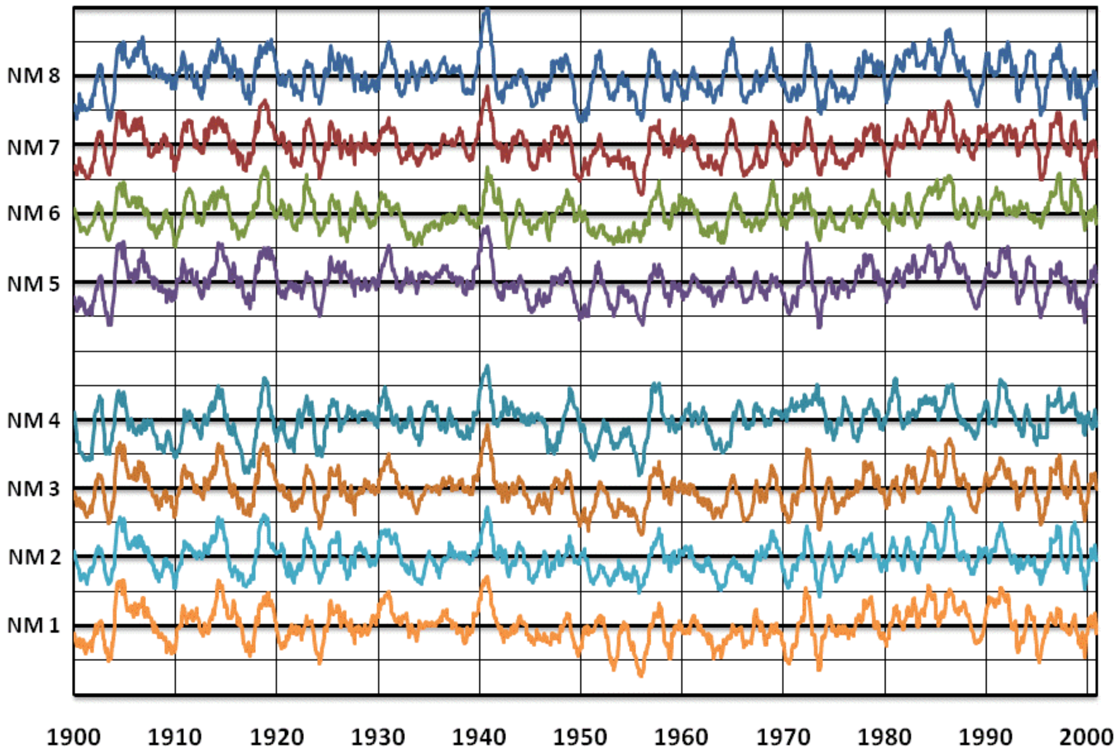
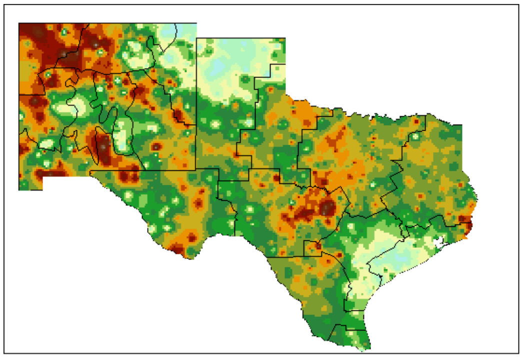
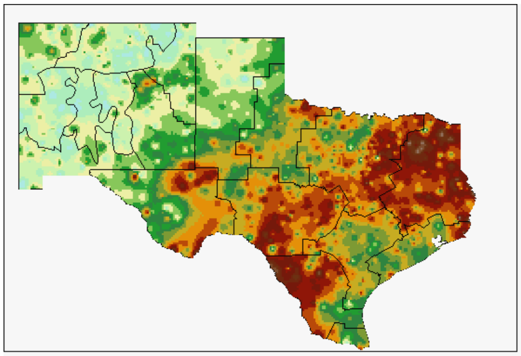


FIG A3.17. Time series of climate division averaged 12-month running precipitation MWZ values for the New Mexico region using the CTY dataset, with each bold line representative of a climate division averaged MWZ value of zero and each horizontal line an increment of two.

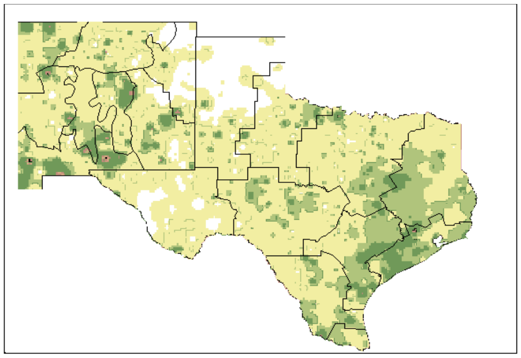
The last set of analyses looks at the 20th percentile (Figure A3.18) and the 2nd percentile (Figure A3.19) in a similar manner to the decadal maps showing drought percentages with good spatial density for the CqY dataset. The exception is that the century-long trend has been subtracted from each of the 12-month values; more plainly the CTY dataset is used. Again, the goal of this analysis is to judge drought on the assumption that the mean precipitation has not remained static over the past century and that the criteria for drought have changed along with a shift in the COOP station precipitation distributions. Figures A3.18 and A3.19 are sets of contour maps showing the spatial differences in drought across the ten decades of the 20th century.



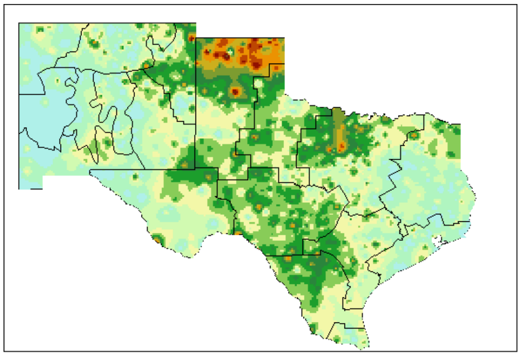
(a) 1900-1910



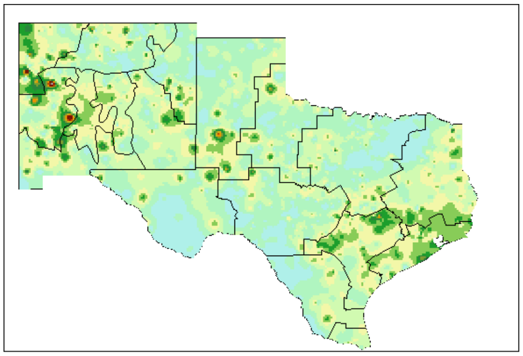
(b) 1910-1920



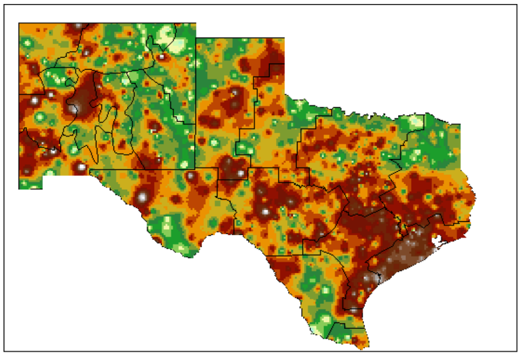
(c) 1920-1930



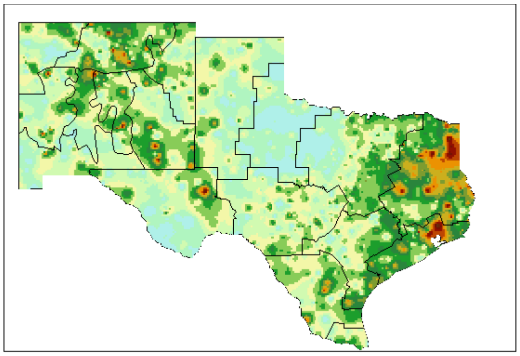
(d) 1930-1940



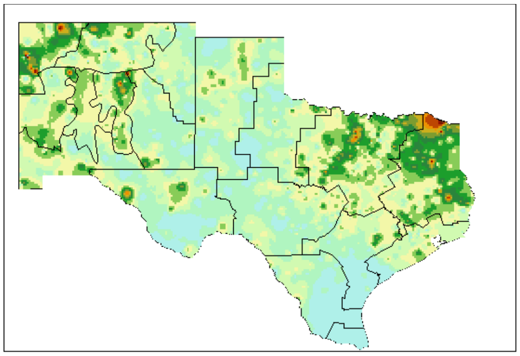
(e) 1940-1950



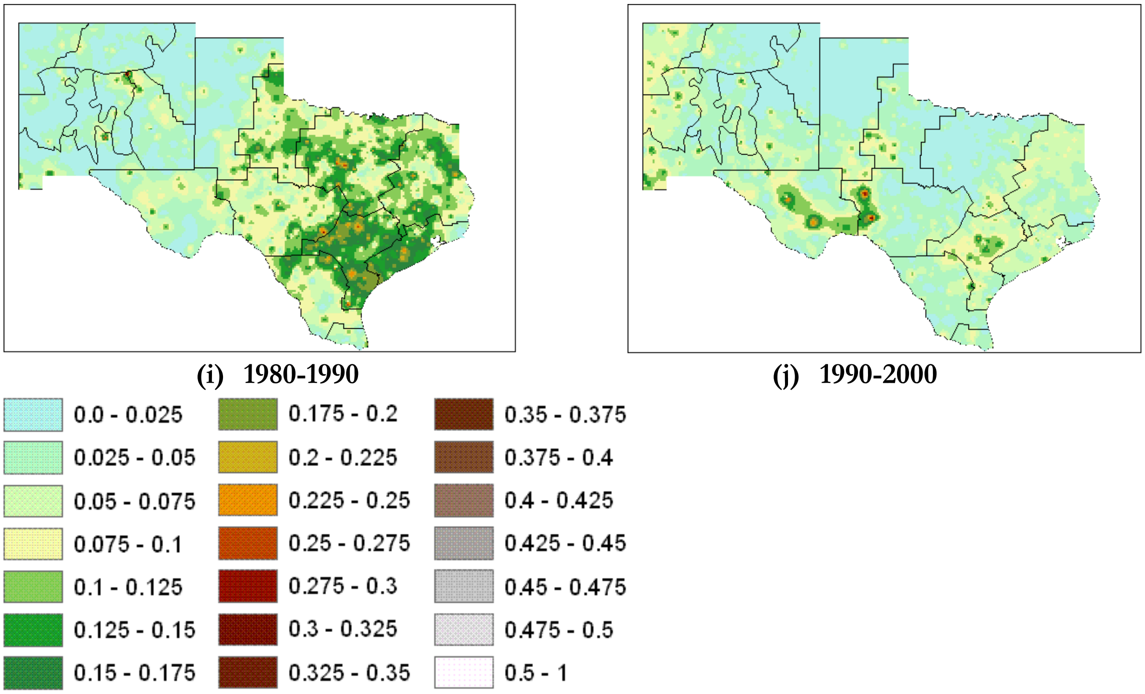
(f) 1950-1960



(g) 1960-1970



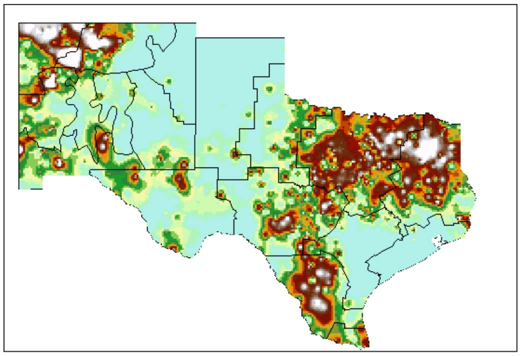
(h) 1970-1980



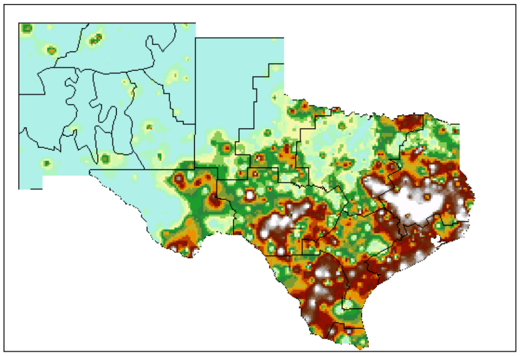
(i) 1980-1990

(j) 1990-2000

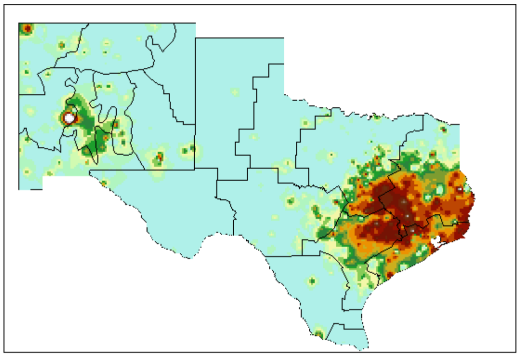
FIG A3.18. COOP station maps color-coded according to the percentage of months below the 20th percentile of its given distributions for the periods 1900-1910 (a), 1910-1920 (b), 1920-1930 (c), and 1930-1940 (d), 1940-1950 (a), 1950-1960 (b), 1960-1970 (c), and 1970-1980 (d), 1980-1990 (a), 1990-2000 (j) using the CTY dataset. The legend denotes the fractional percentage for the colors on the maps.



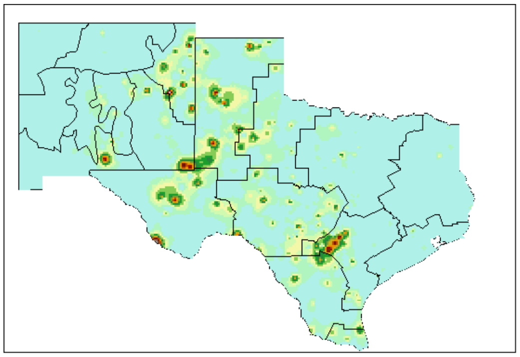
(a) 1900-1910



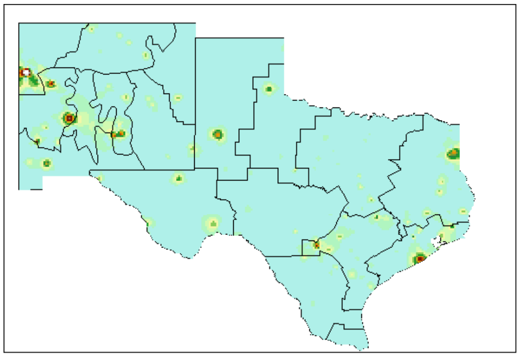
(b) 1910-1920



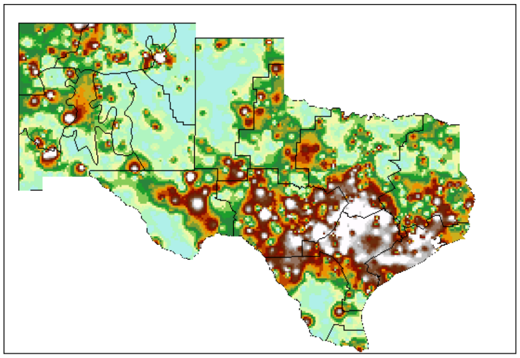
(c) 1920-1930



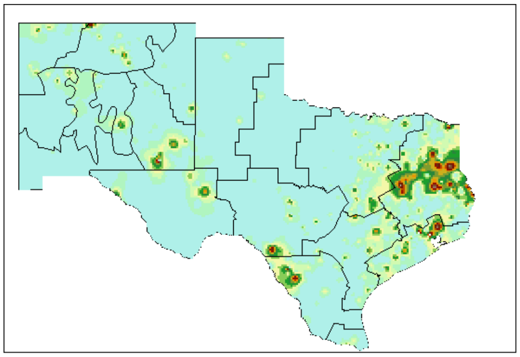
(d) 1930-1940



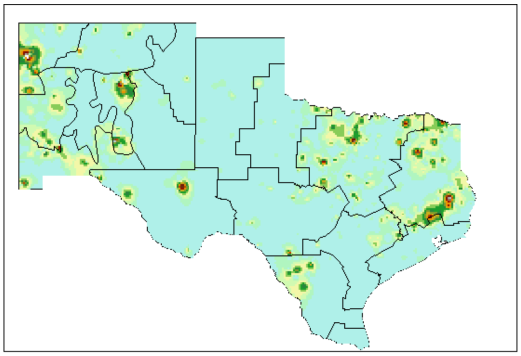
(e) 1940-1950



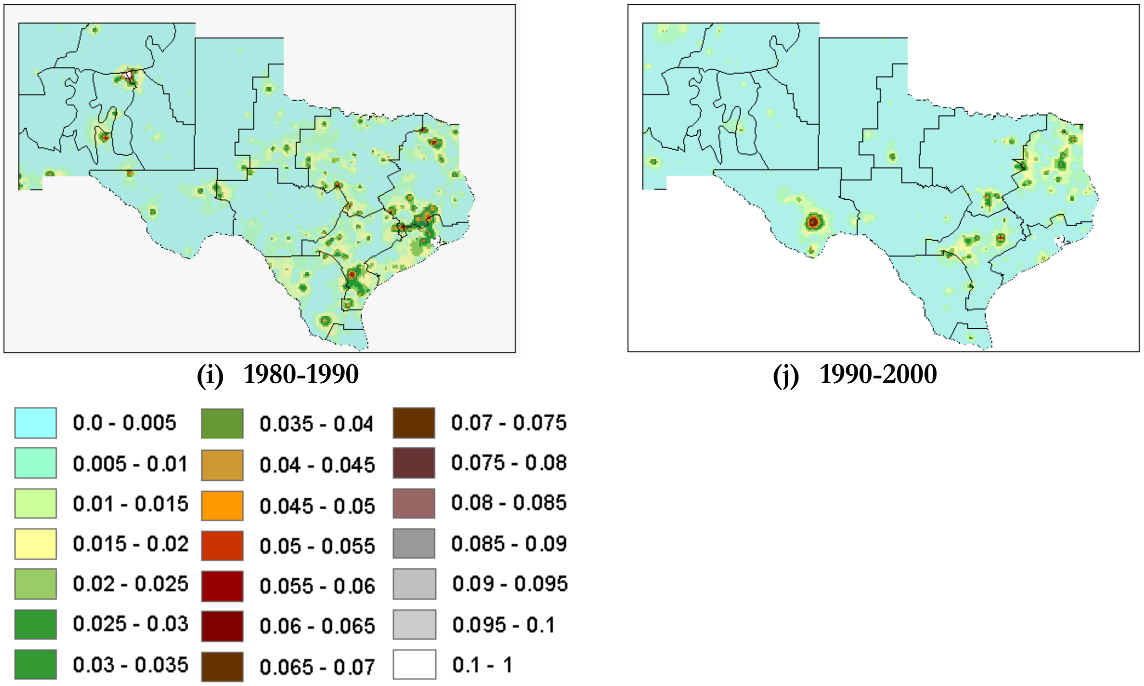
(f) 1950-1960



(g) 1960-1970



(h) 1970-1980



(i) 1980-1990

(j) 1990-2000

FIG A3.19. COOP station maps color-coded according to the percentage of months below the 2nd percentile of its given distributions for the periods 1900-1910 (a), 1910-1920 (b), 1920-1930 (c), and 1930-1940 (d), 1940-1950 (a), 1950-1960 (b), 1960-1970 (c), and 1970-1980 (d), 1980-1990 (a), 1990-2000 (j). using the CTY dataset. The legend denotes the fractional percentage for the colors on the maps.

4. Summary

The goal of the work done in the following study was to design a method to create a homogeneous datasets for the specific purpose of studying drought over the past century in Texas and New Mexico. This was a complicated process because there were a number of deterrents that get in the way of transforming data at specific stations into time series data that are useful in terms of detecting climate trends. Of course, the only manner to study past climate trends that may signal drought or any other event is to have datasets that have disturbances not related to climate at a minimum.

Therefore, it was deemed vitally important to create a process by which to take the numerous COOP precipitation data available for study and transform these data into something useful for studying drought. Though temperature data were not explicitly analyzed in this specific study, steps were taken to create a process to homogenize these data as well. The IWSD interpolation scheme was chosen as the best candidate to accomplish these goals after a thorough investigation of several data interpolation schemes.

However, the Sun and Peterson (2005) scheme was designed to investigate climate normals so some adjustment was needed to work with the monthly data that was the foundation of this study. Several tests were created in order to adjust the scheme to fit monthly data and this was possible due to the presence of the USHCN dataset created by NCDC. These highly quality-controlled data were used as the cornerstone of the interpolation process and any values created were indirectly related to this subset of stations.

The COOP dataset was a much more expansive dataset, but in order to maintain the integrity of the interpolation scheme designed in this study, not all of the available stations could be used. Therefore the creation of a thorough quality-control check of the COOP data was necessary to ensure that rogue values did not disrupt the interpolation process of the several analyses related to drought that followed. Also, the accuracy of the USHCN data values were not taken for granted so a fairly detailed metadata study was performed on the Texas and USHCN stations. The goal of this was to ensure that there was a subset of USHCN stations with a high degree of confidence in the homogeneity of the values.

The result of the interpolation process was the creation of several COOP and USHCN datasets each of which had some aspect of the interpolation process tweaked. The result of each dataset were two distinct time series at each COOP and USHCN station, one containing the actual values and another containing the data from the interpolation process.

The interpolated data are important not only because they are designed to reduce inhomogeneities but because they are more numerous. For the most part, the resultant interpolated data times series at each station were serially complete with values over the entirety of the 20th century. This was important because the vast majority of the COOP stations used in this study contained data records for less than half of the 20th century.

Further research into the distributions of monthly precipitation totals led to the approximation of these time series as containing data fitting a gamma distribution. Also, tests on the variance of the interpolated data found that the interpolated process created distributions with artificially low variances. This was adjusted for with the creation of a third time series at each station that adjusted these interpolated variances to more realistic values.

Several of the datasets were investigated to determine the spatial characteristics of precipitation over the 20th century in Texas and New Mexico. A strength of the COOP dataset is its spatial density, but unfortunately these data are too numerous to show any specific statistical analyses so it was deemed necessary to group these data by climate division in order to show the trends and characteristics of these data. The analyses on precipitation trends showed that datasets agreed for the most part, but that the presence of the interpolated and variance-adjusted datasets compensated for some unrealistic values in the actual datasets.

The first of two datasets considered to have the most reliable data for analyzing past precipitation data were the USHCN dataset containing only the actual recorded data for stations containing century-long precipitation records. The second was the COOP datset containing the variance-adjusted data derived from the interpolation process in which only USHCN station with a high degree of confidence in their homogeneity were used.

The analyses created by the several datasets did not uncover any trends in climate or drought that were not known before the start of this project. However, the reduction of inhomogeneities in the datasets was the goal of this study because using data free from signals unrelated to natural climatic trends will be the key to understanding the behavior of drought. A clear understanding of past climatic trends preceding drought conditions, such as those in the 1950s, will enable those in charge to better allocate resources and prepare for droughts that are bound to happen in the future.

Supporting Material: Section A. Interpolation Methodology for Filling Missing Precipitation Values

This IWSD weighting technique for neighboring stations used by Sun and Peterson (2005) is described, followed be followed by discussion of modifications to the process. IWSD is a scheme that assigns more weight to the neighboring stations with precipitation (temperature) values closer to the value at the target station based on the year for which both the target and neighboring stations have precipitation (Sun and Peterson, 2005). An important note is that a separate time series is created for each station containing interpolated values. However, datasets containing interpolated data and used for analyses contain actual data at each station when available and use an interpolated value when this value is not available. The equation of interest is Eq. (1):

$$w = \frac{1}{\sum_{i=1}^{12} (P_{neigh} - P_{target})_i^2} \tag{1}$$

In Eq. (1), *i* represents the month in a year from January to December, *neigh* refers to a neighboring station, and. *target* refers to a target station. The weighting scheme for temperature is identical to that used for precipitation, based on data-driven correlations between a target station and neighboring stations.

Instead of monthly precipitation totals, Sun and Peterson (2005) are interested in monthly anomalies to climate normals for a target station. The method to estimate normals is based on the fact that monthly anomalies at any given location are similar to those in neighboring stations. The relationship for precipitation can be described as either a departure, $(P - N)_{target} \approx (P - N)_{neigh}$, or as a ratio, $(P / N)_{target} \approx (P / N)_{neigh}$.

Sun and Peterson (2005) sought to determine the ideal number of stations to be used in the interpolation of monthly precipitation normals at a target station. Sun and Peterson (2005) found that the January and July numbers for TMIN are 22 and 32 and for TMAX are 18 and 23 respectively. For precipitation, it was decided that 11 neighboring stations within ~78 km of a target station was suitable. Results indicate that errors for the stations using the ratio method are slightly greater than those using the departure method. For example, the difference of error between the two methods associated with the use of COOP data from 11 neighboring COOP stations reaches about 1.0% in January and 1.7% in July (Sun and Peterson 2005).

The modified equation from Sun and Peterson (2005) for weighting each USHCN station for a particular month is shown in the following Eq. (2).

$$Weight(neigh, month) = \frac{n}{\sum_{k=1}^{n} (value_{neigh,month,k} - value_{target,month,k})^2} \tag{2}$$

In Eq. (2), the subscript *k* refers to a particular year that both the target COOP station and the USHCN station had available data and *n* refers to the number of years this occurred. For instance if there are 12 years in which January data appears for both the target COOP station and a USHCN station the sum will include twelve differences. For each month, the weights are normalized for all USHCN stations by multiplying by the number of years (*n*) in which both the COOP and USHCN data are available. This is done so that the 221 weights totaled for each of the 12 months can be accurately compared.

The total precipitation for both the COOP stations and the USHCN stations are then calculated for each month to determine a bias. Continuing on the example above, the January bias for the USHCN station would be calculated by dividing the sum of the 12 USHCN precipitation totals by the sum of the 12 COOP totals to get a ratio bias. This ratio bias is very similar to the ratio described by Sun and Peterson (2005). The possible interpolation of negative precipitation values was the deciding factor of not using a departure bias. In addition, there were small differences in error values between the ratio and departure methods used by Sun and Peterson (2005). A bias greater than one indicates a USHCN station has a wet bias compared to the target COOP station for that month. The bias of each USHCN station for a particular month with respect to a target station is described by the following Eq. (3).

$$Bias(neigh,month) = \frac{\sum_{k=1}^{n} value_{neigh,month,k}}{\sum_{k=1}^{n} value_{target,month,k}} \qquad (3)$$

The subscript k in Eq. (3) refers to a particular year in which both data from the COOP and target USHCN station were available for the month of interest and n refers to the number of years this occurred. For both the weighting and bias calculations for the twelve months at each USHCN station, less randomness will occur with an increase in the available number of data.

The final few steps of the interpolation involve a slight modification of the Sun and Peterson (2005) IWSD scheme in which distance becomes an important variable. Starting with January 1900 through December 2001, each month is analyzed to see if an interpolated value can be created, which leads to a serially complete record for precipitation at any given station.

For each month in this period, the closest twenty USHCN stations are analyzed to see if four or more stations have data available for this month. If so, the four stations with the highest weights for this particular month of the year are used to create an interpolated value. The use of four stations in the final interpolation value is based on the work of Eischeid et al. (1995), which concluded using four target stations was ideal using this type of interpolation scheme.

The following Eq. (4) shows how this value is calculated for any particular month in this period.

$$Interpolated\ value(month,\ year) = \frac{\sum_{i=1}^{4} weight_{i,month} \times value_{i,month,year}}{\sum_{i=1}^{4} weight_{i,month} \times bias_{i,month}} \qquad (4)$$

When there are fewer than four stations available for a month and year within the twenty closest USHCN stations to the target station, the process is repeated continuously by adding the next closest station until four stations with data for a particular month and year are found. For instance, if the 20 closest USHCN stations to a target station for January 1900 yield only three with data available, the program will continue to look for the next closest station until one with data is found. This process keeps distance as an important variable but assures that four stations will be used in the interpolation regardless of their distance to the target station.

At each COOP station, the dataset used in the precipitation trend and drought analyses have modifications because of the differences in variance between the actual and interpolated time series distributions. Therefore, each interpolated value used to fill gaps in a station's time series must be adjusted to account for this difference. This adjustment of interpolated values is described in further detail in the supporting materials, section B.

Supporting Material:
Section B. Variance-adjustment of Interpolated Values

The variance-adjustment of monthly precipitation totals for a given USHCN or COOP station is based on gamma distribution statistics. Research on the fit of gamma distributions to monthly precipitation distributions stretches back several decades. Barger and Thom (1949) found that the gamma distribution provided good fit to precipitation series in the United States. Momiyama and Mitsudera (1952) fit the gamma distribution to monthly rainfall totals over Japan while Mooley (1972) used a gamma distribution modal for the Asian summer monsoon. Klein and Bloom (1987) found filling monthly precipitation totals using a gamma distribution was desirable. The NCDC bases their monthly precipitation probabilities from the 1971-2000 United States Climate Normals on fitting a gamma distribution.

The actual data time series and interpolated data time series for a station can be represented as distinct gamma distributions. Eq. (5) describes the probability of a particular monthly total *x* for a given series. The gamma distribution is a two-parameter family of continuous probability distributions with shape parameter □ and scale parameter□□

$$f(x,\alpha,\beta) = x^{\alpha-1}\frac{e^{-x/\beta}}{\beta^{\alpha}\Gamma(\alpha)} \quad \text{for } x > 0 \text{ and □□□□ } > 0 \qquad (5)$$

Because the data is limited for each time series, it is necessary to estimate the shape parameter $\ddot{\alpha}$ and the scale parameter $\ddot{\beta}$ using another quantity *D* (Wilks 2006). The equation for *D* in Eq. (6) is given and uses the mean of the time series and the natural logarithms of each value within the time series. Using this quantity D for a given time series, whether it is an actual time series or interpolated time series, it is possible to find the estimator $\ddot{\alpha}$ given in Eq. (7). After the estimator $\ddot{\alpha}$ is found, it is then possible to find the estimator for the size parameter $\ddot{\beta}$ using Eq. (8) given $\ddot{\alpha}$ and the mean of the time series $\overline{X}$. The gamma distributions for the actual and interpolated time series for a given station determine the sample mean $\overline{X}$ and sample variance s^2, shown in Eq. (9) for each series.

$$D = ln\left(\sum_{i=0}^{n} x_n\right) - \sum_{i=0}^{n} ln(x_i) \qquad (6)$$

$$\ddot{\alpha} = \frac{1+\sqrt{1+(4D/3)}}{4D} \qquad (7)$$

$$\ddot{\beta} = \frac{\overline{X}}{\ddot{\alpha}} \qquad (8)$$

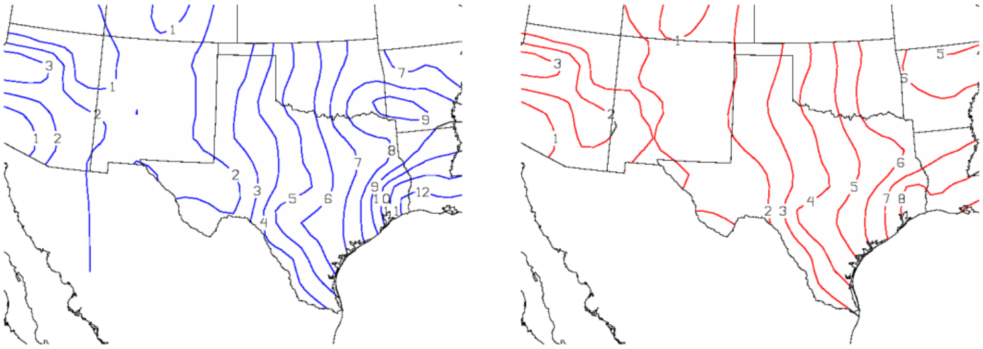
$$s^2 = \alpha\beta^2 \qquad (9)$$

In an ideal world the sample mean of the actual time series and interpolated time series for a particular station would be equal. However, the interpolated time series generally samples a larger time period whereas most stations have an actual time series with large gaps in the record. For instance, if a COOP station has actual values (sample population) only taken in a relatively wet period, the actual mean for that distribution will be larger than the interpolated mean for that same station.

Therefore, the interpolated time series sample mean ($\overline{X}_{interpolated}$) and actual time series sample mean ($\overline{X}_{actual}$) are unequal for the vast majority of COOP and USHCN stations. Because $\overline{X}_{interpolated}$ is in the majority of cases based on a more temporally complete time series and larger sample population, the mean of the variance-adjusted time series ($\mu_{variance-adjusted}$) is assumed to be equal to $\overline{X}_{interpolated}$.

Using the estimators of the shape $\ddot{\alpha}$ and scale parameter□ $\ddot{\beta}$□ for each series at a particular station, cumulative distribution function (CDF) values for each series were calculated. The CDF value for a given random variable X represents the probability that the X takes on a value less than or equal to x, where $0 \leq x \leq 1$ (Wilks 2006). Precipitation values were increased incrementally from zero by a hundredth of an inch, with each value assigned a CDF value. This process is repeated until the CDF value reaches one. For each hundredth of an inch, the CDF value represents the probability of precipitation being less than or equal to that monthly precipitation total.

Differences in the precipitation variance values between the actual and interpolated time sereis datasets are important to adjust for in creating accurate long-term records at each COOP station. Analysis of these variances for both the actual and interpolated USHCN station time series datasets appear in Figure A-B.1. An intracomparison within each map demonstrates the spatial differences throughout Texas, New Mexico, and surrounding states. Comparisons between the two maps demonstrate the differences in variance magnitudes between the actual and interpolated USHCN time series datasets for each station. Figure A-B.1 contours the variances for the actual (a) and interpolated (b) USHCN monthly variances.



(a) Actual

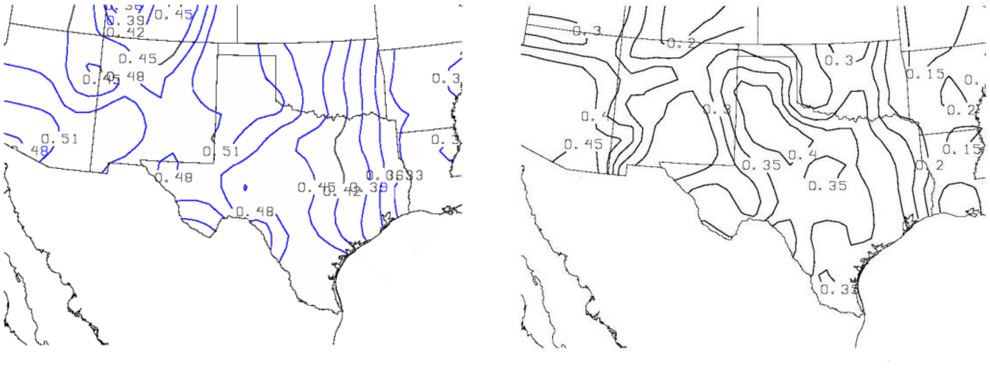
(b) Interpolated

FIG A-B.1. Maps of USHCN variances using the actual dataset (a) and the interpolated dataset (b).

The spatial distributions of monthly precipitation variance are similar when compaing the actual and interpolated USHCN datasets. Generally, the variance decreases from East to West, with a minimum in monthly variances in New Mexico and the largest monthly variances in Louisiana. The main difference between the two datasets is the magnitudes of the variances in the actual dataset are larger than variances in the interpolated dataset.

The differences in variance are the driving force behind the creation of a third dataset that acts to replicate the variance of the actual USHCN monthly precipitation variances but has the data availability of the interpolated dataset. A spatial distribution map of variances for the third variance-adjusted dataset for both USHCN and COOP stations would be nearly identical to that in Figure A-B.1(a). This is because the variance at each station is an average of the variances from the nearest two USHCN stations.

Another measure of variability would be the normalized variance which takes the variance of a distribution divided by its mean. Figure A-B.2 is a spatial plot of the actual dataset normalized variance (a) and the interpolated normalized variances. The normalized variance takes the variance of a particular time series and divides by the sum of the squared values in the time series (Wilks 2006).



(a) Actual (b) Interpolated

FIG A-B.2. Maps of USHCN normalized variances using the actual dataset (a) and the interpolated dataset (b).

The results from Figure A-B.2 show the variance of precipitation normalized by how much precipitation an area actually receives. This statistic has important implications for drought because higher values of normalized variance would mean an area is more likely to be at either end of its precipitation distribution. From both maps on Figure A-B.2, it is plain to see the largest magnitudes of normalized variance are in West Texas and New Mexico.

A large percentage of the COOP time series have periods of records shorter than 20 years. This small sample population might lead to unrealistic means and variances for these stations. The variances of all the interpolated precipitation time series are unrealistically low. In order to get a variance representative of a century-long time series, the variance of this third series ($\sigma^{2}{}_{variance-adjusted}$) was assumed to be an average of the two closest USHCN station variances. The two USHCN station variances were based on the actual time series data and not the interpolated time series of values. Therefore, $\sigma^{2}{}_{variance-adjusted}$ is more indicative of the variance of actual time series data for a given station.

The interpolated dataset variances for each station are generally smaller than the actual dataset variances. Because each interpolated value is a weighted average of four stations, extreme actual values may be moved closer to the mean value for a data series by the interpolation if the actual monthly value is isolated in nature. This can be especially problematic of summertime precipitation which is very erratic and can produce isolated monthly rainfall totals far exceeding the mean total of surrounding regions.

For a specific station, the data in the third time series uses data from the actual time series and interpolated time series for that station. In the case an interpolated monthly value is available, the actual value is assigned a CDF value based on the distribution of interpolated precipitation values for that station. The variance-adjusted precipitation value for that particular month is the precipitation value that matches the CDF value in the variance-adjusted distribution. For months an actual value is available, that actual value is used in the time series.

Supporting Material:
Section C. Mann-Whitney Z Values

To compare trends between different USHCN stations and COOP climate divisions with different precipitation means and variances, it is important to create a dimensionless variable that can indicate extremes in precipitation trends. The Z-statistic normalizes the data within a station's time series based on its mean and variance. Higher magnitude Z-statistics that are negative are indicative of drought and higher magnitudes of positive Z-statistics indicate a positive anomaly of precipitation for a given time period.

For precipitation, Z values were calculated using the Mann-Whitney method developed by Mann and Whitney (1947). Mauget (2003) looked at peak periods of the Z-statistic value for both high precipitation ($Z > +1.645$) and drought ($Z < -1.645$) using the Mann-Whitney Z (MWZ) statistic. The MWZ for precipitation at a given time is calculated according to the Mann-Whitney U statistic. This U statistic introduces an element of objectivity and identifies extreme rankings in a sample (Mendenhall et al., 1990).

Depending on the accumulation period of interest, the monthly precipitation totals for a given dataset are divided into two classes of data (Class I and Class II). If one is interested in trends on annual time scales, Class II contains monthly values for one specific year-long period, and the other class (Class I) contains the rest of the monthly values for the entire time series.

For example, in a comparison of the 12-month period in the year 1999 to every other available 12-month period at a given station, Class II contains the twelve monthly values from the year 1999 and Class I contains the rest of the monthly values available in that station's time series. The Mann-Whitney U statistic for each period in Eq. (11) equals the number of Class I members that precede each member of Class II when all the data values are ranked from smallest to largest.. Rank I_i is the rank of the *i*th member of Class I and □ (Rank I_i, Rank II_j) = 1 if RankI_i < Rank II_j and □ (Rank I_i, Rank II_j) = 0 otherwise.

$$U_{II} = \sum_{i=1}^{n_I} \sum_{j=1}^{n_{II}} \varphi\left(Rank\, I_{i,}\ Rank\, II_{j}\right) \qquad (11)$$

For each Mann-Whitney U statistic, one can calculate the MWZ based on a mean (□$_u$) and standard deviation (□$_u$) of all the U statistics calculated in the time series. In the mean, Eq. (12), and standard deviation, Eq. (13), for the time series of Mann-Whitney , n_1 and n_2 refer to the number of Class I members and Class II respectively. In a study of 12-month accumulation periods, n_2 is equal to twelve. Table AC.1 relates several important CDF probabilities used in this study to MWZ values.

$$\mu_U = \frac{n_1 + n_2}{2} \qquad (12)$$

$$\sigma_U = \left(\frac{n_1 n_2 \left(n_1 + n_2 + 1\right)}{12} \right)^{1/2} \qquad (13)$$

TABLE AC.1. Mann-Whitney Z values matched to several important CDF values.

CDF Value	**0.02**	**0.05**	**0.10**	**0.20**	**0.80**	**0.90**	**0.95**	**0.98**
MWZ Value	-2.325	-1.96	-1.645	-1.28	1.28	1.645	1.96	2.325

Supporting Material:
Section D. Metadata Investigation of New Mexico and Texas USHCN Stations

This section is devoted to the interrogation of the 24 New Mexico and 44 Texas USHCN station metadata files to determine if the locations and elevations listed in those metadata files matched up with the description of the station location. The overall goal of the metadata study was to determine if inhomogeneities filtered into the USHCN precipitation analyses, since these stations form the baseline of our interpolation process. Davey and Pielke Sr. (2005) investigated the cause of spatial discrepancies in precipitation in the USHCN dataset and found that in the precipitation data, several stations suffered from observer bias.

Therefore it was deemed necessary to further investigate the observing practices at the USHCN stations by tracing the histories of the metadata files and noting anything unusual, most likely a suspicious location. This was a subjective analysis done with the use of an internet mapping tool called *Topozone*, which gives detailed political and topographical maps at most locations around the United States. The basic idea was to match up the location description denoted in the station metadata to the latitude and longitude also provided. An example of a station metadata file, abbreviated somewhat, is included in Table AD.1 from USHCN station 412797 located in El Paso, TX.

Table AD.1. USHCN Station 412797 abbreviated metadata file.

Dates of Interest		Lat	Lon	Station Movement	Elevation	Station Location	Station Description
11 06 1877	08 12 1880	31 47	106 30	999 999	3720	-	EL PASO/ WBO
08 12 1880	11 01 1881	31 47	106 30	000 E	3720	-	EL PASO/ WBO
11 01 1881	11 01 1882	31 47	106 30	000 W	3720	-	EL PASO/ WBO
11 01 1882	04 01 1888	31 47	106 30	001 E	3720	-	EL PASO/ WBO
04 01 1888	08 08 1894	31 47	106 30	001 NW	3720	-	EL PASO/ WBO
08 08 1894	12 29 1907	31 47	106 30	000 NE	3720	-	EL PASO/ WBO
12 29 1907	06 30 1925	31 47	106 30	002 NNE	3731	-	EL PASO/ WBO
07 01 1925	04 28 1936	31 47	106 30	002 SSW	3720	-	EL PASO/ WBO
04 28 1936	12 19 1942	31 47	106 30	003 E	3711	-	EL PASO/ WBO
12 19 1942	05 07 1944	31 48	106 24	999 999	3920	57 ENE	EL PASO/ WSO
05 08 1944	04 22 1959	31 48	106 24	999 999	3920	57 ENE	EL PASO/ WSO
04 23 1959	08 31 1960	31 48	106 24	900 SW	3920	57 ENE	EL PASO/ WSO
09 01 1960	04 01 1964	31 48	106 24	000 000	3918	57 ENE	EL PASO/ WSO
04 01 1964	04 10 1978	31 48	106 24	003 SE	3918	57 ENE	EL PASO/ WSO
04 10 1978	09 20 1978	31 48	106 24	000 000	3918	57 ENE	EL PASO/ WSO
09 20 1978	11 13 1984	31 48	106 24	016 W	3918	57 ENE	EL PASO/ WSO
11 13 1984	99 99 9999	31 48	106 24	000 000	3918	57 ENE	EL PASO/ WSO

There is actually quite a bit more information in each line of a metadata file including the observer for each group of dates included and information about the instrumentation present at these times. All of the metadata files are useful in some aspect, but of most interest to this study are the dates of interest, latitude, longitude, direction and magnitude of station movement, elevation, station location, and station description columns denoted on Table AD.1.

The history for USHCN station 41797 goes back to the year 1877 and is currently still in operation, with seventeen different periods of interest. The beginning of each period denotes a time in which one or more variables have changed, many times variables not noted in Table AD.1. For instance stations entries may be due to instrumentation changes, changes in the person observing, or changes in the observing system. In addition to the metadata file, each station has an entry on the Multi-Network Metadata System kept by NCDC that contain useful remarks about station location.

Each entry in the metadata file contains a latitude and longitude listing with an elevation corresponding to its location. The second row on the metadata file contained in Table AC.1 lists a station movement of "000 E," which translates to moved less than a tenth of a mile to the east. Other magnitudes of station changes are shown in tenths of miles with the direction of movement. These station movement entries can be cues to whether a metadata file. Also of interest is the station location, which at almost every station is in relation to the post office. At the end of 1942, the station location of 412797 was 5.7 miles northeast of the post office and its name changed from "El Paso/WSO" to "El Paso/WBO."

The detailed listing by *Topozone* allows for one to match up the coordinates to an elevation provided. Given that the coordinates provided in the metadata history of each station are not extremely precise, the elevation listed did not always exactly match the coordinates. For entries in which the elevation was reasonable for given coordinates, the station period was not deemed to be suspicious. However, if the elevation departure from the listed value was too much, the station entry was deemed suspicious.

Also of some use in this analysis was the use of the station descriptions in the Multi-Network Metadata System, which often gave a description of the environment surrounding the station. For instance, in the last entry for El Paso, the observing station was described as "located on a fairly level plain about five miles west of the Franklin Mountains." If the description of the surrounding environment did not match the expectation of Topozone, the station entry was deemed suspicious. However, the suspicion in early entries was only warranted if the terrain description was not accurate, since buildings and land use can change over time.

An example of this was a station entry for USHCN Station 415272 in Llano, TX in the 1998. The description mentioned a move to a mile east-northeast of the post office to the sewer plant. However, *Topozone* did not verify this station location to be reasonable and the move was deemed suspicious. The location of the sewer plant in Llano was not in the general vicinity of the coordinates provided in the metadata. Often, the suspicious nature of move was based on a description in relation to a town's post office not matching the coordinates provided.

Another type of problem arose in USHCN station 413873 in Hallettsville, TX in which several elevations listed in the metadata did not correspond to the coordinates provided or the provided location in relation to the post office. Systematic errors in the listed metadata entries were another cause for suspicion in this study.

Through the use of *Topozone* the metadata histories of all the USHCN stations were examined thoroughly for potential biases that could possibly cause inhomogeneities in the climate record for that particular station. Stations deemed as "high quality" were deemed to have no such suspicious entries.

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Appendix B

Aerosol Factors

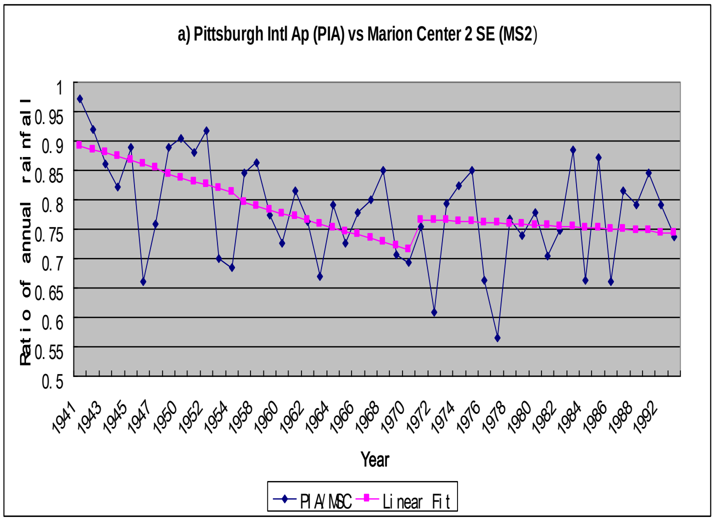
W. H. Marlow, Jun Geng, and Chu Nie

Aerosol Factors

Submicrometer aerosols capable of condensational growth to the 5μm to 10μm size range under the low supersaturation condition of the atmosphere are called cloud condensation nuclei, or CCN. If excessive aerosol particles are present in the atmosphere, there can be too many competing for limited water vapor to permit significant vapor accretion by the aerosol particle, thereby suppressing growth to the vicinity of 10 μm, the requisite first step in the development of rain. This local (urban) suppression may well contribute to formation of regional rainfall when the heavily polluted air parcel moves beyond its principal, urban aerosol sources, becomes diluted, and rises in elevation (Rosenfeld, D., et al, *Science* **321**, 1309(2008)). In the study reported here, we treated only local, urban air pollution and precipitation data.

The operational hypothesis for this study was that for selected cities, changing air quality during many decades of urban air clean-up might be related to changes in local precipitation. Our study focuses on finding the implicit relationship between urban aerosol concentrations and local, urban precipitation amount by the statistical analysis of historical data. For the purpose of our study, we chose four cities as the subjects, Los Angeles, CA, USA, Pittsburgh, PA, USA, Beijing, China, and Mexico City, Mexico. For the first two, multi-decadal records of air pollution and precipitation are available encompassing the periods before and during clean-up, that continues. In the latter cases, pollution clean-up efforts are only recent but the results from Pittsburgh and Los Angeles suggest that an identifiable relationship exists and may potentially be present there, too.

There are many factors other than the concentration of pollutant aerosols in the atmosphere that could cause fluctuations of annual precipitation, including such urban effects as heat island, changes in wind speed, and changes in land use. To eliminate the effects of such factors, our studies of Los Angeles and Pittsburgh are based upon concurrent comparisons of annual precipitation amount between two nearby sites, one polluted and one relatively clean throughout the entire study periods. Then, the changes of rainfall due to changes in synoptic conditions, like El Nino effect etc. can be minimized if not eliminated. To further reduce the urban effects, the two sites for comparison must have the same meteorological conditions. The way we chose polluted and clean sites was according to their attitude and latitude: we choose one from a highly populated urban or suburban district of the area we are interested in as the polluted one, and another one, which is neither highly populated nor heavily industrialized, but, is still nearby, as the clean one. For Beijing and Mexico City, normative data from near-by sampling stations in relatively clean locations were not available. The method of analysis we used is the following: for each pair of sites A and B, we calculated the ratio of their annual precipitation readings. We next examined the entire time period for trends in this ratio and identified what turned out to be very clear temporal changes in these trends. Here, we calculated the cumulative correlation coefficient between the ratio and the year to find the year where the absolute value of the correlation coefficient started to decrease and make this year the end point of the previous period and the starting point of the next period. Finally, we make linear fits for this ratio in every period and analyze them. Because China and Mexico do not provide enough detailed records and observation station information, we only conduct this level of study for Los Angeles and Pittsburgh. Specimen results for Pittsburgh are given in Figure B1.

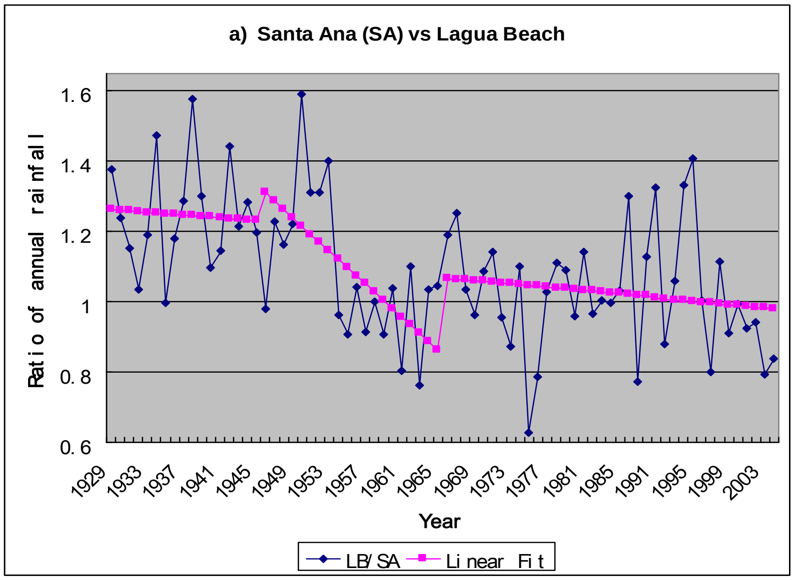


Time Range	Correlation Coefficient	t value from t test
1941-1993	-0.3461	-2.5025
1941-1970	-0.4998	-2.9420
1971-1993	0.2370	1.0631

Figure B1. Trends of ratio of annual precipitation amount of Pittsburgh International Airport (PIA) to Marion Center 2 SE (MC2): a) Raw data & linear fit b) Statistically analyzed results

Figure B1 shows the comparison between Pittsburgh International Airport (PIA), which is a polluted site within the Pittsburgh area, and Marion Center 2 SE (MC2) that is a relatively clean site northeast of the Pittsburgh area. In the time frame of 1941 to 1993 the ratio of precipitation amount for PIA to MC2 decreases with correlation coefficient between this ratio and the year of -0.3462 and t value from t-test of -2.5025. The t value from t-test is directly related to the p value that represents the statistical significance. The higher t value leads to smaller p value, which results in greater statistical significance. For example, with 70 observations and a t value of 1.67 or above, the p value is below 0.05, which shows great significance. So here, the correlation is statistically significant. When we look more closely into this trend, we find that between the years 1941 and 1970 this ratio decreases drastically with a correlation coefficient of -0.4998 and t value of -2.9420; and between 1971 and 1993 this ratio increases with a correlation coefficient of 0.2370 and t value of 1.06301. Since we know that clean-up measures for Pittsburgh started to become effective in the 1960s, this decrease and increase is clearly correlated with the cleaning up process.

Figure B2 shows the comparison between Laguna Beach (LB), which is relatively clean being very close to Los Angeles area and Santa Ana Fire Station (SA), which is a polluted area in Los Angeles. The ratio of precipitation amount for LB to SA decreases with a correlation coefficient of -0.4489 and t value of -4.2617; and between year 1946 and 1965 this ratio decreases drastically with a correlation coefficient of -0.5470 and t value of -2.8481. Like Pittsburgh, the city of Los Angeles had its worst time for air quality between about 1940-1960s while clean-up actions started becoming effective in the 1960s; so from the analysis we can see that this decreasing trend stopped about 1960. During the time period 1966-2004, the correlation coefficient between precipitation amount ratio and year is -0.1200 with t value of -0.7153, which means there is no statistical significance.



Time Range	Correlation Coefficient	t Value From t Test
1925-2004	-0.4488	-4.2617
1929-1945	0.0809	0.3247
1946-1965	-0.5470	-2.8481
1966-2004	-0.1200	-0.7153

Figure B2. Trends of ratio of annual precipitation amount of Laguna Beach (LB) to Santa Ana Fire Station (SA): a) Raw data & linear fit, b) Statistically analyzed results.

For Beijing, we found a strong negative relationship between the precipitation amount and air quality with the annual precipitation amount increasing considerably from 2001-2005. Since Beijing was authorized in 2001 to host the 2008 Olympics, the Chinese government has taken a number of actions to improve its air quality. Therefore we may suspect this increase of precipitation is a consequence of these actions much as occurred in the previously discussed examples over more extended periods when similar reductions in air pollution occurred. Further, from the beginning of 2008, the Chinese government has taken the strongest actions to reduce the atmospheric pollution in Beijing, such as shutting down industries and putting very strict limits on traffic. At this point, additional possible evidence is that, from the official report, the precipitation amount in Beijing reached a ten years' high in 2008. It is reported that until August 24, 2008, the precipitation amount of Beijing in 2008 is 207mm, which is 70% higher than the recent years' average, 90% higher than the previous year, and the highest in the last ten years (according to the official government website of Guangdong province).

For Mexico City, the government started to clean up its capital for more than one decade.

From 1996 to 2006 the annual average Total Suspended Particulate matter decreases almost by half. Since the integrated and usable precipitation data of Mexico City of this time period is very hard to obtain, the only indication of an effect is that in Mexico City rainfall has increased almost 200 mm from the turn of the last century, which corresponds well with our earlier results.

In conclusion, we have found by the analysis of historical data sets taken at various locations around the world that decreases in urban air pollution are correlated with increases of urban rainfall. These results are independent of regional precipitation and air pollution data.

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