DRAFT

Guadalupe River Habitat Conservation Plan

TECHNICAL MEMORANDUM:
CLIMATE CHANGE INFORMATION AND RECOMMENDED APPROACHES IN THE GRHCP

Prepared for

GBRA

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December 1, 2022

Table of Contents

1.0 INTRODUCTION 3
2.0 OVERVIEW 3
2.1 High flow events 3
2.2 Sea level rise 3
2.3 Drought 4
2.4 Temperature 4
2.5 Water quality 4
2.5.1 Dissolved oxygen 4
2.5.2 Turbidity 5
2.5.3 Salinity 5
2.6 Vegetation 5
2.7 Current Temperature and Precipitation Trends in Texas and in the Plan Area 6
2.7.1 Temperature Trends in South Central Texas 6
2.7.2 Precipitation Trends in South Central Texas 8
2.7.3 Extreme Events Trends in South Central Texas 9
2.7.4 Sea Level Rise Trends in the GRHCP Plan Area 10
2.8 Climate Projections 11
2.8.1 Temperature 12
2.8.2 Precipitation 13
2.8.3 Extreme Events 14
2.8.4 Sea Level Rise 15
2.9 Integration of Climate Predictions into Hydrology Model 17
2.10 Climate Change in the GRHCP 18
2.10.1 Impacts of Climate Change on Species .... **Error! Bookmark not defined.**
2.10.2 Conservation and Adaptive Management and Monitoring 18
2.10.3 Changed Circumstances 18
2.11 References 18

Tables

Table 1. Climate Impacts that Could Affect Covered Species 5

Figures

Figure 1. Average August Temperature for South Central Texas (1895-2021).. 7
Figure 2. Average Temperatures in Texas; Climate Division 7 (1895-2021)... 7
Figure 3. Average Precipitation in South Central Texas (1895-2021) 8
Figure 4. Annual Average Precipitation in South Central Texas (1895-2021) 9
Figure 5. Increase in 100-year 24-hour Precipitation Events (1960s-2017) 10
Figure 6. Rates of Sea Level Rise in the Eastern and Western Gulf along the Texas Coast..................... 11
Figure 7. Screenshot of Sea Level Rise Viewer in Rockport, Texas... 11
Figure 8.Visual of Various MACA Outputs for the Continental U.S.. 13
Figure 9. Sample Output for the Ensemble of Models for Summer Precipitation (2099 under RCP8.5)... 14
Figure 10. Sea Level Report Card for Rockport, Texas (1992-2050) 16
Figure 11. Sea Level Rise for Five Scenarios from Low to High (2030-2150) 16

1.0 INTRODUCTION

This technical memorandum lays out a framework for assessing and integrating climate change into the Guadalupe River Habitat Conservation Plan (GRHCP). The analysis of and planning for climate change is now considered integral to developing HCPs. The HCP Handbook directs the applicant to analyze potential climate change effects, such as temperature, drought, increased spread of invasive species, and sea level rise, on future habitat and distribution of covered species. Applicants are encouraged to develop HCP conservation strategies that integrate consideration of climate change effects throughout the process and thus are "climate-aligned" by design. Adaptive management and monitoring will need to reflect the limits of our current understanding of climate change impacts on covered species. Understanding the trajectory of climate change and the limits of that understanding will be crucial to providing no-surprises assurances.

This technical memorandum identifies climate change information that informs terrestrial and aquatic covered species, including water quantity modeling. Historical data and climate change variables will be used to characterize potential future conditions with respect to species effects and species conservation. The technical memorandum is part of the overarching task to compile existing information and assess data gaps. As such, it assesses available information and gaps on climate changes in the proposed GRHCP Plan Area (Plan Area). It will also provide context for how climate change will be integrated into the HCP.

2.0 OVERVIEW

This section provides an overview of climate-induced changes to which covered species may be sensitive (i.e., high-flow events, sea level rise, drought, riverine and coastal water quality, vegetation). The overview below provides context on the different elements that will be considered in the HCP when assessing the net effects of impacts and conservation on covered species. In addition, these elements will be used to identify conservation measures within the conservation strategy that build resiliency to climate change for species.

2.1 High flow events

Increases in flooding are driven by a warming atmosphere, with more precipitation falling in fewer but bigger storms. High-velocity flood waters can scour riverine habitat, and high shear stress has been found to negatively affect mussel survival, recruitment, and growth (Rypel et al. 2009 and references therein). High shear strength can reduce mussel density and diversity (Ranklev et al. 2019). Flood waters are also often associated with high levels of turbidity, and the suspended sediment can block light and hinder filter feeding. Deposited sediment can bury aquatic life. High turbidity waters may find their way into karst aquifers in losing stretches of streams. However, high flows may also be important to the maintenance of mussel assemblages because they remove accumulations of fine sediments (Howard and Cuffey 2003).

2.2 Sea level rise

Sea level rise affects species through the loss of coastal terrestrial habitat. Rising sea levels are permanently inundating coastal land and resulting in the conversion of some types of coastal habitats. Habitat changes resulting from sea level rise may affect future species distributions (Metzger 2020).

The combination of king tides (the highest predicted one or two high tides of the year at a coastal location) and other high tides with sea level rise causes temporary coastal flooding that can result in habitat degradation (e.g., saline water reaching areas not typically exposed to that degree of salinity at that frequency) if salinity thresholds are exceeded.

2.3 Drought

While droughts are generally thought of as extended events lasting months, years or even decades and starting with periods of reduced rainfall, "flash droughts" brought on in a matter of days because of precipitation deficits accompanied by extreme high temperatures or high winds coupled with lack of humidity are a growing phenomenon (Otkin et al. 2018). Texas experienced such a flash drought in 2012. Seasonal summer droughts accompanied by seasonal low flows are commonplace in Texas, and many small creeks run intermittently during the summer months when precipitation is often less than needed to compensate for high levels of evapotranspiration and minimal surface runoff. Spring flow may also decrease. Low instream flows reduce the availability of aquatic habitat. However, extended periods of reduced or no precipitation are also common in Texas. Those periods of time, combined with high summer temperatures, can lead to extensive drought conditions in which even larger creeks, streams and springs run dry and inflows into mainstem rivers are greatly reduced.

While freshwater inflows to bays and estuaries fluctuate seasonally, drought will significantly reduce those inflows, and salinities may reach levels that impair bay health and disrupt the food chain.

2.4 Temperature

An increase in ambient (air) temperature results in higher maximum summer temperature, reduces overnight cooling, and increases low temperatures in the winter. For instance, the number of days with a summer maximum temperature over 90° or even 95° degrees is increasing. Likewise, the number of freezing nights is decreasing. These temperature shifts may be significant for terrestrial species. Year-round increases in ambient air temperature are also increasing water temperature in rivers, bays, and springs. Effects of increased water temperature, especially summer maximums, can lead to impacts on aquatic species. Higher air temperature drives increased evaporative demand, which leads to reduced streamflow, bay inflows, and spring recharge, and higher water temperatures. Increased ambient air and surface, groundwater and coastal water temperatures may cause biological impairment or lethality to organisms as they approach the biological limits of cellular function. Temperature thresholds will differ by species with temperatures for lethality being higher than those for sublethal (e.g., reduced growth and reproduction) effects.

2.5 Water quality

2.5.1 Dissolved oxygen

Climate change can lead to reduced levels of dissolved oxygen during periods of higher temperature and/or lower streamflow with attendant adverse effects on aquatic life. Dissolved oxygen levels are dependent on water temperature and turbulence. Reduced instream flows and aquifer recharge and warmer water temperature have the potential to reduce dissolved oxygen levels and cause biological impairment or lethality to aquatic organisms (Mahler and Bourgeais 2013).

2.5.2 Turbidity

Increases in turbidity and sediment transport that can be detrimental to aquatic life are associated with extreme events. High velocity streamflow may scour and transport sediment from upstream beds and banks to downstream beds. Extreme events may also carry eroded sediment from the land surface into the water column. Groundwater may be impacted at recharge sites and along losing stretches of rivers. Suspended sediment consisting primarily of fine inorganic particles of clay, silt, and fine sand and particulate organic matter suspended in the water column may cause transient adverse effects on aquatic organisms during high flows such as reduced photosynthesis due to decreased light penetration and reduced efficiency by filter feeders. Downstream deposition in rivers and bays can cause longer-lasting adverse effects on aquatic organisms depending on the quantity of material deposited. Those same flood waters also carry necessary sediment and nutrients to bays and can help mobilize and clear out sediment previously deposited. The potential for increased turbidity during flood events with attendant adverse effects on aquatic life may be balanced by the benefit of sediment and nutrients into the system. (Sediments | US EPA.)

2.5.3 Salinity

The potential for increased salinity from climate change due to reduced freshwater inflows and increased evaporation could have an adverse effect on bay-dependent species because of reduced bay productivity (Climate Adaptation and Estuaries | US EPA). Note however, that the HCP does not cover any bay-dependent species. Increased salinity has the potential to affect marsh habitats, beach and tidal flat habitats, and potentially prey species for covered species such as piping plover and red knot.

2.6 Vegetation

Vegetation structure and composition can be affected by several factors related to climate change including direct impacts of changing temperature and precipitation regimes and indirectly through species competition and invasion of non-native species. These natural community changes have the potential to affect conditions for covered species. There may be "winners" and "losers" as species migrate, outcompete one another, and reach biological thresholds of temperature, salinity, or drought stress.

In the aquatic environment, the frequency of eutrophication and nuisance algal blooms may be magnified by increasing temperature and changing precipitation patterns (Ho and Michalak 2020). Intensified storms may result in increased nutrient loads from surface runoff (i.e., nonpoint source pollution). More frequent or prolonged droughts will reduce water available to dilute nutrient loads.

Table 1 provides a summary of the potential climate effects and how they might affect species covered under the proposed HCP.

Table 1. Climate Impacts that Could Affect Covered Species

Covered Species	High Flow Events	Sea Level Rise	Drought	Temperature	Vegetation

Cascade Caverns salamander	X		X	X	
Fern Bank salamander	X		X	X	
Undescribed salamander	X		X	X	
Eastern black rail	X	X	X	X	
Piping plover		X		X	
Red knot		X		X	
Whooping crane	X	X	X	X	
Monarch butterfly			X	X	X
False spike	X		X	X	
Guadalupe fatmucket	X		X	X	
Guadalupe orb	X		X	X	

Note: Water quality is the result of changes in water availability and temperature, and thus was not included as a column in this table

2.7 Current Temperature and Precipitation Trends in Texas and in the Plan Area

This technical memorandum is a summary of existing information on the possible trends in climate change impacts in south central Texas. An understanding of current conditions, with a focus on temperature and precipitation, will provide a framework for analyzing effects of climate change, describing changed circumstances, developing adaptive management, and establishing conservation measures. This section describes data sources and provides background information to understand current climate trends.

The climate of south central Texas is subtropical, with a regional gradient from subhumid in the east to semi-arid in the west. In addition to the Gulf of Mexico, which is the dominant moisture source in this region, winter precipitation is supplemented by moisture from the west (Bomar 1995). Some of the most extreme 1-day duration storms in the world have occurred along the Balcones Escarpment, which can trigger high-intensity rain events (Slade 1986).

Historical climate data starting from 1895 are available from NOAA (through portals such as Southern Regional Climate Center | Dashboard (tamu.edu) or www.ncei.noaa.gov) for the entire state, for climate divisions such as the one covering south-central Texas (TX07), counties and cities. Records from individual weather stations are available, but they are numerous within the Plan Area and analyzing them is beyond the scope of this work.

The Multivariate Adaptive Constructive Analog (MACA) Statistical Downscaling Method website (http://climate.northwestknowledge.net/MACA/index.php) that provides downscaled climate model output also provides 1971-2000 historical data for mean, maximum, and minimum temperatures on a seasonal and annual basis. This time period is used in the climate projection comparisons available through their website.

2.7.1 Temperature Trends in South Central Texas

Texas-wide averages may not fully reflect climate trends in a specific region of the state, but the information is readily available in national climate publications and may still serve as a reasonable descriptor of overall trends. Additional data, as described herein, can be accessed to query trends in the region associated with the Plan Area. Temperatures in Texas have risen almost 1.5˚F since the beginning of the 20th century (Runkle et al. 2022).

Temperature trends in the Plan Area can be analyzed in a variety of ways. **Figure 1** provides a sample of average temperature for August since 1895 for the South Central Climate Division (TX07) as generated by the Southern Regional Climate Center Dashboard.

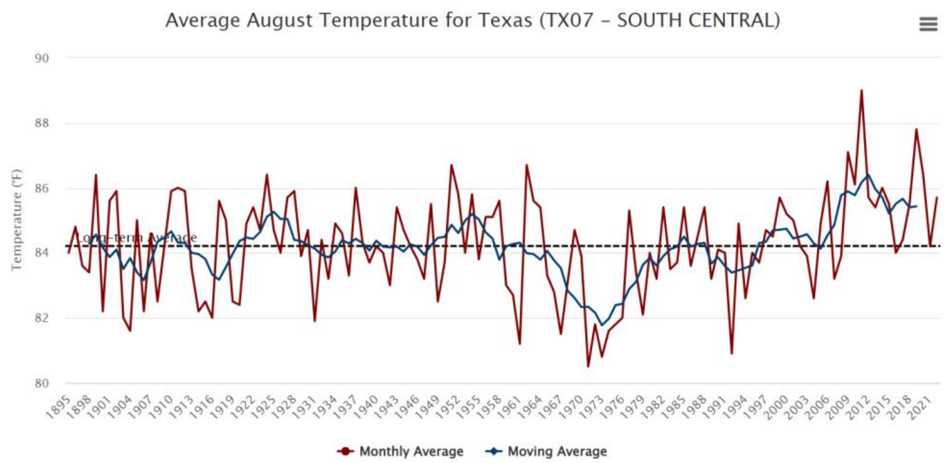

Figure 1. Average August Temperature for South Central Texas (1895-2021)

Monthly, annual, and other aggregated time periods are also available for analysis by climate division, county, and city using NOAA's Climate at a Glance Tool at [www.ncei.noaa.gov.](http://www.ncei.noaa.gov) **Figure 2** provides a sample analysis of annual average temperature data for the South Central Climate Division:

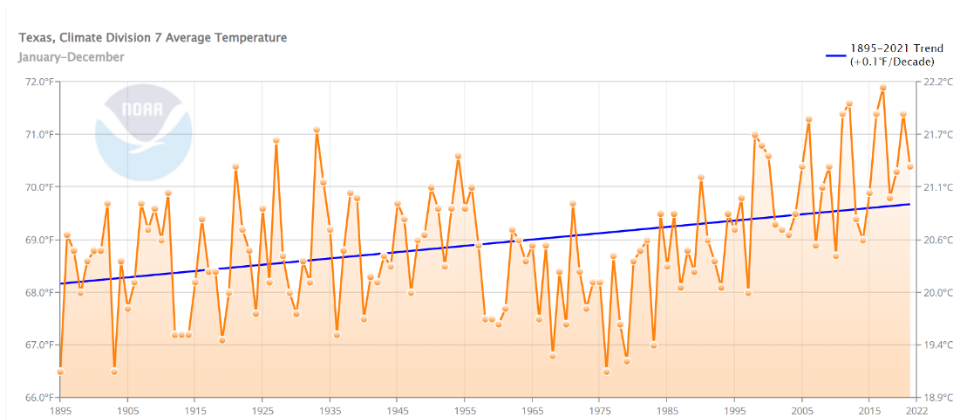

Figure 2. Average Temperatures in Texas; Climate Division 7 (1895-2021)

Any detected trends will be highly dependent on the time period selected and the way the data are analyzed (e.g., individual months versus annually). In addition to average temperature, minimum and maximum temperature data are also available. Reference periods such as 1971-2000 or 1981-2010 for future climate comparisons are common. Historic temperature trends provide context for understanding projections of future changes.

2.7.2 Precipitation Trends in South Central Texas

Precipitation is widely variable across Texas. This section will characterize the variability of precipitation in Texas along with current trends. Since modern record-keeping, there have been historically significant droughts in the late 1910s, the early 1950s, and the early 2010s; the driest calendar years were 1917, 1956, and 2011. The driest consecutive 5 years was the 1952–1956 interval and the wettest was the 2015–2019 period. Droughts often coincide with strong and extended La Niña events. The 1950s multi-year drought continues to be used as the worst-case scenario for water-resources planning in many regions including the Guadalupe-Blanco watersheds, although the 2011 drought was the worst single-year drought in recorded history (Nielson-Gammon 2011a). The current year, 2022, is shaping up to be the state's second-driest year in the past 128 years. Some river gauges in the Guadalupe-Blanco watersheds have recorded zero flow this year and/or have reached or fallen below previously recorded low flows.

In the 1990s and early 2000s, the number of 3-inch extreme precipitation events was above average, and after the dry period of 2005–2014, they were well above average during the 2015–2020 period. The five wettest months on record have all occurred since the year 2000, led by 9.1 inches in May 2015. Hurricane Harvey (2017) was the most destructive event in Texas history, mostly due to the unprecedented rainfall, which contributed to the second wettest month on record despite affecting only part of the state. After making landfall, Harvey slowed and was nearly stationary for several days near Houston. Rainfall exceeded 30 inches in many locations, and a few locations had more than 50 inches. Catastrophic flooding occurred across much of southeast Texas (Runkle et al. 2022).

Precipitation trends in the Plan Area can be analyzed in a variety of ways. **Figure 3** provides a sample of average precipitation for July since 1895 for the South Central Climate Division (TX07) as generated by the Southern Regional Climate Center Dashboard:

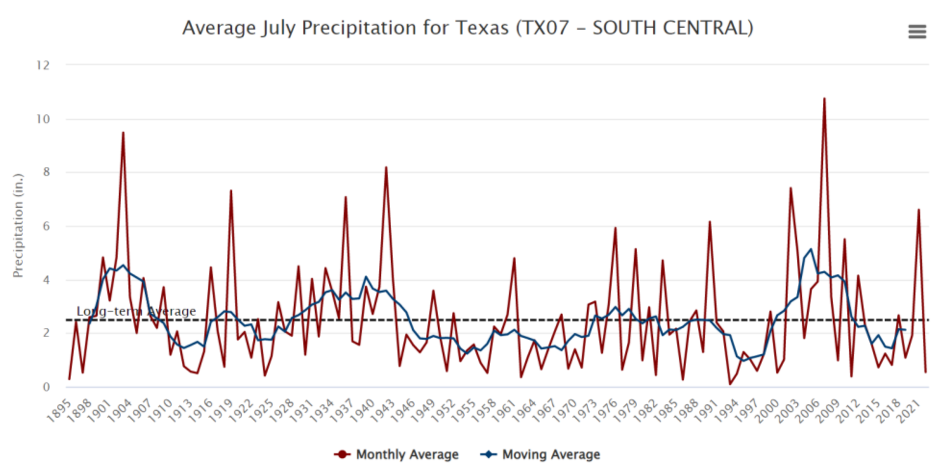

Figure 3. Average Precipitation in South Central Texas (1895-2021)

Monthly, annual, and other aggregated time periods are available for analysis by climate division, county, and city using NOAA's Climate at a Glance Tool at [www.ncei.noaa.gov.](http://www.ncei.noaa.gov) **Figure 4** provides a sample analysis of annual average precipitation data for the South Central Climate Division:

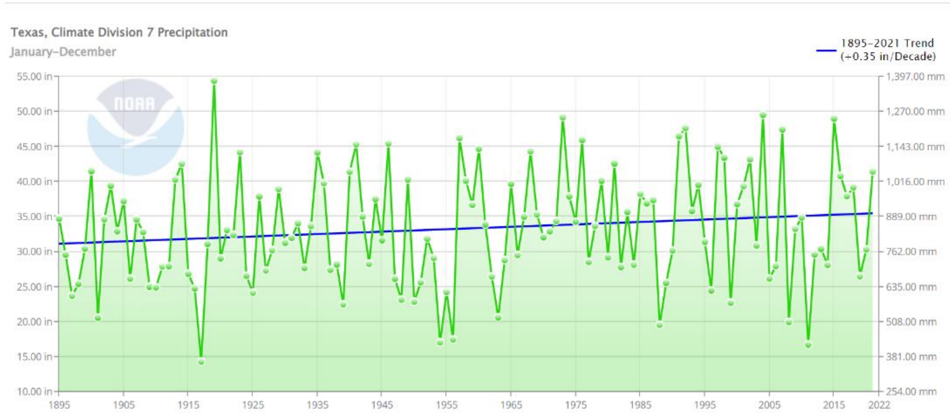

Figure 4. Annual Average Precipitation in South Central Texas (1895-2021)

Any detected trends will be highly dependent on the time period selected and the way the data are analyzed (e.g., individual months versus annually). Precipitation in this region is highly variable so the addition or subtraction of even a couple of years can result in a change in trend sign or no trend at all. Similarly, one calendar month's data may show a trend opposite of another calendar month. Reference periods such as 1971-2000 or 1981-2010 for future climate comparisons are common. Selecting critical months or seasons will help focus the analysis. Historic precipitation trends provide context for understanding projections of future changes.

2.7.3 Extreme Events Trends in South Central Texas

Extreme events include drought, flooding, and storm events. This section will present information on data sources and provide context regarding drought, flooding, hurricanes and tropical storms, and winter storms.

Hydrological extremes, hereby defined as heavy-rainfall and severe-drought events, have occurred throughout the historical record.

2.7.3.1 Drought

The Drought of Record is considered 1950-1956 for the Guadalupe-Blanco River basin. Tree ring studies indicate that severe, decadal-scale droughts have occurred in Texas at least once a century since the 1500s. The recurrence of severe prolonged drought in south central Texas appears to be the norm, not the exception (Cleaveland et al. 2011). Results from this research will be presented.

2.7.3.2 Flooding

NOAA's Atlas 14 or Precipitation Frequency Atlas of the U.S. (Hydrometeorological Design Studies Center [https://weather.gov/owp/hdsc])– contains updated rainfall frequency values. In the Texas volume, NOAA extended the record of analysis from 1960s and 1970s to December 2017 with a few stations extended through June 2018 (Perica et al. 2018). Increased 100-year 24-hour precipitation event is depicted in **Figure 5** below.

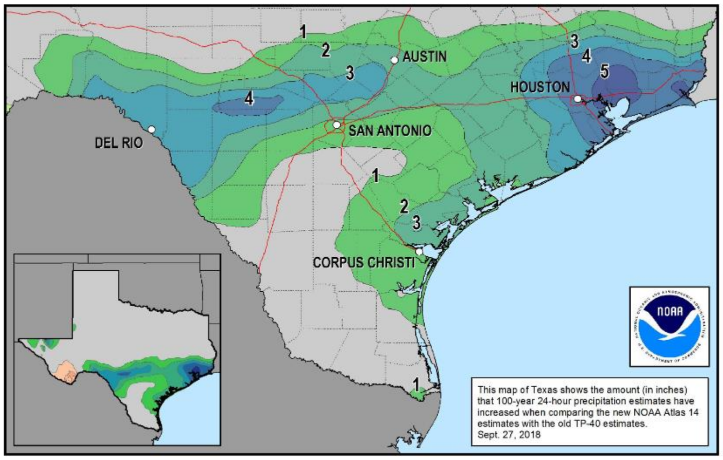

Figure 5. Increase in 100-year 24-hour Precipitation Events (1960s-2017)

The volume also describes the climatology of extreme precipitation events, highlighting some of them and briefly describes detected trends (slightly positive).

2.7.3.3 Hurricanes and Tropical Storms

Over the period of 1900 to 2020, Texas endured more than 85 tropical storms and hurricanes (about 3 storms every 4 years); approximately half of them (46) were hurricanes. Since 2000, Texas has experienced 19 named storms, including 8 destructive hurricanes, with Hurricane Harvey (Category 4), Hurricane Rita (Category 3), and Hurricane Ike (Category 2) causing the most significant damage. Storm surges between 11 and 13 feet along the Texas coast typically have return periods of 25 years (Runkle et al. 2022).

2.7.3.4 Winter Storms

Winter storms accompanied by extremely low temperatures and snow or ice have occurred in the Plan Area in the past, most recently winter storm Uri in February 2021.

2.7.4 Sea Level Rise Trends in the GRHCP Plan Area

As sea level has risen along the Texas coastline, the number of tidal flood days has also increased, with the greatest number occurring in 2020 (Runkle et al. 2022). The Western Gulf of Mexico (Louisiana to Texas) has experienced some of the highest levels of relative sea level rise along the continental U.S. driven, in part, by subsidence. Rates of subsidence vary along the Texas coast. The Western Gulf has the highest extrapolated values in 2050, driven by continued high rates of coastal subsidence in the region (Sweet et al. 2022) (**Figure 6**).

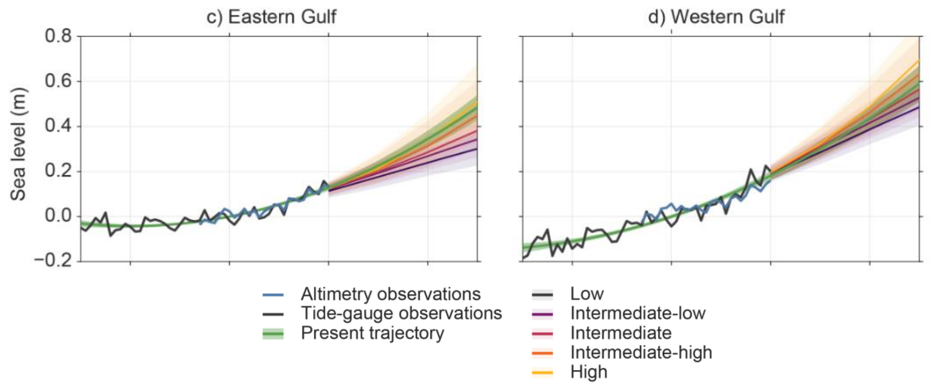

Figure 2.3: Observation-based extrapolations and five regionalized global mean sea level scenario projections, in meters, of relative sea levels for eight coastal regions around the United States from 2020 to 2050 relative to a baseline of 2000. Median values are shown by the solid lines, while the shaded regions represent the likely ranges for the observation-based extrapolations and each scenario. Tide-gauge data (1970 to 2020) are overlaid for reference, along with satellite altimetry observations, which do not include contributions from vertical land motion.

Figure 6. Rates of Sea Level Rise in the Eastern and Western Gulf along the Texas Coast

The Virginia Institute of Marine Science has analyzed trend data for Rockport, TX (Rockport, Texas | Virginia Institute of Marine Science [https://www.vims.edu/research/products/slrc/localities/rotx/index.php]). Rockport, while on the edge of the Plan Area, had the second-highest rates of sea level rise (6.95 mm/yr) in 2019 among 32 tide-gauge stations along the U.S. coastline. High tides now inundate much of the coastal region as depicted in **Figure 7**.

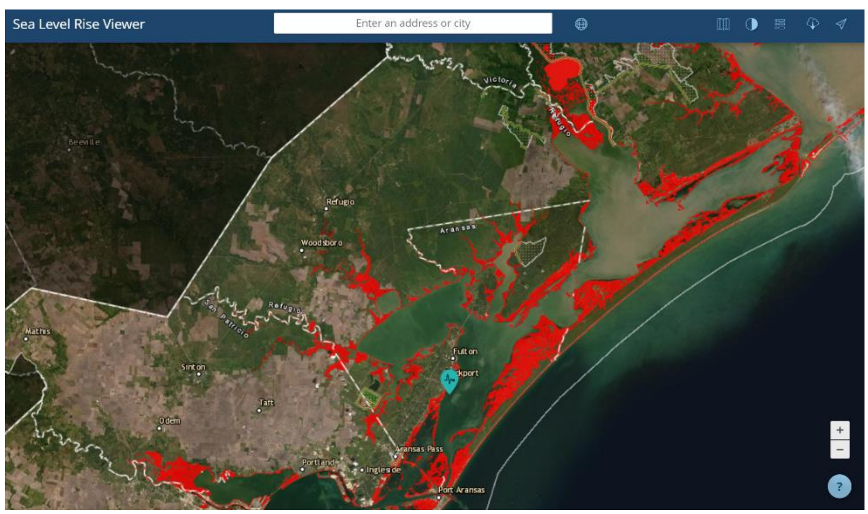

Figure 7. Screenshot of Sea Level Rise Viewer in Rockport, Texas

2.8 Climate Projections

To assess future management scenarios and their feasibility, to help characterize the future environmental conditions for species, and to shape the conservation and adaptive management program, an understanding of potential future climate change scenarios is relevant to the HCP. This section describes climate model outputs that can help characterize the future climate and/or provide an analytical framework for exploring outcomes in the HCP.

The Fourth National Climate Assessment (NCA4) was released in 2017 and incorporated results from the Climate Model Intercomparison Project 5 (CMIP5) models. The Fifth National Climate Assessment (NCA5) is underway with a draft just released in November 2022, and the final report due to be released in Fall 2023. The NCA5 is based on a new crop of models: Climate Model Intercomparison Project 6 (CMIP6). In addition to model updates, more models are participating in CMIP6 than participated in CMIP5. Moreover, CMIP6 models are using a new set of scenarios called Shared Socioeconomic Pathways (SSPs) rather than Representative Concentration Pathways (RCPs) (O'Neill et al. 2016). There is correspondence between RCPs and SSPs, but the latter generate many more possible futures and there is no single worst-case scenario. The SSPs present a wide range of future emissions possible in the absence of climate policy, and all but the lowest baseline scenarios result in at least 3.6°F (2°C) of warming by mid-century 2140-2170 with the high end of warming being 7.2°F (4°C).

It is currently unknown how different the results of NCA5 will be versus NCA4. Scientists' understanding of climate change and the underlying dynamics keeps evolving. Emissions continue to trend upward. Certain processes, like sea ice loss, are accelerating (Slater et al. 2021). NCA5 will be the most up-to-date climate change assessment publicly available.

The NCA4 used the time periods of 2036-2065 and 2070-2099 for evaluation, which means, in essence, that output is readily available for 2050 and 2085. NCA5 references 2040-2070 and 2036-2065 as mid-century markers. A specific end-of-century analysis window appears to be absent. If the GRHCP permit term is 50 years, it would run through approximately 2078, which falls into the second time period of NCA4, but it is not yet determined how NCA5 output will map onto the permit term.

Downscaled output based on NCA4 is currently available at MACA Statistical Downscaling Method (http://climate.northwestknowledge.net/MACA/index.php) from two downscaling methods. Research by the South Central Climate Adaptation Science Center suggests that the CCSM4, the MIROC5, and the MPI-ESM-LR might be the most representative climate models for the region including Texas (Wootten 2020, final project report). As NCA5 is based on a different and larger set of climate models and scenarios, it is possible the same three climate models might not be the most representative for the region in the new assessment. Moreover, downscaled output may not be available from NCA5 in a timeframe that would inform this HCP.

2.8.1 Temperature

The temperature variables available are mean, maximum, and minimum on a seasonal and annual basis for 2040-2060 and 2070-2099 for each of 20 Global Climate Models (GCMs) as well as for the ensemble under the RCP4.5 and RCP8.5 emissions scenarios. There are also derived variables such as the annual average number of days over 86 degrees F, potential evaporation, and first and last freeze dates.

Output from MACA displays on a U.S. map (see **Figure 8** below). There may be ways to access more location-specific values, but the MACA interface is not well designed, and downloading data files to display in another work environment may be necessary. Here is sample output for the ensemble of climate models displaying summer maximum temperature for end of century under RCP8.5 from one of the two downscaling methods available:

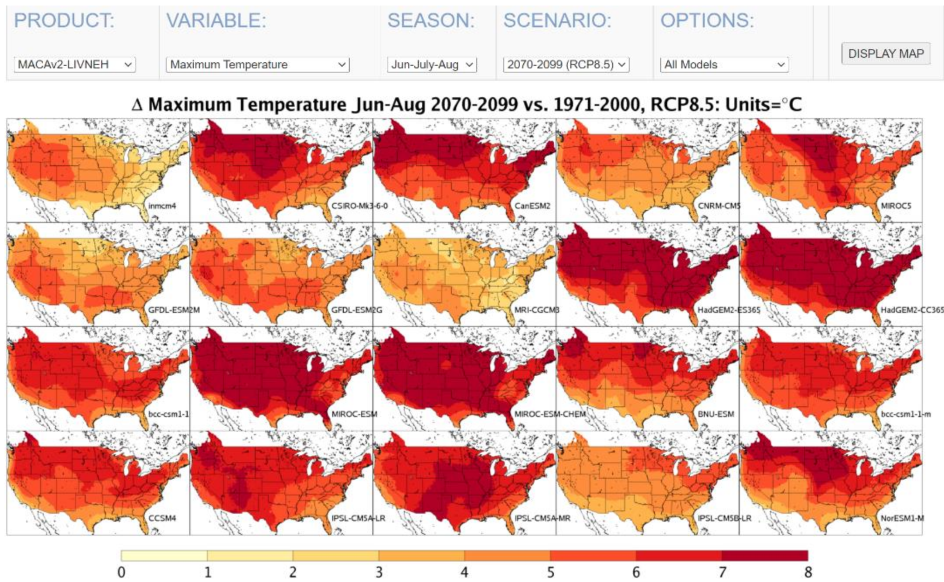

Figure 8. Visual of Various MACA Outputs for the Continental U.S.

GCM temperature output will be explored corresponding to the targeted incidental take permit end date with a focus on variables meaningful to the Covered Species.

2.8.2 Precipitation

This section addresses precipitation projections for future planning. Seasonal and annual precipitation from MACA is available for 2040-2060 and 2070-2099 for each of 20 GCMs as well as for the ensemble under RCP4.5 and RCP8.5 scenarios. There is a tremendous amount of divergence across precipitation projections amongst the climate models not only for a single analysis, such as summer precipitation, but also across different analyses. These climate models have been found to better recreate historical temperature than precipitation (e.g., Venkataraman et al. 2016). For instance, one climate model will produce a very dry summer, while a different climate model will produce a dry winter or spring. The HadGEM2-ES365 produces the driest summer months but the IPSL-CM5A-MR produces the driest winter months.

The variability in the GCMs mirrors naturally occurring precipitation variability and the difficulty in modeling precipitation events in Texas given the interacting influences (described previously), mixed with regional-scale topography that govern these events. The uncertainty in climate change effects on local precipitation has been underscored by Nielson-Gammon (2011b), who noted that observed variations in precipitation over the past century in Texas are larger than most future climate projections of precipitation changes by mid-century.

The simulation of climate from a single GCM is not sufficient to provide a thorough assessment of future hydrologic impacts or to adequately capture the uncertainties involved in global climate modeling. However, in the case of projected precipitation in Texas, the ensemble average of all 20 climate models from NCA4 is also not very informative because the large range of variability, when averaged, yields no change. Prior studies of projected precipitation in Texas have not found clear future trends over much of the state (Venkataraman et al. 2016 and references therein). **Figure 9** provides sample output for the ensemble of climate models displaying summer precipitation for end of century under RCP8.5 from one of the two downscaling methods that illustrates the large range of projected outcomes:

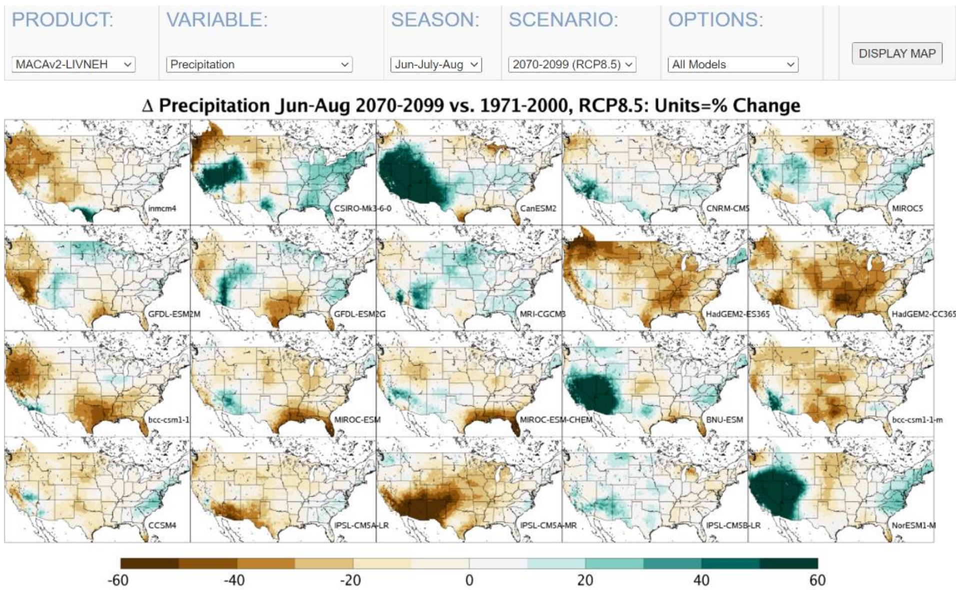

Figure 9. Sample Output for the Ensemble of Climate Models for Summer Precipitation (2099 under RCP8.5)

Future precipitation may be impossible to predict given its variability. However, GCM outputs will be explored corresponding to the targeted permit timeframe with a focus on variables meaningful to the Covered Species.

2.8.3 Extreme Events

Hydrological extremes, hereby defined as heavy rainfall and severe drought, have occurred throughout the historical record, and evidence suggests extreme events are occurring more frequently and with more intensity as climate changes (e.g., Perica et al. 2018, Alizadeh et al. 2020, Overpeck and Udell 2020, Runkle et al. 2022). The atmosphere's capacity to hold water vapor increases by about 7% for every additional degree Celsius of warming. Changes in atmospheric water capacity influence both drought and heavy precipitation. Greater atmospheric water capacity means a greater evaporative force exerted over the Earth's surface, which can intensify drought conditions. It also translates into larger rainfall events because the atmosphere holds more water when it rains.

2.8.3.1 Drought

Although drought is defined based on a range of hydroclimatic or socio-economic variables, droughts generally result from lack of precipitation for a sustained period. However, as described above, flash droughts brought on suddenly by a combination of extreme weather conditions, are a growing trend. Evapotranspiration can play a significant role in drought production by producing moisture deficits. Several drought indices, such as the Palmer Drought Severity Index, the Standardized Runoff Index, and the Standardized Precipitation Index, are routinely used to detect and monitor drought but they each focus on a different drought constituent and have been criticized as not being sufficiently representative of drought processes. A newer index, the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al. 2010), is now often cited in climate studies. By including evapotranspiration, the SPEI accounts for the impact of trends in another important climatic variable, temperature.

Venkataraman et al. (2016) analyzed CMIP5 output by climate division for future drought trends in Texas.

2.8.3.2 Floods

Flood-prone regions are projected to get larger floods as the atmosphere holds more moisture. Hurricanes and tropical storm intensity and rainfall are projected to increase for Texas as the climate warms (Runkle et al. 2022). The Gulf Coast is projected to experience increases in "compound" flooding from rising sea levels, higher storm surge from stronger storms, and increased flooding from heavier precipitation (Wahl et al. 2015),

2.8.3.3 Hurricanes and Tropical Storms

The outlook for hurricanes and tropical storms affecting south central Texas in relation to climate change will be presented. While climate modeling is inconclusive about whether the number of tropical cyclones will increase, decrease or stay the same, there is greater unanimity that projected increases in sea surface temperature will result in an increase in the proportion of Category 4-5 hurricanes and these storms will precipitate more (Knutson et al. 2015; Bhatia et al. 2018).

2.8.3.4 Winter Storms

Winter storms with extremely low temperatures accompanied by snow or ice are likely to occur again in the future given climate change. The disproportionate warming occurring in the arctic is thought to weaken the pressure system known as the polar vortex around the North Pole, sending the jet stream and cold air further south. The polar vortex is breaking down more frequently in recent decades than it did in the past, forming patterns that have the potential to bring those big blasts of cold air deeper into the U.S. (Cohen et al. 2021). Even in the face of overall milder winters, extreme cold spells are also a risk.

2.8.4 Sea Level Rise

Sea level science is dynamic and rapidly evolving, and sea level modeling results rapidly become outdated. Currently, the Western Gulf of Mexico has some of highest projected rates of sea level rise (Sweet et al. 2022). Future sea level rise will increase the frequency of nuisance flooding and the potential for greater damage from storm surge (Runkle et al. 2022).

Based on extrapolation, if current trends measured at Rockport were to continue, sea level at Rockport will be 0.82 meters (2.69 feet) higher in 2050 compared to 1992 (Rockport, Texas | Virginia Institute of Marine Science [https://www.vims.edu/research/products/slrc/localities/rotx/index.php]). These projections may be an underestimate given the most recent sea level rise modeling published by NOAA in 2022 (Sweet et al. 2022) (**Figure 10**).

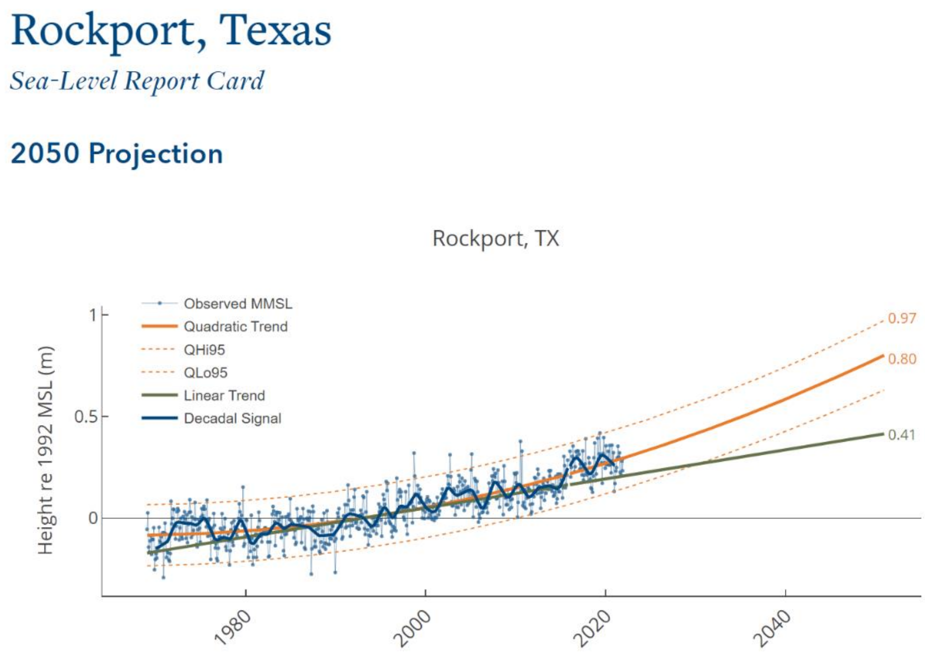

Figure 10. Sea Level Report Card for Rockport, Texas (1992-2050)

NASA has decadal projections from GCMs ([Interagency Sea Level Rise Scenario Tool – NASA Sea Level Change Portal)](#) for five scenarios. Relative to 2000, the Shared Socioeconomic Pathways (SPP) scenarios produce sea level rise ranging from 0.59 to 1.23 meters at Rockport in 2070. Sea level rise projections are available on a decadal basis starting in 2030 through 2100 based on modeling of sea level rise (Figure 11):

Sea Level Rise Scenarios from 2030 to 2150

Median Sea level projection values from years 2030 to 2150 for 5 sea level scenarios and the observation-based extrapolation, relative to a baseline of year 2000.

Values in meters

	Observation Extrapolation	Low	Intermediate Low	Intermediate	Intermediate High	High
Total (2030)	0.39	0.26	0.28	0.28	0.30	0.30
Total (2040)	0.57	0.35	0.38	0.39	0.42	0.45
Total (2050)	0.78	0.44	0.48	0.51	0.58	0.64
Total (2060)	—	0.51	0.58	0.65	0.77	0.90
Total (2070)	—	0.59	0.68	0.80	1.02	1.23
Total (2080)	—	0.65	0.78	0.98	1.30	1.61
Total (2090)	—	0.71	0.88	1.20	1.60	2.03
Total (2100)	—	0.79	0.98	1.44	1.93	2.45

Figure 11. Sea Level Rise for Five Scenarios from Low to High (2030-2150)

NOAA's Sea Level Rise Viewer Sea Level Rise and Coastal Flooding Impacts ([noaa.gov](#)) is a tool that can be used to simulate the effects of different heights of sea level on the Texas coast and coastal habitats. It was updated in 2022 to include the latest sea level rise modeling. One can manipulate the scenario viewer by year and emissions pathway to simulate the impacts of different climate modeling conditions on sea level rise at Rockport. Output is available for 2060 or 2080.

The effects of sea level rise on the whooping crane habitat have been previously examined with a decision support tool commissioned by USFWS that reviewed habitat suitability with up to 2 meters of sea level rise (Metzger et al. 2020). Findings were that 1 meter of sea level rise would still support a 12% increase in habitat carrying capacity but that 2 meters would result in a 6% decline in carrying capacity. In this specific analysis, development was held constant.

2.9 Integration of Climate Predictions into Hydrology Model

The future climate of south central Texas has a high likelihood of being hotter than the present day. However, precipitation in this region has historically very variable. The region experiences drought, often broken or punctuated by extreme flood events, followed by drought yet again. In 2022, the Plan Area is experiencing record-breaking heat and drought. Some CMIP5 climate models show marked reductions in precipitation late in the century (while others show much wetter conditions) but do not depict drought in the way it is currently being experienced or has been in the past.

Per the HCP Handbook, the focus of integrating climate change into HCPs is to ensure that the conservation strategy properly considers climate change as part of species protections and that measures are in place to build climate resiliency and adaptiveness into the Plan. HCPs are not required to integrate climate change into the *impact analysis*. This is because a) it is the permittee's responsibility to quantify and fully offset their own impacts, not those attributed to climate change and b) the specific future conditions anticipated to arise from climate change can differ drastically across different climate models. The Handbook advocates for understanding species vulnerability to climate change and reviewing/revising the conservation goals accordingly. Climate change modeling will be incorporated into the hydrology model as part of an independent scenario that assesses an identified set of future conditions. It will also be built into future "conservation strategy" scenarios to examine the tradeoffs of various conservation actions.

The purpose of the climate change and conservation strategy scenarios (which include climate change) is to ask and answer questions about species risk and species conservation under the plan. These scenarios do not definitively select a future climate condition, but rather identify one or more CMIP5 or CMIP6 models to inform how future conditions might affect key life history stages or vulnerabilities. For example, for mussels, a hotter, drier future is more likely to cause problems than a hotter, wetter future. Thus, climate models that reflect hotter and drier conditions will be integrated into the WAM. Results will be used to see how whether mussels are conserved in these problematic future scenarios. Understanding how the conservation strategy builds resiliency to climate change is an important goal of the hydrology modeling effort. Selecting a climate change model for integration into the hydrology model that represents particularly adverse conditions for mussels, for example, will allow the GBRA to weigh tradeoffs across different conservation measures and ensure that climate change is integrated into conservation.

For terrestrial species, the possible effects of future climate conditions will be assessed, most likely in narrative form. The HCP will review trends and future projections to understand how terrestrial species may be affected by a hotter, more extreme climate and use this understanding to build resiliency for species into the HCP.

2.10 Climate Change in the GRHCP

Climate change will be integrated into the HCP by developing conservation measures intended to be robust against anticipated climate change effects, and building in adaptive management and monitoring to track effectiveness and make adjustments. Climate change will also be discussed as part of the impacts of the taking, and in the changed circumstances sections.

While it is important to note that climate change is not a covered activity – and thus not an impact for which GBRA will be required to mitigate –understanding the future effects of climate helps provide context for decision making during GRHCP development. Understanding the potential range of future conditions will help the GRHCP build in appropriate protective measures for species.

2.10.1 Conservation and Adaptive Management and Monitoring

The GRHCP conservation measures will need to address climate resiliency to ensure successful outcomes for covered species. Climate change will influence the development of the biological goals and objectives to ensure they are evaluated and can be functional with the effects of climate change in mind. For example, conservation measures should be developed that increase the likelihood of success given the expected effects of climate changes. The results of hydrologic scenarios for climate change and conservation will be referenced in the conservation strategy chapter to demonstrate that plan is resilient and sufficiently protective. Scenario outputs can subsequently be included as an appendix. Adaptive management and monitoring will need to both anticipate and be responsive to changes in the environment that will result directly and indirectly from climate change and pose threats to the covered species. A robust adaptive management and monitoring section is particularly important to aid future conservation in the Plan Area.

2.10.2 Changed Circumstances

Changed and unforeseen circumstances are part of no-surprises assurances provided by HCPs. Climate change that is unforeseen by the plan will not require additional commitment of land and resources by the permittee. The effect of a changing climate will need to be considered when developing the changed circumstances and their associated remedial actions. Changed circumstances could include a faster pace of warming or a more variable hydrologic cycle with storms of strength and frequency beyond that currently experienced but still within the bounds of expectations, or droughts of much greater length than the drought of record such as those documented from tree ring studies.

2.11 References

Alizadeh, M.R., J. Adamowski, M.R. Nikoo, A. AghaKouchak, P. Dennison, and M. Sadegh, 2020: A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes. Science Advances, 6 (39), 4571. http://dx.doi.org/10.1126/sciadv.aaz4571.

Bhatia, K., Vecchi, G., Murakami, H., Underwood, S. & Kossin, J. Projected Response of Tropical Cyclone Intensity and Intensification in a Global Climate Model. J. Clim. 31, 8281–8303 (2018).

Bomar, G. W. 1995. Texas weather (2d ed.): Austin, Tex., University of Texas Press, 287 p.

Cleaveland, M. K, T. H. Votteler, D. K. Stahle, R. C. Casteel, and J. L. Banner. 2011. Extended chronology of drought in South Central, Southeastern, and West Texas. Texas Water Journal. 2(1):54-96. Available at https://doi.org/10.21423/twj.v2i1.2049.

Cohen, J., L. Agel, M. Barlow, C. Garfinkel, and I. White. 2021: Linking Arctic variability and change with extreme winter weather in the United States. Science, 373, 1116–1121, Available at https://doi.org/10.1126/science.abi9167.

Frelich, L. E., and P. B. Reich. 2010. Will environmental changes reinforce the impact of global warming on the prairie–forest border of central North America? Frontiers in Ecology and Environment 8: 371-378. DOI: 10.1890/080191.

Ho JC, & Michalak AM (2020). Exploring temperature and precipitation impacts on harmful algal blooms across continental U.S. lakes. Limnology and Oceanography, 65, 992–1009.

Howard, J. K., and K. M. Cuffey. 2003. Freshwater mussels in a California North Coast Range river: occurrence, distribution, and controls. Journal of the North American Benthological Society 22:63–77.

IPCC, 2021b: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of 37 Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-38 Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. 39 Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Ed. 40 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 3−32.

Knutson, T. R., Sirutis, J. J., Zhao, M., Tuleya, R. E., Bender, M., Vecchi, G. A., et al. (2015). Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. Journal of Climate, 28(18), 7203–7224. https://doi.org/10.1175/JCLI-D-15-0129.1

Mahler, B. J., and R. Bourgeais. 2013. Dissolved oxygen fluctuations in karst spring flow and implications for endemic species: Barton Springs, Edwards aquifer, Texas, USA. Journal of Hydrology 505: 291-298.

Metzger, K. L., S. E. Lehnen, S. E. Sesnie, M. J. Butler, A.T. Pearse, and G. Harris. 2020. Identifying sustainable winter habitat for whooping cranes. J. Nature Conservation 57: 125892 https://www.sciencedirect.com/science/article/pii/S1617138120301382?via%3Dihub.

Nielson-Gammon, J. W. 2011a. The 2011 Texas drought, a briefing packet for the Texas Legislature: Office of the State Climatologist, Texas, 43 p. Available at http://climatexas.tamu.edu/index.php/news/588-the-2011-texas-drought. Accessed September 26, 2012.

Nielson-Gammon, J. 2011b. The changing climate of Texas. In: *The Impact of Global Warming on Texas: Second Edition.* G. North, J. Schmandt and J. Clarkson (eds.), The University of

Texas Press. Nickels, D., M.

O'Neill, B. C., C. Tebaldi, D. P. van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J-F. Lamarque, J. Lowe, G. A. Meehl, R. Moss, K. Riahi, and B. M. Sanderson. 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci. Model Dev., 9, 3461–3482, 2016. Available at www.geosci-model-dev.net/9/3461/2016/ doi:10.5194/gmd-9-3461-2016.

Otkin, J.A., M. Svoboda, E.D. Hunt, T. W. Ford, M. C. Anderson, C. Hain and J. B. Basara. 2018. Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States. Bulletin of the American Meteorological Society 99: 911-919. https://doi.org/10.1175/BAMS-D-17-0149.1.

Overpeck, J.T. and D. Udall, 2020: Climate change and the aridification of North America. Proceedings of the National Academy of Sciences, 117 (22), 11856-11858. http://dx.doi.org/10.1073/pnas.2006323117.Perica, S., S. Pavlovic, M. St. Laurent, C. Trypaluk, D. Unruh, and O. Wilhite. 2018. NOAA Atlas 14 Volume 11 Version 2, Precipitation-Frequency Atlas of the United States, Texas. NOAA, National Weather Service, Silver Spring, MD.

Randklev, C. R., M. A. Hart, J. M. Khan, E. T. Tsakiris, and C. R. Robertson. 2019. Hydraulic requirements of freshwater mussels (Unionidae) and a conceptual framework for how they respond to high flows. Ecosphere 10(12): e02975. 10.1002/ecs2.2975

Runkle, J., K. E. Kunkel, J. Nielson-Gammon, R. Frankson, S. M. Champion, B. C. Stewart, L. Romolo, and W. Sweet, 2022: Texas State Climate Summary 2022. NOAA Technical Report NESDIS 150-TX. NOAA/NESDIS, Silver Spring, MD, 5 pp.

Rypel, A. L., W. R. Haag, and R. H. Findley. 2009. Pervasive, hydrologic effects on freshwater mussels and riparian trees in southeastern floodplain ecosystems. Wetlands 29: 497-504.

Slade, R. M., Jr. 1986. Large rainstorms along the Balcones Escarpment in central Texas, in Abbott, P.L., and Woodruff, C.M., Jr., eds., The Balcones Escarpment—Geology, hydrology, ecology and social development in central Texas: Field Trip Guidebook, 1986 Geological Society of America Annual Meeting, San Antonio, Tex., p. 15–19. Slater, T., I.R. Lawrence, I.N. Otosaka, A. Shepherd, N. Gourmelen, L. Jakob, P. Tepes, L. Gilbert, and P. Nienow. Review article: Earth's ice imbalance. The Cryosphere, 2021; 15 (1): 233 DOI: 10.5194/tc-15-233-2021

Sweet, W. V., B. D. Hamlington, R. E. Kopp, C. P. Weaver, P. L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A. S. Genz, J. P. Krasting, E. Larour, D. Marcy, J. J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K. D. White, and C. Zuzak. 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. Available at https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf.

Venkataraman, K., S. Tummuri, A. Medina, J. Perry. 2016. 21st century drought outlook for major climate divisions of Texas based on CMIP5 multimodel ensemble: implications for water resource management. J. Hydrol. 534, 300–316. Available at https://doi.org/10.1016/j. jhydrol.2016.01.001.

Vicente-Serrano, S. M., S. Begueria, and J. I. Lopez-Moreno. 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index, Journal of Climate 23, 1696-1718.

Wahl, T., S. Jain, J. Bender, S.D. Meyers, and M.E. Luther, 2015: Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nature Climate Change, 5 (12), 1093-1097. http://dx.doi.org/10.1038/nclimate2736.

Wootten, A. 2020. Characterizing uncertainties in climate projections to regional decision-making. Final Report. South Central Climate Adaptation Science Center. Norman, OK.