Anthropogenic Influence on Climate Change Induced Drought in the American Southwest

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Abstract

Anthropogenic influence on climate change induced drought in the predominantly arid region of the American Southwest plays a major role in the effects it has over climate, environment, and sustainability. Topics such as fossil fuels, megadroughts, sustainability, and human roles are addressed specifically. Background and discussion sections are included as a literature review that goes over the different variables involving anthropogenic influence on climate change induced drought. Drought and climate change and natural phenomena such as monsoons are found to be linked together. However, human influences from fossil fuels and water resource usage are also a significant factor in climate change induced drought in the American Southwest. This paper demonstrates how human influence on global warming has caused an increase in drought conditions and human water usage is putting them further at risk by depleting water resources. Two paths are considered to combat water shortage issues and with one being to acquire new water resources and the other to conserve and recycle water. There may not be a single resolution to drought, but sustainable practices appear to be the best way to combat the negative effects of climate change induced drought in the American Southwest.

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INTRODUCTION

Climate change has become a very prominent topic in recent years and a source of a constant debate about global warming and its effect on the environment. Climate change is summarized as the dynamic nature of the long-term climate of a region, and it can involve many changes, of which drought is one of the most prominent (Henson 2014). Climate change is a diverse phenomenon that can mean either cooling or warming (Henson 2014). In this paper, the primary focus will be on the rising temperatures of climate change also known as global warming. The changing of temperatures globally is resulting in the regional occurrence of extreme climatic events such as drought.

Drought is an extreme event within a climate and can result in negative environmental impact and great socioeconomic loss. The interconnectedness that has stemmed from globalization has resulted in people feeling the effects of the phenomenon of drought across the globe. The days of when events were generally localized have long passed. If there is a drought that negatively affects one location, it can affect other locations across the world. Models of drought frequency predictions have tried to assess the frequency and length of drought in drought-prone regions. These models bring the possibility of being able to prepare for and mitigate the effects of future droughts.

In this paper, the focus will be on the American Southwest, a region that is highly prone to drought and one that has been extensively researched. The historical narrative of droughts throughout the world further assists in the understanding of the ever-changing nature of drought. Therefore, the case of the Sahel droughts (Zeng 2003) is discussed here as a supplement to the droughts in the American Southwest, particularly concerning natural and anthropogenic factors on droughts. The narratives provide further understanding when addressing the complexity of global warming and drought.

The connection between climate change and drought is that the increase in global warming has exacerbated the conditions within areas where drought occurs. Drylands have fragile environments and even the smallest changes in climate can have a great impact on their ecosystems. Drylands are not just uninhabited deserts; they are also rapidly developing regions, especially the American Southwest, where there is fast-growing economic and urban development. The American Southwest includes some of the fastest growing cities in the United States such as Tucson, AZ, Phoenix, AZ, El Paso, TX and Albuquerque, NM. With the increasing population in this region, understanding the causes and effects upon drought is a critical issue. Increasing population raises the demand and stress on water supplies, and results in the amplification of the negative impacts of drought in the American Southwest. The American Southwest covers a wide region and ultimately affects several states and many people when impacted by drought. Thus, analyzing the causes of global warming-induced drought is the first step to a solution to proper mitigation of drought effects on society and economic activities. Fortunately, there are plenty of historical drought records in this region providing an extensive narrative of drought and climate conditions to utilize in understanding the current trends in drought occurrence.

Global warming results from natural and anthropogenic causes and the goal of this paper is to assess how these two influencers impact drought in the American Southwest. By further understanding how these factors interrelate with drought, it will assist those managing water resources to better understand the situation and what courses of action to take. Environmental impacts can include stress on native species, increase in wildfires, and plant stress specifically in trees, all of which can be greatly influenced by the conditions that stem from global warming-induced drought. This demonstrates that drought is not a simple event as it can endanger species, increase wildfires, and cause stress that decreases growth and increases mortality amongst plant populations. Climate change has brought the increase in temperatures known as global warming, a decrease in precipitation, and the shifting of the subtropical highs (IPCC 2007). Some of the influential factors that have caused climatic changes are natural and anthropogenic causes. Naturally occurring events can result in climate change that stems from the environment. Natural phenomena that can cause climate change include volcanic eruptions, solar radiance increase or decrease, and ocean dynamics such as El Niño or La Niña events (Henson 2014). Some human activities that cause climate change include fossil fuel use, aerosol emissions, and land-cover change (National Aeronautics and Space Administration 2019a).

Despite overwhelming scientific evidence, the influence of humans in driving climate change is often overlooked, usually by the conservative ruling establishment and most fuel-related corporations, and the primary focus usually stays on the natural causes of global warming-induced drought. By further understanding the influence of anthropogenic causes on global warming-induced drought, we can expand the narrative of drought in the American Southwest. The American Southwest is facing new conditions created by globalization and the rise of the human population. Humans have introduced increased water consumption, expansion of agriculture/ranching, increased fossil fuel emissions, and change in the landscape. People who have historically inhabited the American Southwest prior to the last two hundred years affected the environment, but today the population is far larger and creates more stress. Due to the changing conditions of the region, it makes it imperative that the anthropogenic causes are further explored to better understand global-warming induced drought.

OBJECTIVES AND KEY POINTS OF THIS RESEARCH

The objective of this paper is to address the role of anthropogenic influences on global warming induced drought. In the background, the narrative of what and where is the American Southwest, what is drought, what are the different types of drought, and what is climate change and its different factors will be explained. In the discussion, the assessment of humans' role in the drought faced in the American Southwest will be the main topic. Key points that will be made in this section is how much have humans increased the use of fossil fuels and various gases and how has that impacted global warming which in turn effects drought. What is the possibility of the occurrence and impact of megadrought on the regional population, and is there proper preparation by state governments who fall in this region? How have humans affected an already limited resource region? Along with what are humans in the region doing to reduce the conditions that influence drought? The purpose is to explain how natural effects are no longer the primary cause of drought in the region because anthropogenic causes are equally important in the discussion of global-warming induced drought.

BACKGROUND

The current global climatic trends are pointing towards an overall warmer Earth presenting the necessity of understanding climate change, drought, and their relation to drylands. Drylands hold in common with each that they are arid and ranging from hyper-arid, arid, to semi-arid (Ffolliott, Gottfried, and Rietveld 1995). Drylands are facing the burdens of a rapidly growing human population, which increases stress on an already resource-limited biome. These regions are facing an upcoming dilemma in the future due to global warming influencing drought occurrence and the continuous expansion and development of cities in drylands, especially in the United States.

The focus area of this paper is on the predominantly arid region known as the American Southwest. This region has a history of drought and has a past of long severe droughts (Colby and Frisvold 2011: 83). “The climate of the Southwest is hot and dry, with bimodal rainfall patterns of winter storms and summer monsoons” (Colby and Frisvold 2011:7). The American Southwest has been highly studied with respect to hydrology and climate as it has some of the fastest growing states and cities in the United States within its vernacular boundaries. The boundaries of this region on only broadly defined and subjected to various criteria. However, a good description of the region’s range is, “The U.S. southwest extends from the Edwards Plateau (in central Texas) in the east to the Pacific coast in the west. The area covers four physiographic regions: the Interior Plains, the Rocky Mountain System, the Intermontane Plateaus, and the Pacific Mountain System” (Feng et al. 2014). The physiographic region range is displayed below in Figure 1. For this paper, I will be defining the American Southwest as extending from southern California to west Texas, including the Oklahoma Panhandle along with the southern portions of Colorado, Utah, and Nevada. The primary focus states that comprise the American Southwest, though, are southern California, Arizona, New Mexico, and west Texas. These primary states truly embody the culture and historical background of the American Southwest. Figure 2 below is a map from the United States Drought Monitor for October 16, 2018 that demonstrates where drought is concentrated and presents clearly the states’ boundaries. The areas I have chosen to define as the American Southwest are easily discernible due to the clear delineation of the state boundaries.

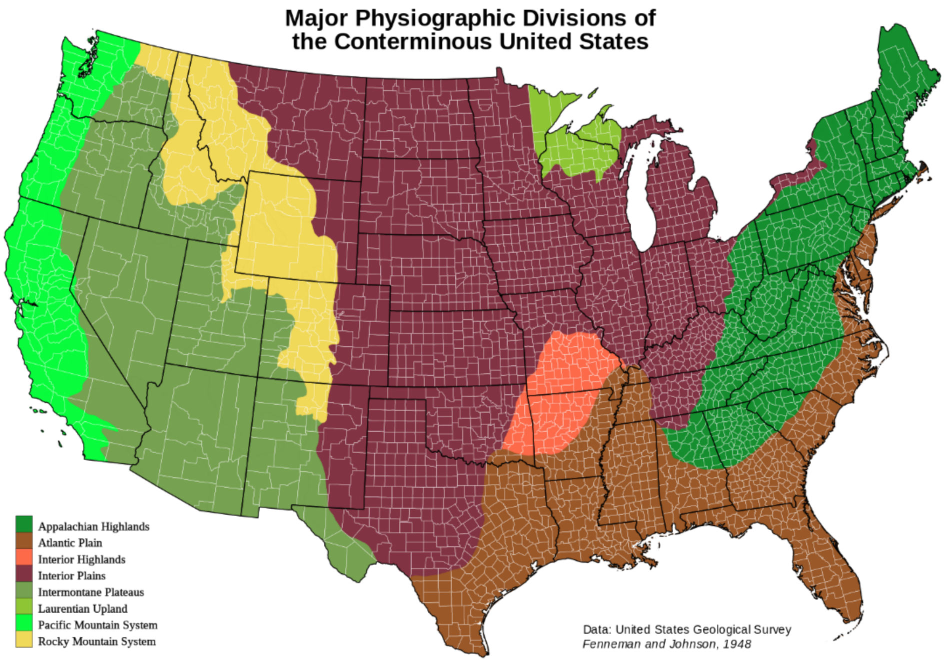


Figure 1: This map presents identifies the different physiographic areas are located in the United States (Wikimedia Commons 2009).

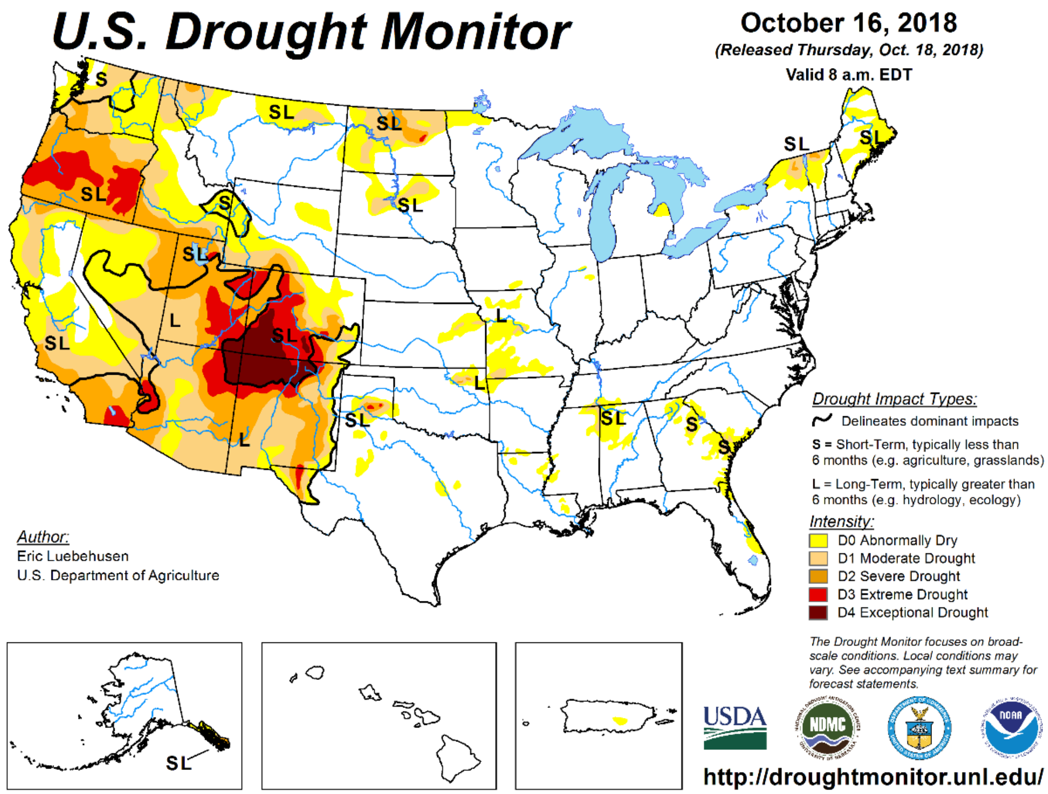


Figure 2: U.S. Drought monitor map from October 16, 2018 displays how drought covers the American Southwest states and where drought is severe and commonly located (National Drought Mitigation Center at the University of Nebraska-Lincoln. 2018).

Droughts in the American Southwest are generally characterized "by above-average temperatures because of factors such as subsidence, a lack of cloud cover, drying soils, and reduced evapotranspiration" (Woodhouse et al. 2010: 21283). Drought is essentially defined as a prolonged abnormal deficiency of moisture within an environment, and this definition is very similar to the one given by the American Meteorological Society (Palmer 1965). All types of drought such as agricultural, hydrological, socioeconomic, and meteorological focus on moisture shortage (Palmer 1965). Agricultural drought is characterized by lack of soil moisture that results in loss of crop yield (Wilhite and Glantz 2009). Hydrological drought is characterized by the severity and frequency and is often defined by river basin flow adequacy (Wilhite and Glantz 2009). Socioeconomic drought is characterized by the incorporation of all three other types of drought and it focuses on social impacts and how it affects everyday life (Wilhite and Glantz 2009). Meteorological drought has been defined as a “period of more than some particular number of days with precipitation less than some specified small amount” (Wilhite and Glantz 2009: 113). Figure 3 presents the connectivity of environmental and social aspects of drought showing how the different types of drought are interconnected to one another. Figure 3 shows how with time drought moves from meteorological to agricultural to hydrological as duration increases.

This emphasis on the lack of moisture is how drought will be defined in this paper. “Droughts are, by nature, a regional phenomenon” (Alley 1984: 1100), and the American Southwest is a prime example of the regional phenomenon of drought. Some terminology that is necessary to understand when describing drought is duration, magnitude, intensity, severity, geographic extent, and frequency. Duration is the length of time the drought occurs; magnitude is the accumulated deficit of water below a threshold; intensity is the ratio of magnitude to duration; severity is the extent of precipitation deficit or drought impacts; geographic extent is area coverage of the drought; and frequency is the rate of reoccurrence for drought (Zagar et al. 2011).

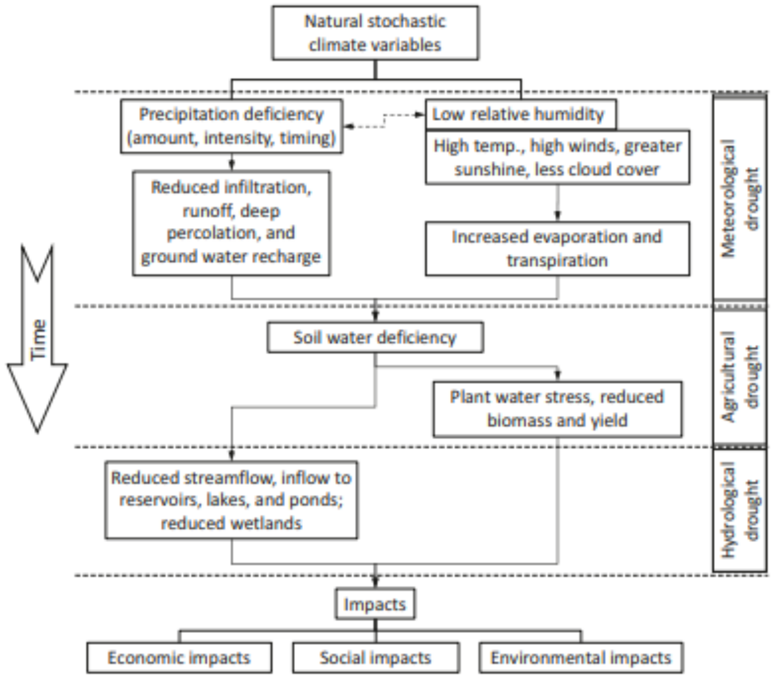


Figure 3: This diagram shows the transition as time advances through the different types of drought and the variables that comprise each along with the impacts of drought (Zagar et al. 2011).

Drought

Drought is an extreme form of climatic variability and can have varying levels of severity. Climatic variability essentially is defined as the variations found in the state of climate and whether it is composed of natural processes or external forcing (Adedeji, Reuben, and Olatoye 2014). To measure drought severity through different measures different indices are utilized. "Drought *indices* are quantitative measures that characterize drought levels by assimilating data from one or several variables (*indicators*) such as precipitation and evapotranspiration into a single numerical value" (Zagar et al. 2011:333). The severity of drought is often scaled in accordance with the Palmer Drought Severity Index (PDSI). The PDSI is referred to as the index for meteorological drought, and this index considers precipitation, evapotranspiration, and soil moisture conditions (Alley 1984). Although there are other indices for the different drought types, the PDSI is the most widely used. The issue some individuals have with the utilization of a drought index is that drought is a broad issue and has many variables that cannot all be encompassed in one index. Many worry that by using an index that some droughts will not be fully recognized or will be considered less severe because its conditions are atypical. This issue requires the researcher to choose accordingly when choosing a drought index to measure drought severity. Drought indices can many times relate back to a specific type of drought. "The nature of drought indices reflects different events and conditions; they can reflect the climate dryness anomalies (mainly based on precipitation) or correspond to delayed agricultural and hydrological impacts such as soil moisture loss or lowered reservoir levels" (Zagar et al. 2011:333). This really comes back to the natural and social impacts of drought because they can affect what index is used to measure drought severity. The index, in turn, can affect the policies implemented because it determines how severe the drought is presented. Indices determine how the drought is presented making them an important aspect of understanding the relationship between global warming induced drought.

Notable droughts of the American Southwest include megadroughts during the medieval period between 900-1300 A.D. and the 16th century (Stahle et al. 2007). Unlike the recent droughts in the 20th and 21st centuries, the medieval drought period was caused by several different factors. "The root causes of warming for the medieval period, increased solar radiance coupled with decreased volcanic activity, and in recent decades, anthropogenic activities with some contribution from solar radiance, are not identical" (Woodhouse et al. 2010: 21284). Drought has not been limited to the distance past alone, and over time has added anthropogenic activities as one of the influential factors in its occurrence. Several regional droughts have occurred in more recent times such as the 1930s, 1950s, and the early 2000s, which are good examples of persistent drought conditions in the region (Swetnam and Betancourt 1998). The 1950s drought is less known due to the decreased economic impact on agriculture because of the use of groundwater to support agriculture (Swetnam and Betancourt 1998). Drought becomes more apparent to an agricultural region because it touches lives more than water restrictions for lawn care. Drought creates a burden on the agricultural industry since “80% of all water withdrawals are used for agricultural purposes” (MacDonald 2010: 21257). Since agriculture plays such a large role in water consumption, drought can cause serious disruption and severe economic loss. The American Southwest faces tough decisions regarding water management for agriculture, industrial, and domestic purposes.

Southwest Drought in the Context of Global Climate Change

One of the main problems the public has when trying to understand the extent and frequency of droughts is the poor understanding of weather and climate. Weather is the current state of the atmosphere at a specific time and place (Adedeji, Reuben, and Olatoye 2014). Climate change is the long-term variation in weather patterns over a period of decades or greater (Rahman 2012). In contrast, climate comprises of the long-term weather patterns that define the area (Adedeji, Reuben, and Olatoye 2014). Therefore, climate change is not about everyday weather; instead, it involves changes over decades, centuries, and millennia. This differentiation is important to keep in mind when determining the occurrence of drought because climate data is what is utilized in climate simulation models. The occurrence of drought varies greatly, but there have been attempts through these models to assess the likelihood of drought.

“Climate models are based on well-established physical principles and have been demonstrated to reproduce observed features of recent climate and past climate changes”

(Randall et al. 2007: 591). These climate models are tested to see how well they can represent the last century of documented climate data to check accuracy (Henson 2014). With such a short-documented history, many climate models used to analyze the American Southwest employ paleoclimate data instead of historical data. "Four main types of paleoclimate proxy data – records that can be used to infer atmospheric properties such as temperature or precipitation: biological, cryological, geological, and historical" (Henson 2014: 265). Biological data includes biological material such as tree rings, pollen, and fossils of different organisms (Henson 2014). Biological data is heavily used for climate models in the American Southwest because of the usage of dendrochronology, which is the study of tree rings. "Ring patterns obtained from several trees in the same area are matched, cross-dated, and analyzed to produce an annual localized set of tree-ring growth indices known as a site chronology" (Henson 2014: 266). Cryological data include ice cores that preserve frozen greenhouse gases and dust (Henson 2014). Geological data includes volcanic rock, sedimentary materials collected from lake beds, and shells preserved in ocean sediments (Henson 2014). Historical data includes are written records about the climate (Henson 2014). Unlike other regions in the world, the American Southwest has a shorter history of instrumental records of atmospheric phenomena. The limited amount of historical data on the region makes it difficult to run statistics because of the size of the sample data. Paleoclimate records, though, are also scarce as previously mentioned (Feng, et al 2014). Stations are scattered making it difficult to predict the American Southwest's likelihood of drought and to determine changing climatic patterns as well (Salazar et al. 2011). The use of tree data has made up for limitations in historical data by providing long-term paleoclimate data to be used when calculating the different models.

Many different climate models have been implemented in climate research on the American Southwest. One model used is the Community Earth System Model (CESM), which "is one of the few open-source, high-end global models that anyone with sufficient power can download and use" (Henson 2011: 304). CESM is a model that can simulate past climate and consider many factors either natural or anthropogenic (NCAR 2019). The Goddard Institute for Space Studies ModelE-R (GISS-ER-R LM) "provides the ability to stimulate many different configurations of Earth System Models-including interactive atmospheric chemistry, aerosols, carbon cycle and other tracers, as well as the standard atmosphere, ocean, sea ice and land surface components" (National Aeronautics and Space Administration 2018). Coupled Model Intercomparison Project Phase 5(CMIP5 LM) can stimulate past climate, and "provide projections of future climate change on two-time scales, near term (out to about 2035) and long term (out to 2100 and beyond)" (Lawrence Livermore National Laboratory 2008). "The CESM LME, GISS-ER-R LM, CMIP5 LM, and paleoclimate data tend to show that the region experiences distinct drought intervals lasting 2-3 years at least twice per century, intervals lasting 5-10 years about once every other century, and a decadal-multidecadal drought interval once every few centuries. The NADAv2a model indicates the region has a lower risk of interannual drought (2-4 years in length) and a higher risk of decadal drought (15-20 years in length) than the model ensemble means" (Parsons, Coats, and Overpeck. 2018). It is important to note that every model is considered imperfect because each calculates and simulates the climate differently than the other (Parsons, Coats, and Overpeck 2018). However, all of these models provide an idea of the frequency of droughts in the American Southwest (Parsons, Coats, and Overpeck 2018). They present the possible future problem of drought for the region and its ever-growing population. In addition, the models in relation to paleoclimate data show how the possibility of a multidecadal long megadrought could be lingering on the horizon. One issue with climate models is that they cannot accurately account for variables that are increasing in value such as temperature, greenhouse gas emissions, and population growth. Biological and historical data can only predict so much of the increase rate of the variables. Robustness of models can truly only account for so much, especially when faced with variables that will continue to increase at rates we cannot easily predict. This demonstrates that climate models provide valuable predictions, but they cannot be fully relied on because climate is an ever-changing phenomenon.

Climate Change

As previously mentioned, climate is the long-term patterns of an area. Climate change is considered to be one of the most pressing issues facing the world's population (Rahman 2012), as it is an issue that affects our planet and all living things that inhabit it because it affects the conditions needed to survive and prosper. The concept of climate change emerged in the early 19^{th} century and until the late 20^{th} century was primarily an issue discussed amongst academics, and only when the 1980s came did the issue become a part of the public's agenda (Rahman 2012). Despite a large amount of evidence in support of climate change, there is still a lot of skepticism and even denial of the issue. "Climate on earth has changed on all time scales even since long before human activity could have played a role in its transformation" (IPCC 2007). However, the main issue discussed is whether the current climatic changes are driven by anthropogenic or natural cause.

Anthropogenic causes range in fossil fuel emissions to human land use practices. Anthropogenic causes are more of a recent regional phenomenon with the continuous development of the American Southwest. Population in the region has grown intensively in the past few decades. Table 1 below presents how six of the states in the American Southwest excluding west Texas range from a 25-59% projected growth increase in population from 2010-2030. Population growth has created a very new set of circumstances and factors when studying global warming induced drought than prior historical populations. Figure 4 shows the population increase and projections from 1920-2060 showing how substantially historical populations till now and will continue to increase in the American Southwest. This population increase creates a greater demand on water resources for consumption. Globally, the rise in human population and industrialization has affected climate and affected the earth in several ways that affect drought. The increase in fossil fuel emissions and other impacts by humans has affected the overall climate and resulted in climatic variability in temperature, precipitation, and the shifting of the subtropical highs.

State	1990	2000	2010	Total Growth 1990–2010	% Growth 1990-2010	Projected Pop. 2030	% Growth 2010–2030	Total Growth 2010–2030
Arizona	3,665	5,130	6,392	2,726	74	9,480	48	3,088
California	29,760	33,871	37,253	7,493	25	48,380	30	11,127
Colorado	3,294	4,301	5,029	1,734	53	6,564	31	1,535
Nevada	1,201	1,998	2,700	1,498	125	3,363	25	663
New Mexico	1,515	1,819	2,059	544	36	2,825	37	767
Utah	1,722	2,233	2,763	1,041	60	4,394	59	1,631
TOTAL	**41,159**	**49,353**	**56,198**	**15,039**	**37**	**75,010**	**33**	**18,811**

Sources: U.S. Census sources [for pre-2010] and state demographer's projections [for 2010 and beyond].

Table 1: This table displays the total population growth from 1990 to 2010 and the projected growth for 2010 to 2010 for the states in the American Southwest (Theobald et al. 2013).

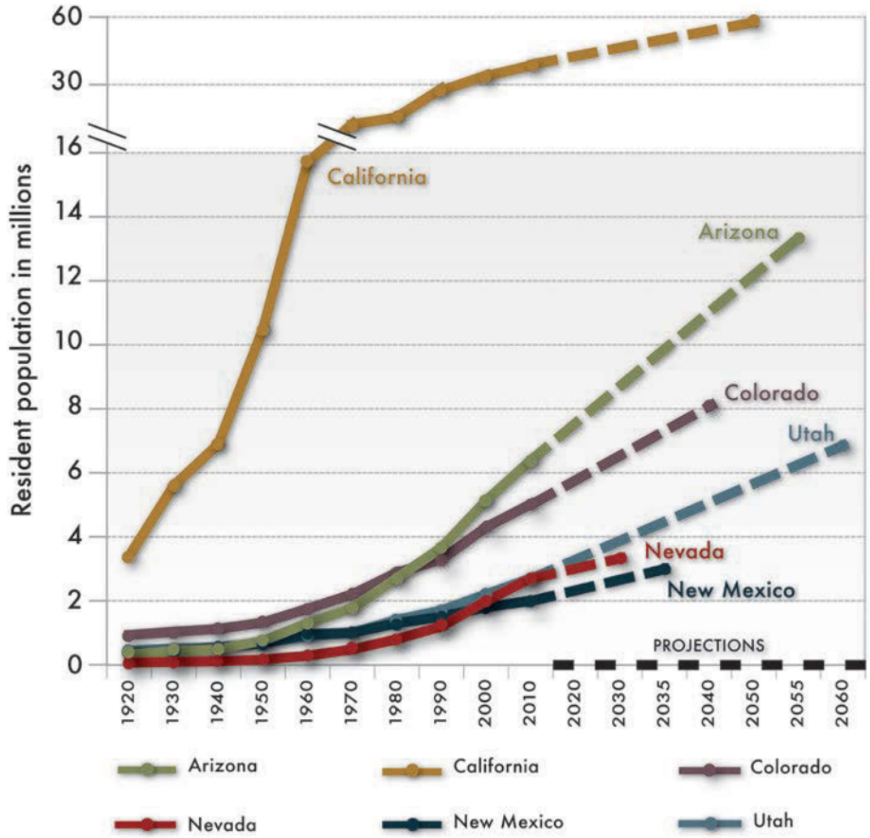


Figure 4: Displays in a graph the resident population in the millions for the states in the American Southwest and their projected growth from 2020 to 2060 (Theobald et al. 2013).

Natural causes that influence drought are the variability and cycles of the environment. Gaining a better understanding of climate change and its natural causes is critical to grasp the impact of anthropogenic influence on the earth (Gao, Robock, and Ammann 2008). Understanding the natural causes that influence climate change which in turn influences drought is important to understand the anthropogenic influence. Studies have leaned towards the idea that "a combination of land-atmosphere feedbacks, coupled atmosphere-ocean interactions, external forcing and/or random shifts in atmospheric circulation" (Parsons, Coats and Overpeck 2018: 8627) are influential causes in drought. One natural cause of climatic change is the Milankovitch

Theory, which states the earth has 3 cyclical changes in its orbit that occur from thousands to hundreds of thousands of years that can influence climate (National Aeronautics and Space Administration 2016). “Milankovitch proposed that glacial periods began when the three cycles align to favor an extended period of more solar radiation in the winter and less solar radiation in the summer at a latitude of 65 degrees N” (National Aeronautics and Space Administration 2016). The Milankovitch Theory despite being a cycle that occurs on the long-term it is extremely impactful. It demonstrates just as we can have cycles of global cooling and great extensions of ice sheets, we can also have periods of warming hence the emphasis on cyclical changes in this the theory. This cycle is a natural phenomenon completely independent of anthropogenic influence.

Another natural cause of climatic change is volcanic eruptions. Volcanic eruptions result in global cooling and affect the overall temperature of the earth. Mainly only strong volcanic eruptions can produce this effect on the climate. This is because large powerful eruptions throw sulfur dioxide into the atmosphere that reflects the solar radiance back into space and it cools the earth’s temperature because of the loss of energy (Man 2014). Volcanic activity clearly is not the cause of the rise in global temperatures. On top of this, there have been detections in precipitation decrease due to the greenhouse gas increase from volcanic eruption (Man 2014). This reduction in precipitation from volcanic eruptions can be impactful on drought. The aerosols usually move with the easterly and westerly winds, and due to this factor, volcanoes in lower latitudes have a greater chance of causing global cooling (Man 2014). The ability for general wind circulation to move the aerosols increases the overall area affected by volcanic eruptions. Volcanic activity does not appear to be the cause of climate change American Southwest’s drought because the region is not facing cooling.

Natural causes of climate change also include the fluctuations in solar radiation. Solar radiation reaching the earth is affected by the total amount of aerosols and dust in the atmosphere because the particles reflect it back into space. This relates solar radiation back to the impact of volcanoes on climate change. Solar radiation itself can fluctuate and is not controlled just by how much dust is in the atmosphere. “The change of solar radiation is related to the number of sunspots” (National Aeronautics and Space Administration 2016). There is no limiting the amount of solar radiation making it truly a natural factor of global warming. Thirty percent of solar radiation is reflected back into space while 70% is not reflected back and is factored into the radiation balance of earth (Ramanthan and Feng 2009). The issue arises with the increase in greenhouse gases that absorb and emit this same longwave energy as the solar radiation (Ramanthan and Feng 2009). This creates an imbalance in the energy received and results in more energy and thus raises temperature. “The increase in radiative heating over the tropical Pacific has been shown to enhance the development of La Niña-like conditions that promote drought” (Woodhouse et al. 2010: 21283). The influence of increased radiation can ultimately create and enhance conditions that promote drought in the region. This demonstrates how increased radiation may not seem major, but it can truly affect the long-term climate and cause extreme conditions such as drought in the American Southwest.

The Climatic Elements in the American Southwest Drought

Temperature is important when considering drought because of the temperature impacts of the PDSI. Data is currently pointing towards an increase in temperature in the region. “General circulation models project annual temperatures to be 3-5 °C above the current temperatures by the end of the century” (Woodhouse et al. 2010: 21285). Another study also predicted from its best climate model that from 1971-2070 there would be a mean summer temperature increase of around 3 °C (Salazar et al. 2011). Several sources show how different models are all predicting an increase in temperature in the region. Greenhouse gas emissions are predicted to globally raise mean global surface temperatures around 1-6 °C (Stewart et al. 2015). Beyond just cycling through natural extremes and forcing, the impact of anthropogenic forcing is becoming more prominent. Anthropogenic forcing is human-generated forcing such as greenhouse gas emissions and other human-induced changes. "Fossil fuel emissions in North America have been increasing at a rate of 0.017 Pg C yr^{-1}, which is greater than that of the modeled terrestrial sink in North America over the last three decades" (Mekonnen, Grant, and Schwalm 2017). This demonstrates that fossil fuel emissions are greater than the carbon sink of the environment and are causing anthropogenic forcing on the climate by their rate of increase. Some say the current global trends are considered far too extreme and are beyond natural forcing and leaning more towards anthropogenically influenced (Peterson and Heim 2013). The greenhouse gas carbon dioxide (CO_2) is 410ppm currently and is still on the rise in the mid-troposphere, which is demonstrated below in Figure 5 (National Aeronautics and Space Administration 2019b). Figure 6 shows, in millions of metric tons, the increase of carbon dioxide from 1900 to 2014, the up close rapid increase of carbon dioxide in the atmosphere after industrialization, and this is also present on a smaller scale in Figure 5. Carbon dioxide is a product of anthropogenic and natural processes. With the rate of increase of greenhouse gases like CO_2 in the atmosphere, the temperature will continue to increase, which in turns influences the likelihood and severity of drought by climatic changes in the region.

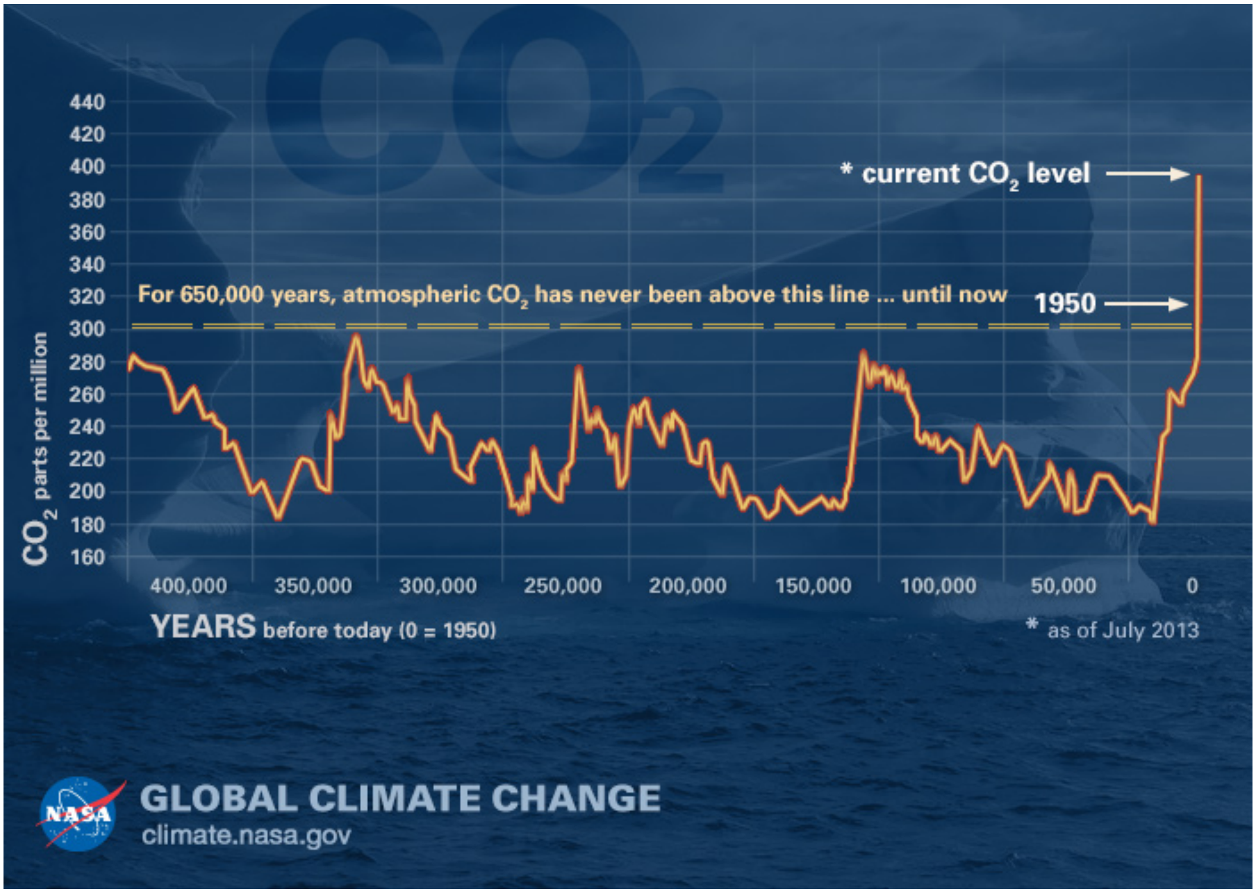


Figure 5: This graph displays the increasing trend in the amount of carbon dioxide parts per million in earth's atmosphere from 400,000 years ago to today (National Aeronautics and Space Administration 2019b).

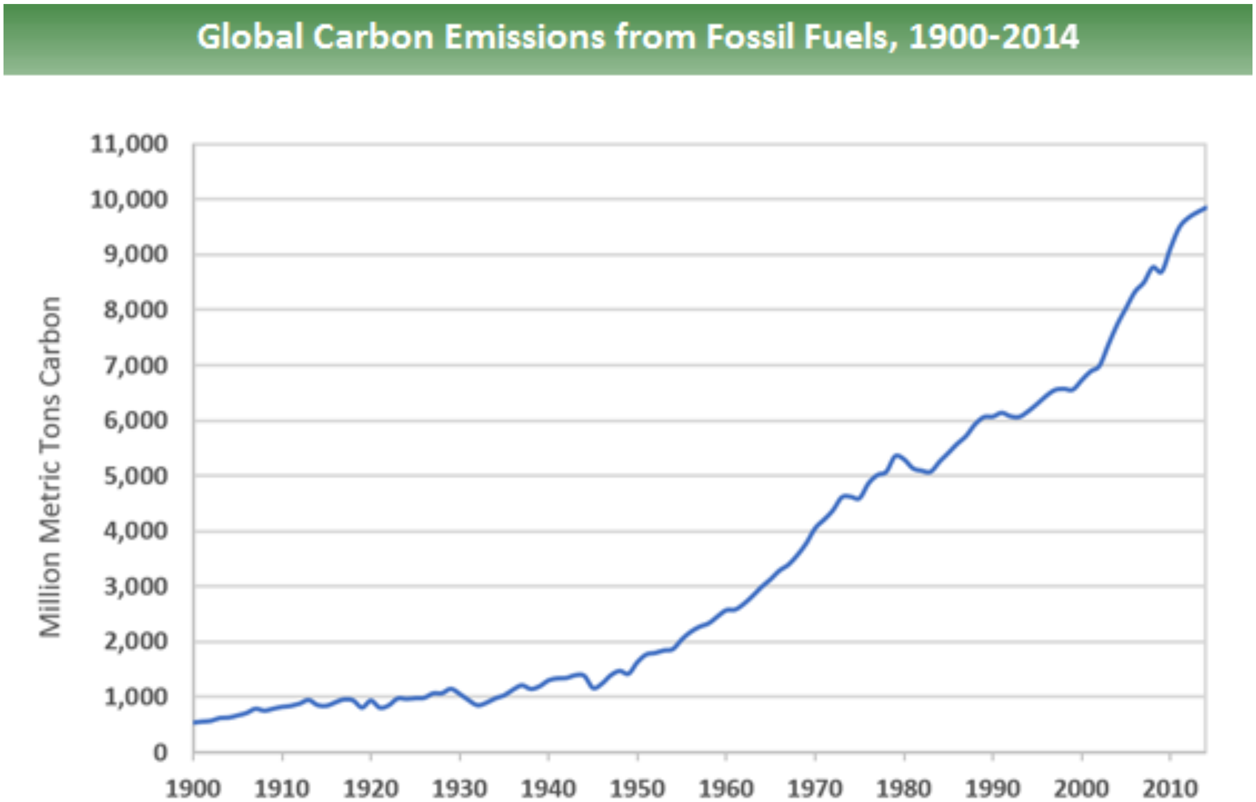


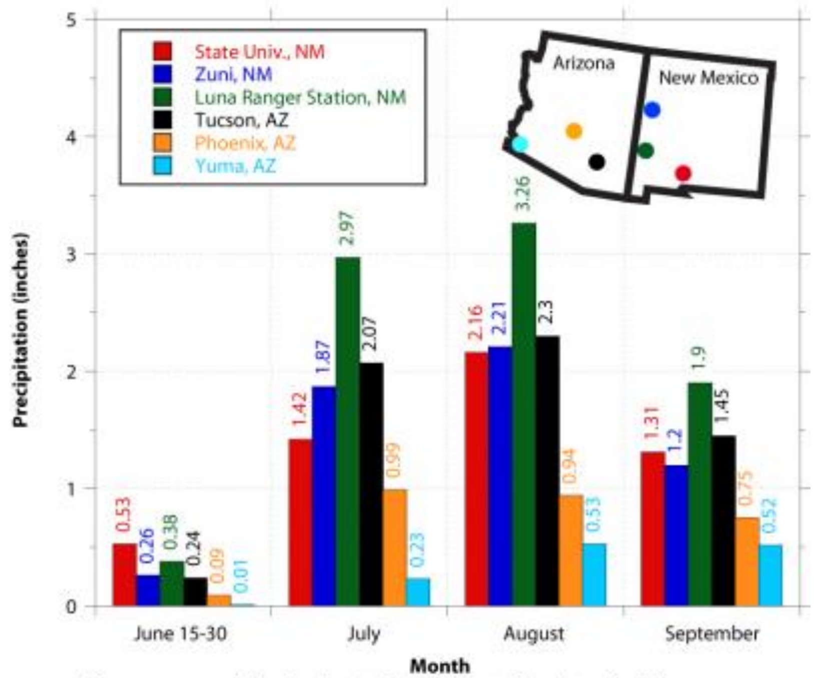
Figure 6: This graph displays carbon dioxide in million metric tons per year from 1900 to 2014 (U.S. Environmental Protection Agency 2017).

Precipitation Change

Temperature alone is not the sole factor in increasing aridity in the region. Precipitation is an important factor when considering drought because it is a factor in determining drought severity. However, the current issue of low precipitation has been exacerbated by increasing temperatures (MacDonald 2010). This interrelation demonstrates how elements of climate change influence one another. The lack of precipitation is about 22-25% below the mean precipitation of the 20th century (MacDonald 2010). The rising temperature and decreased precipitation affect the winter snowpack that feeds reservoir supplies. “Warming surface temperatures in response to greenhouse gas increases provide a strong basis from which to project a long-term further reduction of total snowpack and still an earlier release of spring and summer meltwater to rivers during this century" (Seager and Vecchi 2010). Along with the decrease in winter snowpack, some scholars point to decreased winter precipitation as the cause of southwest drying (MacDonald 2010). Some towns in the regions that rely on snowmelt are facing issues with global warming, which increases factors that increase drought. With a decrease in snowmelt that supplies a good portion of rivers and reservoirs water, the likelihood of socioeconomic and agricultural drought increases. Half of the headwaters of major rivers in the southwest are fed by snowmelt (Jones and Gutzler 2016). Without this water to supply the demand of communities and for agriculture, it places a large burden on water management in the area. Changes in the flow affect the quality of water and the ability of water managers to manage the situation (Stewart et al. 2015). The prediction is that ultimately the northern areas of the United States will become wetter while dry places like the American Southwest will become drier. One effect of the decrease and change in precipitation in relation to snowmelt is that native species are being negatively impacted. The drying of stream beds and reduced flow are causing stress in endemic fish populations, and the loss of these species results in reduced biodiversity and disrupts the ecosystem (Jaegar, Olden, and Pelland 2014). Drought and climate change are interrelated when it comes to fish species of the American Southwest. Global warming induced drought is affecting the timing and amount of precipitation and in return increasing the occurrence of drought and affecting the fish populations in the American Southwest.

Southwestern Monsoon

The occurrence of the southwestern monsoon also affects the occurrence of drought in the American Southwest. For a while, the southwestern monsoon has been overlooked and its impact not fully understood (Hales 1974). This event brings above average precipitation to the region of northern Mexico and the American Southwest. This event primarily occurs in July and August from an increase in moist tropical air coming from the southeast winds from the Gulf of Mexico (Hales 1974). There is a lack of moisture in June prior to the southwestern monsoon, which is demonstrated in Figure 7. This region relies heavily on the occurrence of the monsoon to relieve the region from prolonged dryness. The above average rainfall that can occur from southwestern monsoon is displayed in Figure 7. It is important to realize how scattered the stations are in Figure 7 because the monsoon rains can vary over such a large area. Even if the monsoon occurs this means some areas still may not receive adequate recharge rates from precipitation. This lack of precipitation can negatively impact the water resources in the American Southwest, resulting in serious water deficiencies if there have been periods of dryness or drought due to the failure of the American Monsoon. The rates of precipitations can vary from year to year, but Figure 7 shows how the precipitation can vary by location and even in a given year. Overall, this event is highly critical to water management plans because, like snowpack, water resource managers rely on the occurrence of these events to properly plan the distribution of water resources to residents and industry.



Monsoon precipitation in the Southwest. The data for Arizona was obtained from the NWS Tucson; New Mexico data was compiled from the Western Regional Climate Center.

Figure 7: This graph displays the variation in Monsoon precipitation for Arizona and New Mexico from different stations across both states from June to September (CLIMAS 2019).

Subtropical Highs

The dynamics of subtropical highs also plays a substantial role in the narrative of climate change induced drought in the American Southwest. "Subtropical highs (or subtropical anticyclones) are regions of semi-permanent high atmospheric pressure typically located between 20 and 40° of latitude in each hemisphere. At the surface, the subtropical high-pressure belt divides the easterly trade winds from the mid-latitude westerly winds" (Cherchi et al. 2018: 371). The subtropical highs also contribute to the warm and cool currents of the western continents, and along with being an integral part of the process formation of subtropical deserts (Cherchi et al. 2018). These cool and warm currents in the western hemisphere impact events like El Niño and La Niña. “Most droughts are associated with persistent anticyclones, with poleward expansion of the subtropical dry zone projected to play an increasingly important role” in the future of the American Southwest (Peterson and Heim 2013:6). Changes in the subtropical highs can impact events like the American Monsoon. As climate has been changing, this zone of subtropical highs has been shifting north. “In recent decades, in the context of anthropogenic effects on climate and related global warming, changes have been observed in the position and intensity of the subtropical highs, with decreased subtropical precipitation likely driven by the intensification and poleward expansion of both subtropical dry zones and Hadley cell” (Cherchi et al. 2018: 372). Just as global climate change affects subtropical highs the changes in subtropical highs affect the regional climate change of an area (Cherchi et al. 2018). Global warming assists in a shift in the subtropical zones causing a poleward expansion of arid zones (Henson 2014). Many consider the rise in temperatures along with this shift in the subtropical highs will increase the risk of drought in the American Southwest (Henson 2014). “IPCC AR4 (2007) climate model projections have also shown that the southwest US, similar to the subtropical dry zones of the world, will dry and expand to the north due to increasing warming” (Mekonnen, Grant, and Schwalm 2017). This connection of temperature and the subtropical highs represents the interrelationship of factors that are influenced and leading to global warming and increased drought risk. The subtropical highs shifting is an issue that effects global climate in many different fashions, but it affects the American Southwest in the direction towards the belief of drier places are becoming substantially drier.

DISCUSSION

The issue of anthropogenic influence on global warming induced drought has become more prevalent in understanding the narrative of drought in the American Southwest. Increasing human population, industrialization, and consumerism is a strain on Earth's overall environment. Drought is an extreme weather event that is influenced by a multitude of factors and impacts the human population. I will be assessing the questions that were previously stated in the objectives and how they factor into climate change induced drought. One focus will be how human fossil fuel usage and various gas emissions have impacted global warming and induced drought. Another focus will be the possibility of the occurrence and impact of megadrought on the regional population, and is there proper preparation by state governments who fall in this region? Along with answering the following questions: how have humans impacted an already limited resource region? What are humans in the region doing to reduce the conditions that influence drought such as political policies? These questions answer key components in the narrative of global warming induced drought on how humans have increasingly played a role.

As previously shown in Figure 5, carbon dioxide in the atmosphere has been steadily increasing over the years. Carbon dioxide is just one of many different types of gases in the earth's atmosphere. Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons, nitrous oxide (N_2O), ozone, and aerosol particles (IPCC 1990). Water vapor is an important greenhouse gas but is not affected greatly by anthropogenic activity (IPCC 1990). Water vapor will, therefore, be excluded from the discussion of greenhouse gases and their influence on global warming induced drought. The issue with fossil fuels is how they trap heat in the atmosphere. The greenhouse effect is where gases or aerosols trap portions of the solar energy in the lower atmosphere of the earth, which raises the earth's temperature (Wuebbles and Jain 2001). The problem is that humans are causing the release of more greenhouse gas emissions, which will cause global temperatures over the next century to rise 1 to 5º C (Wuebbles and Jain 2001). Even the Intergovernmental Panel on Climate Change (IPCC) suggested that the evidence showed human influence on Earth's climate (Wuebbles and Jain 2001). We are currently facing a period of warming that has not had any precedent in the last 500 to 1,000 years (Wuebbles and Jain 2001). Human population has been increasing along with industrialization, which influences the emissions of greenhouse gases into the atmosphere. Biota exchanges the most CO_2 with the atmosphere, despite being small in comparison with deforestation and fossil fuel, which emissions do contribute enough to create an imbalance (IPCC 1990). In 1990, the human activities were essentially considered enough to create an imbalance in CO_2, demonstrating with the increasing human population that those activities will grow with demand and need. Deforestation results in the loss of plant life that helps balance CO_2 in the atmosphere and produce oxygen. "The vegetation and soils of unmanaged forests hold 20 to 100 times more carbon per unit area than agricultural systems" (IPCC 1990: 10). The amount of carbon held in the biomass determines how much is released into the atmosphere (IPCC 1990). Deforestation is the cutting down of trees which trees vary in time for regrowth making replanting, not an immediate solution to lowering CO_2 in the atmosphere. One reason why humans greatly account for this increase in CO_2 is after examining variability in ice cores comprising 160,000 years that none are higher than the current CO_2 353 ppmv in the atmosphere (IPCC 1990). This may have been in 1990, but CO_2 has only been increasing in the atmosphere as we saw in Figure 5. CO_2 has been around 280ppm +/- 10 in the atmosphere (Wuebbles and Jain 2001). Another reason for the increase of CO_2 in the atmosphere is due to the emission of fossil fuels and deforestation (IPCC 1990). The final and third reason humans are the main cause is isotopic trends of 13C and 14C agree with the greenhouse gas emissions like CO_2 (IPCC 1990). This demonstrates humans are causing a rise in CO_2 that goes beyond the natural carbon cycle and natural forcing. As previously mentioned in the background, rising temperatures also affect precipitation rates. Rising temperatures also cause early melting of snowpack, which affects the recharge of water resources that are fed by the runoff. As precipitation and snowpack after affected by the rising temperature, the likelihood of drought increases in these conditions. With increasing global temperatures that are impacted heavily on fossil fuel emissions and other activities, it is easy to see how global warming induced drought occurs from anthropogenic influence.

With the increasing threat of drought, the possibility of megadrought in the American Southwest is a looming issue. Human influence has greatly affected the conditions that produce drought by increasing global warming. Anthropogenic forcing and natural variability will determine the future prospect of megadrought (Coats and Mankin 2016). The increase in drought conditions could mean a possible megadrought in the future. Megadroughts are important because with such a large growing population in the American Southwest many people are at risk. Anthropogenic influence in the next few decades "increases megadrought risk in the ASW by 20 pp or at least 100 times relative to preindustrial conditions in a CESM control simulation" (Coats and Mankin 2016: 8). Megadroughts may not occur often, but with the increasing risks, it could be sooner than thought. As discussed in the background, climate models cannot totally account for all the variables and their ever-changing nature. Previous megadroughts have been extremely impactful on the human population. The drought that lasted from 1276-1299 A.D. is considered a possible cause of the abandonment of the Anasazi cliff dwellings (Cook et al. 2010). This is one example of how humans have been impacted by long-term drought in the American Southwest. Modern technology and transportation have aided in further water management since that period, but an intense drought lasting several decades may greatly test even our modern water management capabilities. The increasing temperatures will not necessarily cause megadrought, but IPCC models do not show a positive outlook either (Cook et al. 2010). Megadrought is a concept still not fully understood and there is a need for greater understanding of the El Niño Southern Pacific Oscillation, paleoclimate record, Atlantic Multidecadal Oscillation, and sea surface temperatures similar to La Niña to better understand megadrought (Cook et al. 2010). Megadroughts and drought predictions are still not fully understood making it difficult to assess the total likelihood of megadrought in the near future. It appears though with a history of drought and occasional megadrought occurrence that there is a need to further study the phenomenon to better prepare. A drought of such magnitude could essentially cause a state of emergency in the American Southwest due to the growing population.

The American Southwest is an extremely arid land and it is important to assess how humans are affecting water resources in the American Southwest. By assessing the relation humans in the region have with water resources allows one to better see the influence humans have on global warming induced drought. Seeing this relationship helps determine if humans are further increasing the drought by excessively using water resources. The increased temperatures, low precipitation, and increased evapotranspiration are not helping with water resources (MacDonald 2010). One example of water resources in the American Southwest being affected by global warming induced drought is the Colorado River and how it is experiencing some of its lowest recorded mean flows (MacDonald 2010). The Colorado River is important for supplying the region water, and it is important for freshwater animals and plants. Since the Colorado River also flows into Mexico, there is an allotment of how much the United States can use (MacDonald 2010). Besides needing to ensure flow for animal and plant life, the Colorado River's flow cannot be used up because Mexico also has a right to its water. Diminishing water has not stopped the human demand for water though, and it presents a dilemma if demand is not decreased and a solution found. The demand for domestic water use in the region is 12,334 million m^3 (10 MAF) (MacDonald 2010). Water usage for agricultural and industrial uses has somewhat declined, but by the end of the 20th century, agricultural use was at 61,859 million m^3 (~50 MAF) (MacDonald 2010). This demonstrates that agricultural water consumption is the greatest compared to domestic, but domestic demand is growing and is still a burden on water resources in the American Southwest. "The reservoir system on the Colorado River is one of the most important buffers against drought in the Southwest" (MacDonald 2010:4). With such dependency on this specific water supply, it places the region at the mercy of the resource's variability. The storage levels of the reservoir have significantly decreased over time and in the fall of 2010, the capacity was at 55.6% (MacDonald 2010). If global temperatures continue to rise, the evaporation rates will only increase, and high evaporation rates can cause huge water losses to the reservoir. Not only does the increase in greenhouse gases increase global warming and change climate, but also increases evaporation, which affects reservoirs and rivers. Drought conditions put a burden on reservoirs and cause water levels to drop resulting in farmers having to utilize groundwater (Elias et al. 2016). Pumping of groundwater is costly and it lowers the water table due to the extraction rate being greater than the recharge rate resulting in possible groundwater drawdowns (Elias et al. 2016). The amount of rain that is received can be minimal and makes it difficult for recharge of the aquifers that are being tapped for groundwater. On top of this, the imbalance between the supply and demand for water is that there will always be people not practicing sustainable water practices in the American Southwest. This presents the issue of how humans will combat the issue of water resources with drought, global warming, and a rising regional population.

Furthermore, what are humans in the region doing to reduce and live in the conditions that influence drought? To tackle the issue of limited resources, one must also assess what is being done in a drought prone environment. Rural communities can be vulnerable because their voices are not always heard compared to large cities. Rural community residents in Arizona pointed out that with large-scale federal subsidized water that can be imported and cheap and easily available that one can be wasteful in use (Brugger and Crimmins 2013). As a country, it appears we could be by making things so easily available creating an image that waste is okay. Arid climates climate change and water conservation need to be taught more so individuals understand the reality that water is not infinite. “Even restricting population growth by 50% would not allow current per-capita water usage to be sustained under many water-supply scenarios” (MacDonald 2010:6). This demonstrates that policies need to be implemented because if a megadrought or any drought occurs, it could require extensive tapping into groundwater, which is not a real solution. Tapping into the groundwater will just lead the region on a path towards depleting aquifers. To prevent groundwater drawdown, there needs to be political policies implemented whether with or without climate change being a factor (Gober and Kirkwood 2009). Water sustainability is a need in this region due to the arid conditions and not just because of the possibility of drought and increasing global temperatures. Without solutions, this region and its population could be at risk. There are ultimately two possible strategies for water management solutions, first obtaining additional water resources and the second being reduce the demand along with implementing sustainable consumption practices and processing wastewater (Hess et al. 2016). Obtaining other additional water resources may not even be possible in the first place. Additional water resources could come in the form of “building pipelines for new surface water, by drilling new production wells, by acquiring new surface water and storage rights, by recharging aquifers for future withdrawal or for the improvement of aquifer water quality, by increasing the storage capacity of surface-water reservoirs, and by building desalination plants" (Hess et al. 2016). Now the real issue with the first option is that new water resources may not be even acquirable. Recharging aquifers depends upon rainfall and if drought increases and global warming is causing early snowpack melting, this may not be a viable option. Improvement of water quality is a possibility to utilize water that is already available, but that all depends once again on if water is available. Increasing the storage capacity of surface water reservoirs is not necessarily a good option because of possible high evaporation rates, which could cause huge losses of water from the reservoir. Desalination plants can be extremely costly in the grand scheme and may not be something in which the cities can invest. Also, desalination plants still need water and in drought conditions that water may still not be available in a large enough quantity to supply the whole population. The second option reducing the demand or recycling wastewater could be a real option for the region. Reducing the demand could be in the form of limiting water used for lawn care or recreational such as water parks. In Phoenix, replacing old appliances such as toilets, limiting outdoor water usage, implementation of rate structure, and fixing leaks would account for 19% of the indoor water usage (Gober and Kirkwood 2009). This 19% may seem small but with a city like Phoenix, this would be a lot of water due to its large population. The amount of water available for the future is uncertain, making it difficult to determine the best solution (Gober and Kirkwood 2009). To even create a system to continue the usual water usage with the most negative climate conditions would be costly and most likely impossible (Gober and Kirkwood 2009). It seems there is not a viable solution that humans have come up with to counter global warming induced drought because each option has positives and negatives. With the continued warming of the earth, there are no stopping drought conditions from increasing in arid lands. At some point, there will need to be a better water management plan in the American Southwest.

CONCLUSION

Drought essentially is something we cannot avoid due to the continuous warming of the earth. There are several interconnected variables that factor into the occurrence of drought, which includes temperature, precipitation, monsoons, and the subtropical highs. These variables all have a comparable role in causing drought in the American Southwest. They all play a different role in the occurrence of drought, but it clearly appears that humans have influenced the individual elements through global warming. Global warming has been on the rise since industrialization and has come to shape the climate, but there have been periods of global cooling such as the 1950s and 1960s. These fluctuations are representative of climate change and the variability of global temperature. Anthropogenic influence on global warming through greenhouse gas emissions has greatly affected the variables more so than natural forcing. The written record, when compared to the paleoclimate record, shows how gas emissions have greatly changed above the average natural fluctuations. Gas emissions appear to be a primary cause that humans are contributing to global warming. The variability of the factors that cause drought makes it highly unpredictable, which makes the future of drought in the American Southwest unpredictable. This unpredictability makes it important that people properly manage water resources such as rivers and reservoirs. Due to early snowpack melting, lack of precipitation, and high evaporation rates, these water resources are facing the stress of climate change. The growing population places another burden on these resources which are already at a low level. This demonstrates how the human influence on global warming has caused an increase in drought conditions in arid regions and that water usage is putting humans further at risk by depleting water resources. There are ultimately two paths to obtain additional water resources: first, acquiring new water resources, and second, conserving and recycling water. It appears that human impacts have influenced the creation of a situation that places humans at risk of water shortage in the American Southwest. Only time can tell exactly what route, if any, will be chosen to mitigate the situation that is developing in the American Southwest. One thing is clear that as global warming increases, there needs to be a solution in regard to demand because the one thing the region can control is how it handles demand and supply. Overall, as time progresses it will show how anthropogenic influence on global warming will shape the climate and drought in the American Southwest.

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