STABLE ISOTOPE COMPOSITION OF PRECIPITATION FROM 2015-2016 CENTRAL TEXAS RAINFALL EVENTS

An Undergraduate Research Scholars Thesis

by

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Submitted to the Undergraduate Research Scholars program at
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by Research Advisor: Dr. Brendan Roark

May 2017

Major: Environmental Geoscience

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ABSTRACT

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The Southern Great Plains is a critical area of study due to its climatic variability and resulting socio-economic importance. Little is known about the paleoclimate of the region, particularly hydrologic changes. Paleoclimate proxies, such as speleothems from central Texas caves, record oxygen isotope ratios ($\delta^{18}O$) as a proxy for rainfall amounts. It is therefore important to know through what meteorological conditions the present day precipitation obtains its oxygen isotopic signature. Linking oxygen isotopic composition with such proxies to changes in meteorological conditions allows past hydroclimate events, like drought and pluvial occurrences, to be placed within the context of global past and future climate variability. Here I propose to analyze oxygen isotopic composition from daily precipitation samples collected from Austin, Texas, from April 2015 to June 2016, and assess potential controls such as storm type, temperature, and precipitation amount. My project will contribute to improving interpretation of paleoclimate oxygen isotope records from Central Texas and southern Great Plains region.

CHAPTER I

INTRODUCTION

The southern Great Plains biodiversity, economic importance primarily as a result of its agriculture, as well as its susceptibility to climate change, make it a critical region for paleoclimate and hydrologic studies (Basara, 2013). Despite the climate-related importance of the region, little is known about past changes in rainfall and the hydrologic cycle. It is vital to know how the precipitation changed in response to past climatic events in order to better predict how it will behave in a warming climate. One of the most important ways information can be gathered on past changes in rainfall and the hydrologic cycle on scales from local to global is through proxy archives of the stable oxygen isotopic composition of precipitation (Dansgaard, 1964; Kurita, 2013). Speleothems, or cave deposits, comprise one such proxy archive that can be absolutely dated through uranium-thorium (U/Th) dating (Lachniet, 2009). Speleothems are abundant in the karst landscape of the Southern Great Plains, and the oxygen isotopic composition of speleothem calcite is a direct reflection of the isotopic composition of the rainwater falling on the karst (Lachniet, 2009).

There are many important climate-related mechanisms that control the oxygen isotopic signature of precipitation. One main control is Rayleigh distillation through the latitude effect: there is a progressive rainout of heavier isotopes as a parcel of water vapor moves from warmer to cooler climates (Dansgaard, 1964) As a cloud moves more toward the poles, the temperature decreases and the parcel of air cannot hold as much water, which leaves the cloud as precipitation (Dansgaard, 1964). The farther up in latitude or altitude a parcel of water vapor travels, the more isotopically negative it becomes due to the continual removal of heavy isotopes.

As a secondary consequence of this Rayleigh distillation, rainfall oxygen isotope ratios can be used in some locations as a proxy for temperature changes (Figure 1). Rayleigh distillation through the latitude effect is most commonly seen at mid to upper level latitudes.

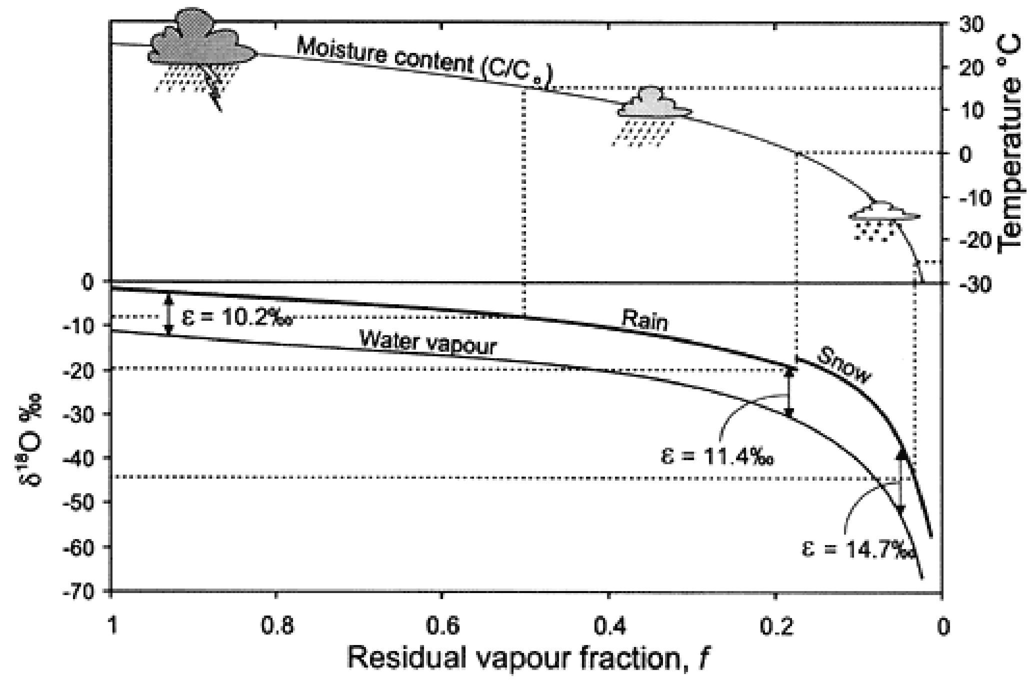

Figure 1. Rayleigh Distillation. Shows the continual depletion of $\delta^{18}O$ as the amount of vapor decreases (reproduced from Clark and Fritz 1997).

Another control on the rainfall oxygen isotope ratio is the amount effect: the observed inverse relationship between the amount of rain that occurs in a storm and the isotopic composition of the storm. As the rainfall total increases, the precipitation is more isotopically negative due to all of the heavy isotopes being rained out first (Dansgaard, 1964) and incorporation of recycled light vapor from storm downdrafts (Kurita, 2013). The isotopic composition of precipitation can also be characterized by the type of storm system it was formed in. For example, the isotopic composition of precipitation for a convective storm is less depleted in $\delta^{18}O$ values than if it were to come from a stratiform cloud (Gedzelman, 1989). The amount effect is primarily seen in the tropics and sub-tropics. Texas's latitude is such where the climate is influenced by both the sub-tropics, where the amount effect occurs and the mid-latitudes, where the latitude effect occurs. It is because of this that it is uncertain what processes control the isotopic signature of precipitation.

Setting and Climatology

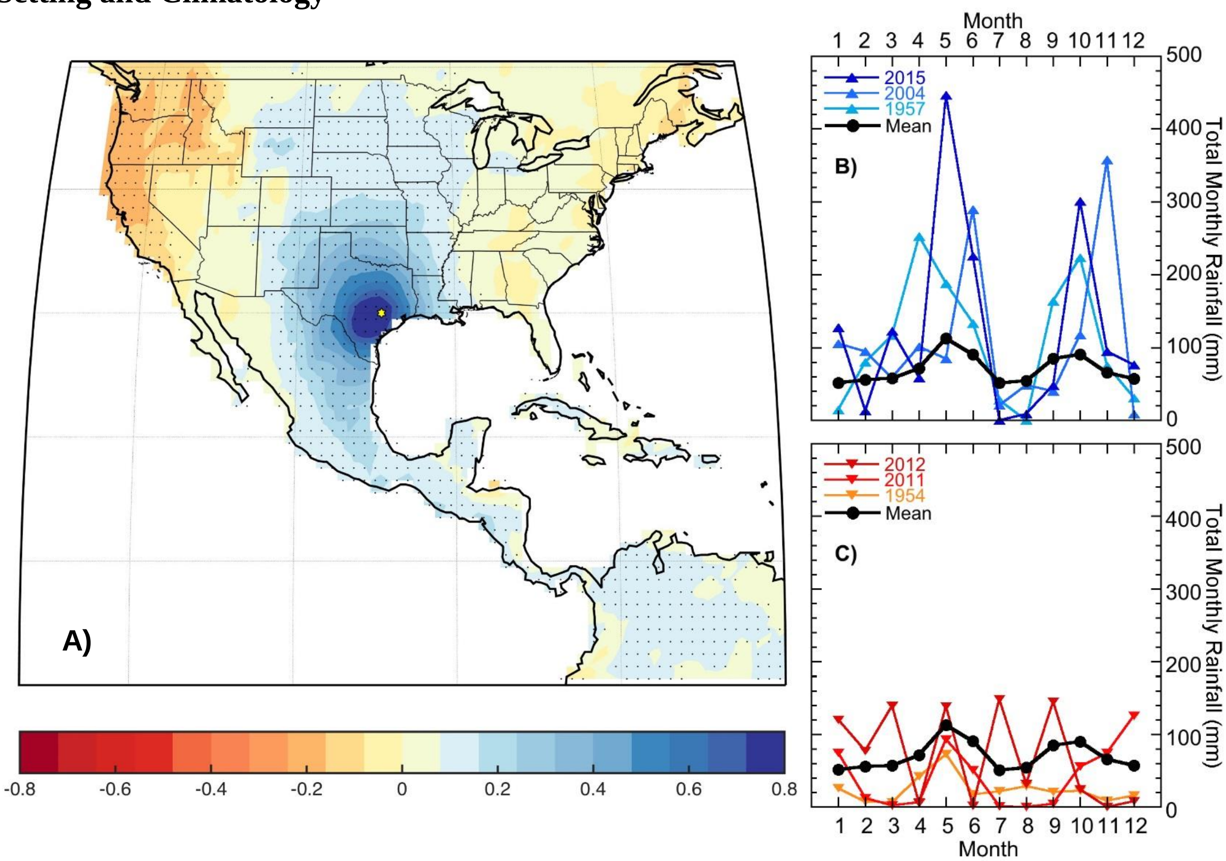

Figure 2. Regional coherence and climatology of precipitation in central Texas and the North American Great Plains. Data is sourced from the Global Precipitation Climatology Centre spanning the years 1901-2011 CE. A) Map of correlation between monthly land rainfall totals at our central Texas study site (yellow circle) and the broader North American Continent at 1° x 1° resolution. Stippling indicates significance at the 95% confidence interval. B) Monthly climatology of the three years with the greatest rainfall totals in comparison with the average monthly climatology of the 1939-2015 CE instrumental precipitation record from Camp Mabry, Austin, TX.. C) The same as panel B) for years considered instrumental "droughts of record".

Since this study ultimately aims at trying to reconstruct the past hydroclimate of the Great Plains region, it is important to know how present day precipitation events that occur at the study site compare to the rest of the region. It is clear that precipitation events that occur in Central Texas are highly correlated to precipitation in the entire Central Great Plains. (Figure 2A). Since the topography of the central plains region is relatively flat, air masses can easily traverse the area and consequently have similar precipitation events (Nielsen-Gammon,2011). This relationship indicates that past hydroclimate events that occurred in Texas, occurred across the entire Great Plains region as well.

Annual Texas rainfall is variable and cycles through periods of droughts and floods, which affect agriculture that is heavily dependent on such hydroclimate events (Basara, 2013). The state experiences peak precipitation in the spring around May and in the Fall around September, which is seen in Figure 2B. No such bimodal distribution is found in Figure 2C which plots the three driest years on record. The bimodal nature of the years of heaviest precipitation indicates that speleothems are more likely to have their isotopic composition signal controlled by rainy years since more oxygen isotopes are being provided through precipitation. This is key when deciphering what the isotopic ratio means for past Texas climates.

The two main geographical features that primarily control Texas climate are the Rocky Mountains, which alters atmospheric processes due to difference in elevation, as well as the Gulf of Mexico which provides a source of moisture. The Gulf of Mexico continually provides Texas and the Great Plains region with a direct source of moisture year round. The warm nature of the Gulf moderates temperatures and acts as a source of precipitation for most of the state and Great Plains region.

The Rocky Mountains cool off faster at night than the Great Plains regions due to the difference in elevation. This differential cooling creates a pressure gradient, and consequently the Great Plains low-level jet is created. The low-level jet is critical in providing the warm, moist Gulf air that fuels mesoscale convective systems. As the air advects from the plains to the mountains, it becomes unstable and conducive for convergence at the surface, which are favorable storm conditions (Kumjian,2006). This instability is exacerbated by the Balcones escarpment, which is a vast geologic feature that runs across Texas and creates a steep elevation change from west to east and a temperature gradient from south to north.

Cold fronts that come from the arctic cause the pronounced rainy season seen in the fall. In the same way that Gulf moisture is transported across the Great Plains, cold arctic air can traverse just as easily. The cold southerly air creates a cold front, thereby creating a lifting mechanism for Gulf Moisture to create storms. The Rockies also act as a geographic barrier allowing more arctic air to travel into Texas and allow for further storm development.

The Bermuda high migration during the spring is another important factor in Texas precipitation. The easterly migration of the high pressure system forces the low level jet to the southwest, carrying with it warm gulf moisture necessary to feed storm growth. Texas experiences pronounced rainy seasons during the spring and fall seasons due to the dry air masses that are taken into the jet stream, and collide with the humid air that is being funneled in by the low-level jet due to the migration of the Bermuda high.

Mesoscale Convective Systems

Mesoscale Convective Systems (MSCs) are storm types that occur in the mid-latitudes due to a multitude of meteorological parameters that the zone provides. MCSs are usually produced by cumulonimbus cloud systems and have a precipitation area greater than 100 km in any direction (Houze, 2004). These systems are the dominant storm type that provide Texas with the majority of its precipitation.

These storms form when instability occurs and convergence at the surface is coupled with divergence aloft, allowing the storm to grow and develop. MCSs are made up by a region of strong convective activity followed by a larger region of stratiform rainfall. The convective updraft that is formed is characterized by heavy, intense precipitation. Surface vapor that was pulled into the convective updraft region, but was not rained out is advected to the stratiform region of the storm. Stratiform precipitation is much lighter isotopically in comparison to convective rainfall. MCSs usually form along fronts. Once a MCS is fully formed, the stratiform region is defined by an updraft that feeds the cloud system as well as a downdraft which is created by the evaporation of falling precipitation. These drafts keep the storm alive and allow new cells to develop. One of the primary differences between the two areas of the storm is that the convective region acquires its vapor from at or below the cloud base while the stratiform region's vapor source is distributed through the entire cloud (Gedzelman,1982). Source of vapor is extremely important because the isotopic signature of the vapor determines the signature of the resulting precipitation.

My project proposes to examine the precise controls on oxygen isotope ratios of rainfall in Central Texas since April 2015, allowing the paleoclimate reconstructions from speleothem oxygen isotope ratios in the southern Great Plains to be accurately interpreted. I hypothesize that due to the mesoscale nature of storms producing the largest precipitation totals, rainfall amount will explain most of the variability in rainfall $\delta^{18}O$ (e.g., Kurita, 2013).

CHAPTER II

METHODS

Rain Collection

Rainwater has been collected since April 2015 for every precipitation event in a rain gauge located under clear sky in Austin, Texas. The rain gauge contains mineral oil which prevents isotopic exchange between the collected precipitation and the surrounding vapor from the air. Rainfall amount, temperature, and type of storm for each precipitation event was recorded. Every day that rainfall occurred, water is collected into a vial. Subsamples of water from the vial are vaporized using a Picarro A2011 High-Precision Vaporizer and introduced into a Picarro Li2120 cavity ringdown spectrometer, an instrument that uses absorption of laser light to calculate the ratios of deuterium to hydrogen and $^{18}O/^{16}O$ present in the vaporized water samples. These ratios will then be compared to additional storm variables, such as temperature during rainfall, type of storm system, rainfall amount, and whether upper level synoptic conditions were favorable for large-scale precipitation.

Storm Classification

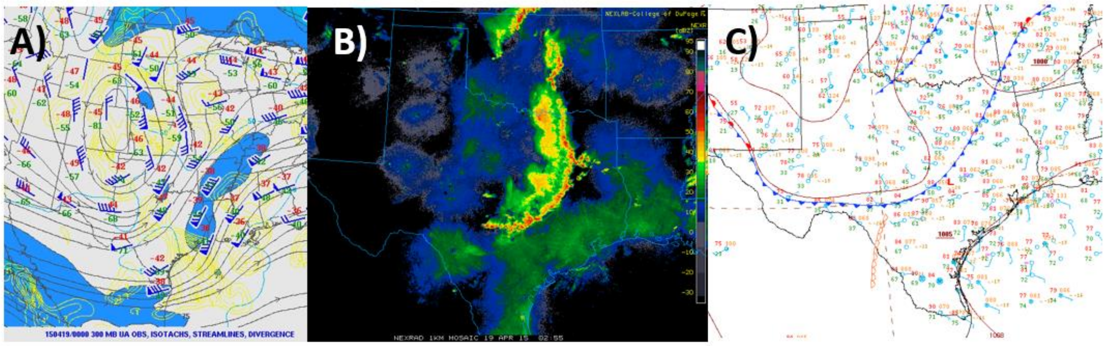

Figure 3 Example of typical atmospheric conditions during a mature mesoscale convective system in Central Texas. A) Upper air trough to the west of the southern Great Plains, providing divergence aloft. B) Radar return showing organized >100 km convective and stratiform regions. C) Surface cold front provides low level lifting.

Each rain event was classified based on a variety of characteristics. Isotopic composition of precipitation can be influenced by the type of storm that it was produced by, thus classifying storm type will further aid in interpreting which climatic processes are at play. The primary storm type that was classified was Mesoscale Convective Systems, which is the dominant storm type that occurs in Texas.

To classify these storms, Doppler radar imagery was analyzed for each recorded storm event. Based on methods similar to Houze 1989, NEXAR Doppler imagery acquired from the Mesoscale and Microscale Meteorology laboratory website was used to classify each storm. A storm was considered to be a MCS if it had an area of high convective activity leading the storm, with reflectivity values greater than 40 dBZ, followed by a larger area of lesser convective activity also known as stratiform precipitation. The trailing stratiform precipitation is defined by reflectivity values of around 30 dBZ (Houze 1989,Steiner et al. 1985). Typically, a MCS is easy to identify based on radar imagery alone, but if there was any uncertainty, upper air and surface meteorological maps were used to further aid in classification. Surface level maps and upper air maps at 500 mb pressure were acquired from the NOAA National Weather Service. The 500 mb upper air map was used to look for areas of low pressure, identified as troughs as well as for lines of divergence that are necessary to form a MCS to allow for the continual organization of the storm. Since MCS are typically frontal storms, if any front was identified on the surface map, it is a good indication that a MCS can form. If both the upper air and surface maps agreed that conditions were suitable for a MCS to form, as seen in Figure 3, the rain event was classified as a MCS.

CHAPTER III

RESULTS & DISCUSSION

Daily Measurements

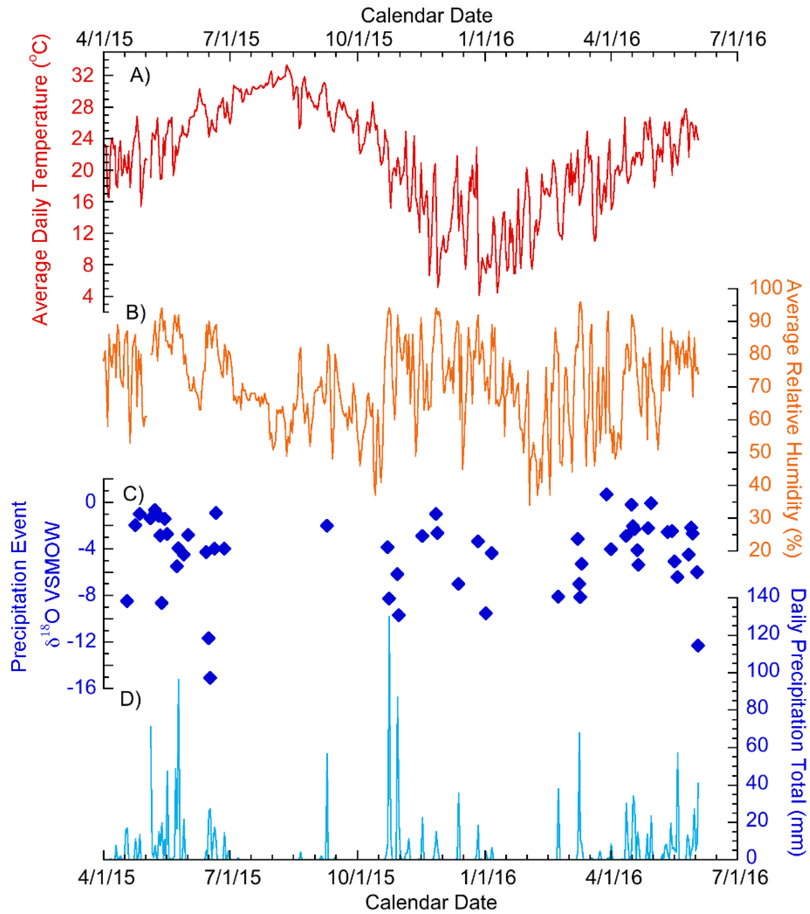

Figure 4. Daily meteorological measurements for rain gauge site in North Austin, Texas from April 2015 – June 2016. A) Daily average temperature, B) average daily humidity, C) $\delta^{18}O$ of collected meteoric waters, and D) precipitation amount. Rainfall accumulation followed climatological pattern of boreal spring and fall maxima.

Daily meteorological measurements including temperature and relative humidity were recorded each day for the study period ranging from April 2015-June 2016. Temperature and humidity were typical for Texas during the entire period. $\delta^{18}O$ values as well as precipitation amount were recorded for each rain event (Figure 4). The pronounced spring and fall rainy season can be seen in the figure, as well as the propensity for isotopes to be more depleted if produced from a rain event with a high total precipitation.

Over the entire study period, there were 56 total rain events. The rainfall amount ranged from 0.1 to 142.7 mm, with the average storm producing 27.8 mm. The $\delta^{18}O$ values ranged from -15.1 to 0.67 ‰, with -4.4 ‰ being the average isotopic signature of the rain events. These values are in agreement with Harvey's paper which studied isotopic composition of precipitation in semi-arid region of the Great Plains.

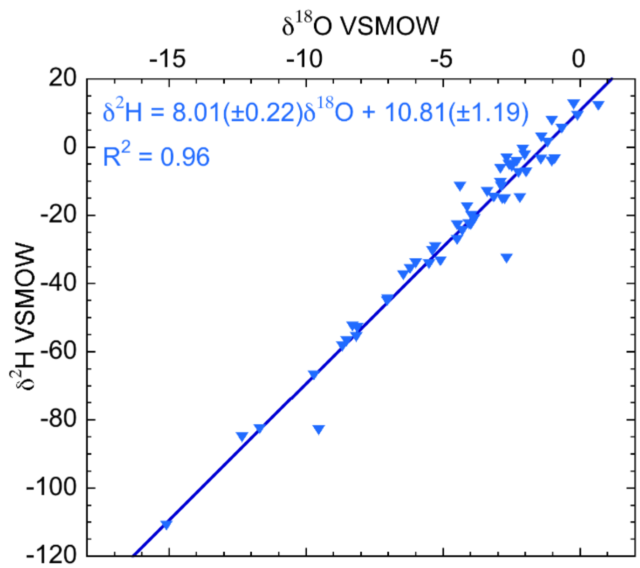

Figure 5. Local meteoric water line for daily rainfall samples. The line is within error of the global meteoric water line.

The graph shown in Figure 5 depicts the relationship between the oxygen and hydrogen isotopic values for each rain event. The regression of the relationship between the $\delta^{18}O$ vs $\delta^{2}H$ isotopic ratios determines the local meteoric water line for the Austin area (Figure 5). The local meteoric water line for the region of study has a slope of 8.01 and a D-excess (y-intercept) of 10.81. The global meteoric waterline (GMWL), which represents the average isotopic composition of global rainfall has a slope of 8 and a y-intercept of 10. Local meteoric water lines are used to infer where an area receives its moisture, and what meteorological conditions are at play in the region. The global meteoric water line and the local meteoric water line are almost identical; meaning that rainfall in the Austin area has nearly the same isotopic composition of average global rainfall. Since most of the earth is Open Ocean, the GMWL is primarily dominated by the evaporation and precipitation that occur over the oceans. The calculated meteoric water line does not deviate substantially from the global meteoric water line, so it can be assumed that there is an open ocean source of moisture.

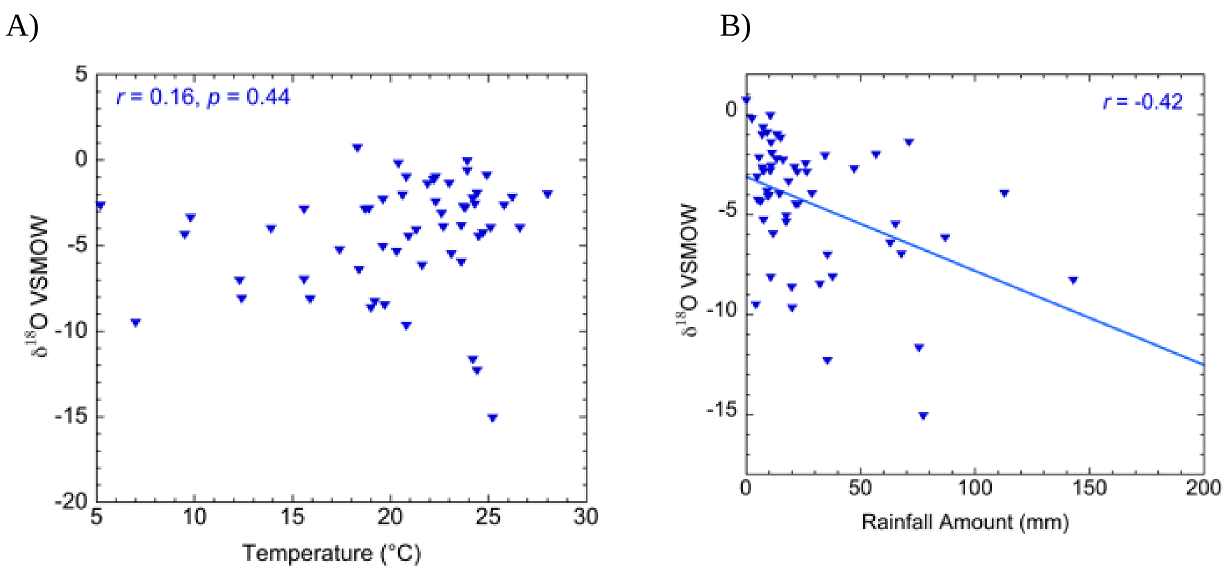

Figure 6. Precipitation $\delta^{18}O$ vs. Temperature (A) and Rainfall Amount (B).

The oxygen isotopic values for each rain event versus temperature and rainfall amount were plotted above (Figure 6). These two specific values were plotted against $\delta^{18}O$ because the latitude effect and the "amount effect," determined by rainfall amount, are the two main hypothesized climatic processes that control the isotopic composition of rainfall in the region. It can be see that there is no relationship between temperature and $\delta^{18}O$. The R^2 value is very low at 0.026, further indicating that there is no trend between temperature increase and $\delta^{18}O$.

There is a negative correlation between rainfall amount and $\delta^{18}O$. The correlation gives an R^2-value of 0.18, indicating that $\delta^{18}O$ values have a stronger relationship with rainfall amount than temperature. This trend follows the "amount effect" phenomena, which states that as rainfall amount increases, the $\delta^{18}O$ values continually deplete.

Classified Storms

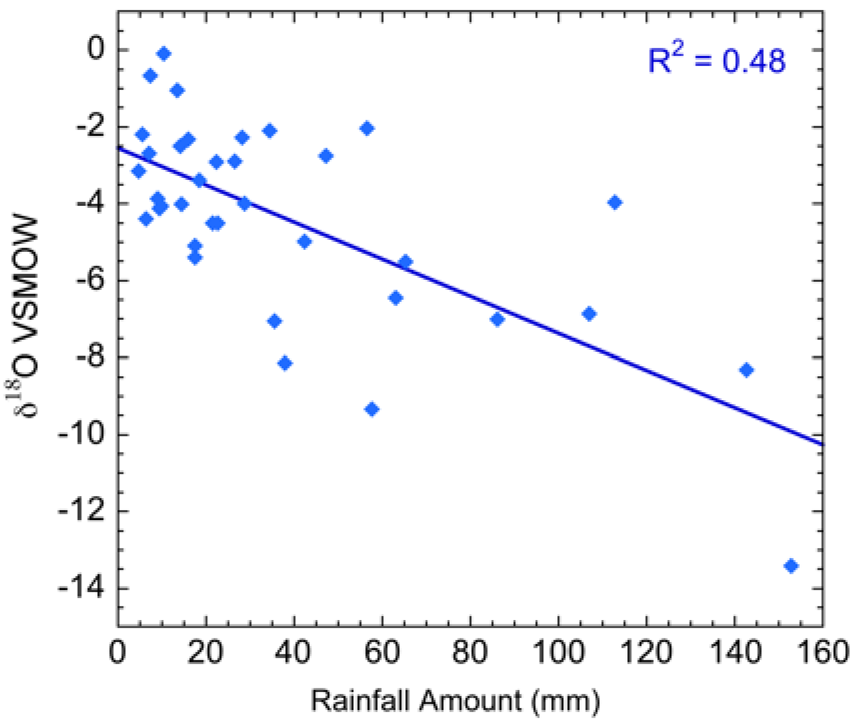

Figure 7. $\delta^{18}O$ of classified Mesoscale Convective Systems vs Rainfall amount.

The classified MCS events were plotted against rainfall amount to further quantify what controls the isotopic composition of precipitation (Figure 7) Out of the 56 storms during the study period, 35 were classified as MCS. MCS accounted for 66% of the total rain over the study period. There is a strengthened negative correlation between amount of rainfall and the $\delta^{18}O$ value. The R^2 value is 0.48, which is significantly higher than the unclassified value of 0.18. The fact that the relationship is strengthened after classifying the storms indicate that the amount effect is more prevalent in organized storm systems.

Amount Effect and Mesoscale Convective Systems

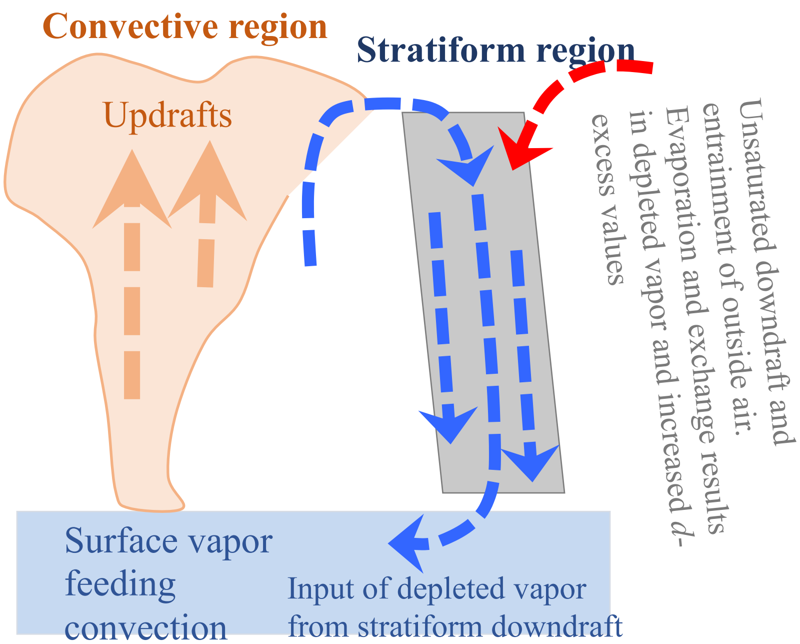

Figure 8. Simplified schematic of downdraft recycling in mesoscale convective systems after *Risi et al.* 2008 and *Kurita* 2013.

The amount effect was exacerbated by the classification of storms, inferring that storm structure has more to do with the isotopic signature rather than rainfall amount. The primary mechanism behind the amount effect is the downdraft that forms as a result of evaporation of precipitation from the stratiform area (Kurita,2013). The process begins with the formation of the convective updraft which is being fed from surface vapor below. The vapor is then advected to the stratiform area of precipitation where it falls as rain. Evaporation of precipitation occurs in unsaturated air where there is a difference in relative humidity between the rain and the surrounding air. Lighter isotopes preferentially evaporate, causing the resulting vapor to be depleted. This depleted vapor source is pulled in to the downdraft where it continues to be rained out and picked up by the downdraft, causing continual depletion (Figure 8). It is believed that this theory is the real reason behind the amount effect phenomena, with stratiform rainfall being the key process (Kurita, 2013).

Table 1. Illustrates increased d-excess from recycling in Central Texas mesoscale versus non-mesoscale precipitation.

***d*-excess**	**non-mesoscale**	**mesoscale**
mean	**8.4**	**12.5**
standard error	**2.0**	**0.7**

The d-excess value, which is the y-intercept component of the LMWL, is typically used as a tracer for moisture origin and evaporation conditions. Higher d-excess values are associated with more arid areas. However, Kurita 2013 found that the d-excess can also be used as a tag for subsidence. A relationship between high d-excess and low δ^2H values was established and is further indication that downdraft recycling is the cause of depleted isotopic values. The d-excess values from the study period support this relationship, with higher values associated with MCS storm events (Table 1). D-excess values increase due to the continual subsidence that occurs when depleted vapor is transported and recycled through the downdraft.

CHAPTER V

CONCLUSION

The purpose of this study was to investigate the isotopic composition of rainfall in the Great Plains region to place historical and recent hydroclimate events in the context of natural variability. No relationship between temperature and isotopic value was found, but there was a slightly stronger relationship between rainfall amount and isotopic value. After classifying each storm as a MCS or not, it was seen that the main control on isotopic composition is storm type. Continual isotopic depletion as a result of downdraft recycling found in MCSs is the mechanism responsible for the amount effect.

Other important hydrological relationships were found in the region. It was calculated that the Local Meteoric Water Lines is indistinguishable from the Global Meteoric Water Line. Putting the findings in the context of paleoclimate, speleothem oxygen isotope records from the region likely reflect changes in rainy season intensity and storm structure. Lower $\delta^{18}O$ and $\delta^{2}H$ values found in the speleothems are indicative of rainier seasons, and more organized storm events. Establishing this relationship will aid in decoding past hydroclimate events in the Great Plains region and will strengthen the predictive power of drought and flood occurrences that may ensue due to climate change.

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