Decoding Water's Journey: Precipitation Isotopes and Weather Interactions

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Natural Resources and Environmental Sciences (NRES) Capstone Project

Kansas State University 2024

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1) Abstract

This study's focus is to create a better understanding of the spatial variation on $\delta^{18}O$ and d-excess in the lower 48 of the United States of America. In this study we found variation of $\delta^{18}O$ and d-excess across the CONUS (lower 48). This variation is correlated with various environmental factors such as temperature, moisture source, precipitation, sub cloud evaporation, and elevation. Due to the high amount of variables the spatial distribution is highly variable across the CONUS, the seasonal variation creates a difference in concentrations in both $\delta^{18}O$ and d-excess due to the change in environmental variables. Using data from sources such as NEON and GDAS, figures were then produced to show spatial-temporal variation in $\delta^{18}O$ and d-excess across the CONUS. In addition, HYSPLIT back-trajectory figures were produced to further understand how moisture sources change seasonally.

2) Introduction

Precipitation significantly influences spatial variation in isotopic composition by altering the local hydrological cycle and modifying the isotopic signatures of water sources. The amount and intensity of rainfall can lead to different isotopic outcomes; for instance, heavy precipitation events tend to dilute isotopic concentrations, resulting in lower ratios of oxygen-18 and deuterium, while lighter rain from shorter, intense storms may be more enriched (Lekshmy et al., 2014; Tappa et al., 2016). Additionally, variations in precipitation patterns across different regions, influenced by geographic and climatic factors, create distinct isotopic landscapes. Areas with frequent rainfall may exhibit more homogenized isotopic signatures due to consistent moisture replenishment, while drier regions may show greater isotopic variability tied to episodic storm events (Kendall &

Coplen, 2001; Tian & Wang, 2019). Moreover, the interplay between precipitation and evaporation rates further modulates isotopic values; higher evaporation can lead to enrichment in residual water, influencing the isotopic characteristics of subsequent precipitation (Gat, 2010). Thus, precipitation not only serves as a key component of the water cycle but also acts as a dynamic factor shaping the spatial distribution of isotopic variations in hydrological systems.

Temperature plays a crucial role in influencing spatial variation in isotopic composition of precipitation by affecting evaporation rates and the dynamics of atmospheric moisture. Warmer temperatures generally enhance evaporation, leading to a higher concentration of isotopes like oxygen-18 and deuterium in the remaining water vapor, which subsequently impacts the isotopic signature of precipitation (Gat, 2010). As moist air moves into cooler regions, it undergoes condensation, and the isotopic composition can shift; colder conditions typically result in isotopically lighter precipitation due to the preferential removal of heavier isotopes during the condensation process (Lekshmy et al., 2014; Liu et al., 2010). Additionally, temperature gradients can create distinct climatic zones, each with unique precipitation patterns and isotopic characteristics. For instance, areas experiencing significant seasonal temperature fluctuations may exhibit greater variability in isotopic ratios, reflecting changes in evaporation and condensation dynamics throughout the year (Tian & Wang, 2019). Overall, the interplay between temperature and hydrological processes fundamentally shapes the spatial distribution of isotopes in precipitation, highlighting the importance of thermal conditions in hydrological studies.

The stable water isotopes $\delta^{18}O$ and Deuterium have significant applications in multiple fields of study, including hydrology, paleoclimatology, ecology, and the environmental sciences. Due to the fractionation differences of isotopes present within water masses, and their relationship to variables such as temperature and pressure, these stable water isotopes are able to act as tracers when determining where water may have originated from in a specific water mass.

Fractionation processes that occur when water undergoes phase transitions allows researchers to determine where moisture in a given geographic region may have originated. For example, there is a relationship between the relative humidity of a water source and the deuterium excess (d-excess) present within the precipitation resulting from that water source that allow for an isotopic “signature” which provides evidence to determine the climatic conditions of that source area (Tang et al.). Generally, regions with water containing low d-excess values have high relative humidity (and vice versa,) and areas with water containing a more negative $\delta^{18}O$ value show correlation with longer distances traveled because of the effects of increased upstream rainout (Tang et al. 2017). Correlations such as these allow the use of $\delta^{18}O$ and d-excess to be of incredible use when determining what climatic conditions water may have traveled from, and therefore what body of water the isotopes may have originated from.

The use of water isotopes has been incorporated into Atmospheric General Circulation Models (AGCMs) in order to further understand the relationship between variables such as temperature and humidity and the effect that they have on atmospheric processes. Due to the coupling of AGCMs and water isotope data, researchers have been able to develop nearly a dozen models what allows for phase transitions such as evaporation, precipitation, condensation, and the transport of water vapor which provides a solid basis for understanding global climate models (Xi 2014).

Not only is research into the movement of stable water isotopes of high importance in studying today's climate, it is essential in understanding the climate of the past as well. The field of paleoclimatology is partially reliant on the relationship between stable water isotopes and temperature, and as such samples containing water from the past are able to be analyzed for their isotopic contents. The relationship between stable water isotope ratios and temperature provide an indispensable resource when trying to understand what temperatures may have been in the geologic past. Analysis of ice wedges, specifically the δ18O and Deuterium contained within the sample, brings to light temperature changes that may have occurred. These wedges form when cold-season precipitation meltwater fills cracks resulting from springtime temperature changes, which create a record of winter precipitation with minimal effects on water fractionation (Porter & Opel, 2020).

Although much progress has been made in the study of stable water isotopes, gaps in research are still present. For example, the Global Network of Isotopes in Rivers (GNIR) lacks spatial coverage which prevents a more complete understanding of how the movement of isotopes is affected and effects river systems across the globe; there is however ongoing work to improve our sampling of these rivers for the end result of a near-complete GNIR database (Nan et al. 2019). Furthermore, current limitations on how we sample the isotopic content of water on a large scale generally are prevalent; due to the lack of duration and amount of samples taken within a given water mass, researchers currently must significantly extrapolate hypotheses based on limited water samples (Penna et al. 2018). These issues are present globally, but also affect our understanding of $\delta^{18}O$ and d-excess across the CONUS.

The main objectives of this research project are outlined as such:

Objective 1:

This first objective for this research is to analyze the spatial variation of $\delta^{18}O$ and d-excess in precipitation across the CONUS, and their linkages to moisture sources and meteorological variables.

Objective 2:

Assess the impact of sub-cloud evaporation on $\delta^{18}O$ and d-excess.

Objective 3:

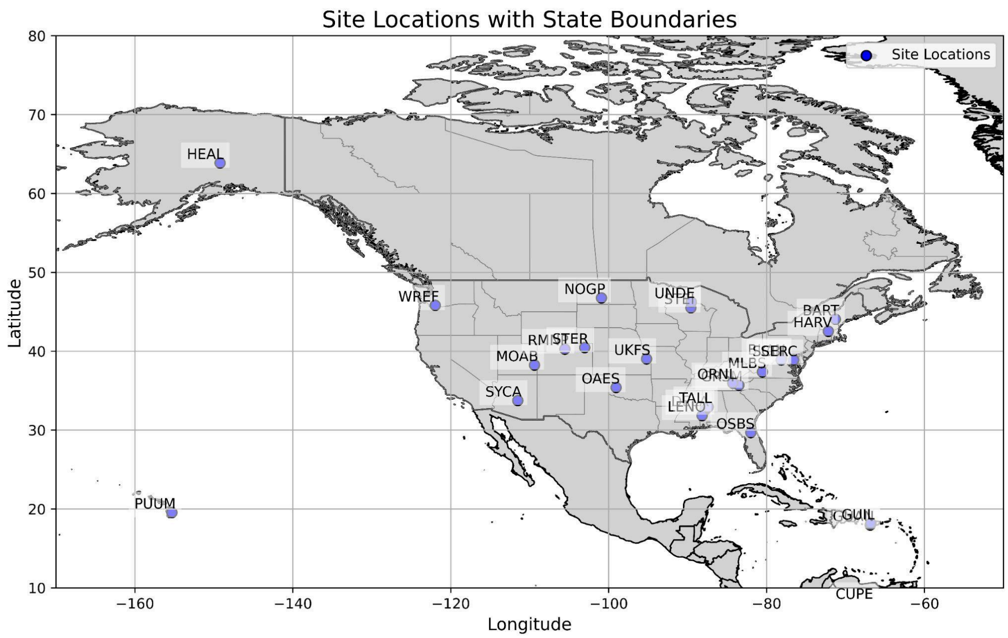
The last objective of this study is to explore the causes of seasonal variations in $\delta^{18}O$ and d-excess.

3) Study Area & Methodology

- **3.1 Study Area**:

The area of study for this research is the Contiguous United States (CONUS), (lower 48 states) and Puerto Rico. Geographically this large land area has a high amount of environmental variability. This creates a large land mass with high variation in temperature, precipitation, elevation, and topography. In the center of the CONUS is a vastly flat area called the Great Plains. This region has flat topography with high seasonal variation in temperature and precipitation. The Eastern region of the CONUS is the Smokey Mountain range and to the East is the coastline. This region has higher precipitation on average due to its respective location to the Gulf of Mexico and East Coast. The Western region contains the Rocky Mountains and the West Coast. This region has some of the highest temperature and precipitation variation than the other regions in the CONUS. It contains the driest place and the wettest place in the lower 48. The CONUS has temperatures ranging in the summer over 100 degrees Fahrenheit and in the winter below 0 degrees Fahrenheit. This large land area has various moisture sources which creates inconsistency in precipitation in the CONUS.

Figure 1



National Ecological Observation Network (NEON) site locations

- **3.2 Methodology**:
    - *3.2.i Geospatial Analysis*:

The completion of the Geospatial Analysis was done in ArcGIS Pro by using various tools to create numerous maps to illustrate the distribution of δ18O and d-excess. The data source for the research was NEON and the data was sorted using the program r. Once calculations were completed the data could be manipulated in ArcGIS. Each station that was collecting isotopic data had a coordinate associated with it. The computed data could then be tied to the set of coordinates for each station. Using the tool XY to Point the coordinates were plotted on the map. By altering the symbology, the δ18O or d-excess values could be displayed on the map. Given the value, there was a range of colors assigned to it. What was left was a map with station locations and the value of δ18O or d-excess shown. We can gain a better understanding of the environmental factors that influence the isotopic values if we can visualize them.

- 3.2 ii Sub-cloud Evaporation Linear Regression Models:

Precipitation, most commonly in the form of rainfall, experiences raindrop evaporation on its way from a saturated air mass (i.e. a cloud) to the ground. During this journey, d-excess values can decrease and δ18O values have the potential to increase. In other words, raindrops lose moisture, altering their chemical makeup. This then ultimately affects the overall patterns of hydrometeorological processes as local factors like sub-cloud evaporation modify large-scale weather patterns.

Observing changes in precipitation via isotope techniques can indicate the significance of secondary processes (sub-cloud evaporation, moisture recycling, and in-cloud supersaturation). Sub-cloud evaporation is an important indicator for moisture and temperature profiles, namely near the surface of Earth. Furthermore, sub-cloud evaporation processes influence the development of precipitation and rainfall amounts (Lutgens et al, 2019).

Using the National Ecological Observation Network (NEON) data, δ18O values and d-excess values were separated into cold and warm seasons. Cold periods were considered the months of winter (December, January, and February) while the rest of the months were labeled as warm seasons. While the stations could have been categorized into the four seasons, winter precipitation data has the largest potential to show contrasts and extremities in variation compared to other seasons/months.

- *3.2 iii HYSPLIT Back-Trajectory Modeling:*

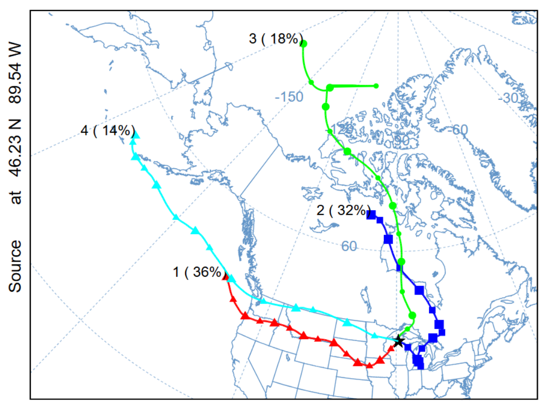
The Hybrid Single-Particle Lagrangian Integrated Trajectory Model, also known as the HYSPLIT Model, produces back trajectory figures in order to visually present how airborne masses move across a geographic area. This model is used in order to track the movement of dust, wildfire, airborne pollutants, volcanic ash, stable water isotopes, and other air parcels.

The model uses a combination of two different approaches in order to produce its figures: the Langrangian and the Eulerian specifications of flow field. The Langrangian approach (which represents the “L” in “HYSPLIT”,) focuses on how individual particles are moving and creates a separate calculation on the trajectory of each particle. The Eulerian approach concerns concentrations of particles, as opposed to single particles, and then calculates convection in addition to the overall diffusion of multiple particles (Saidi et al. 2014). There are benefits to both of these approaches, as Langranian models utilize advection and diffusion components of air pollutant concentrations (or an analogous metric) computed independently, while the Eulerian models will solve an advection-diffusion model along a fixed grid. The results of these two methods of calculation allow for flexibility among back-trajectory calculations, as the Eulerian method excels at complex emission problems where solutions are required at all grid points, and the Langranian method excels when emissions occur from a single source with only a few grid points ultimately needed (Draxler & Hess, 1998).

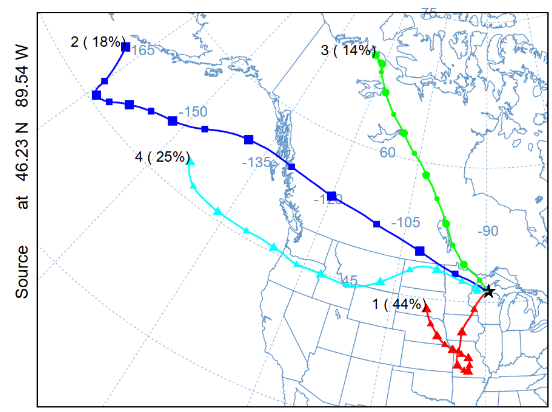
Given that HYSPLIT works off of calculations, inputs in the form of data must be given in order to receive outputs. For a basic calculation, the variables of east-west winds, north-south winds, and vertical winds (referred to as U, V, and W respectively) must be applied, as well as height (Z), pressure (P), and surface pressure (P_0) (Draxler & Hess, 1998). If these variables are input, as well as a timeframe and location, HYSPLIT will be able to successfully calculate a back trajectory.

The data used to produce the HYSPLIT figures is sourced from the Global Data Assimilation System (GDAS). NEON sites were chosen as the locations for analysis, but not all 81 sites were analyzed. After data inputs and parameter controls, here are a few choice figures produced:

UNDE Station Back-Trajectory in Cold Season

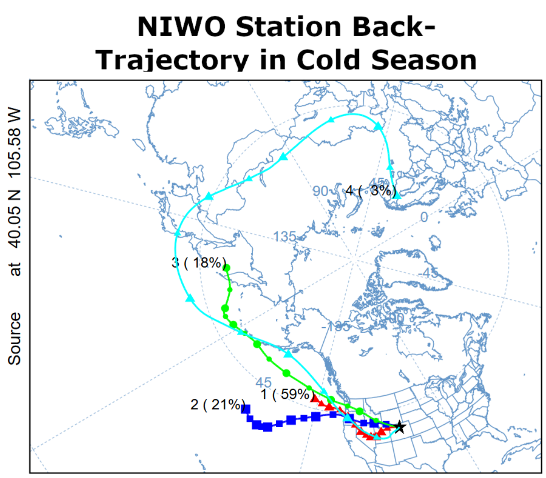


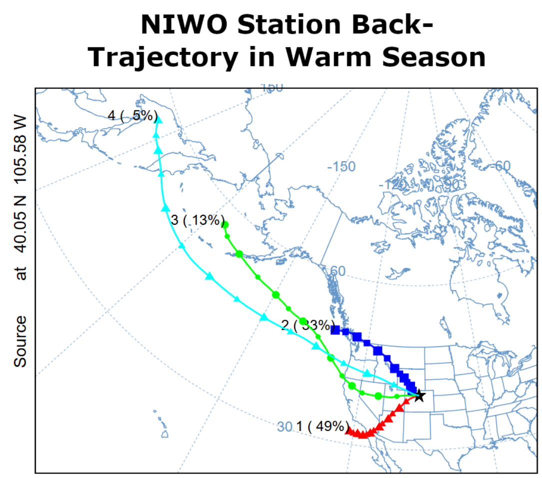
UNDE Station Back-Trajectory in Warm Season



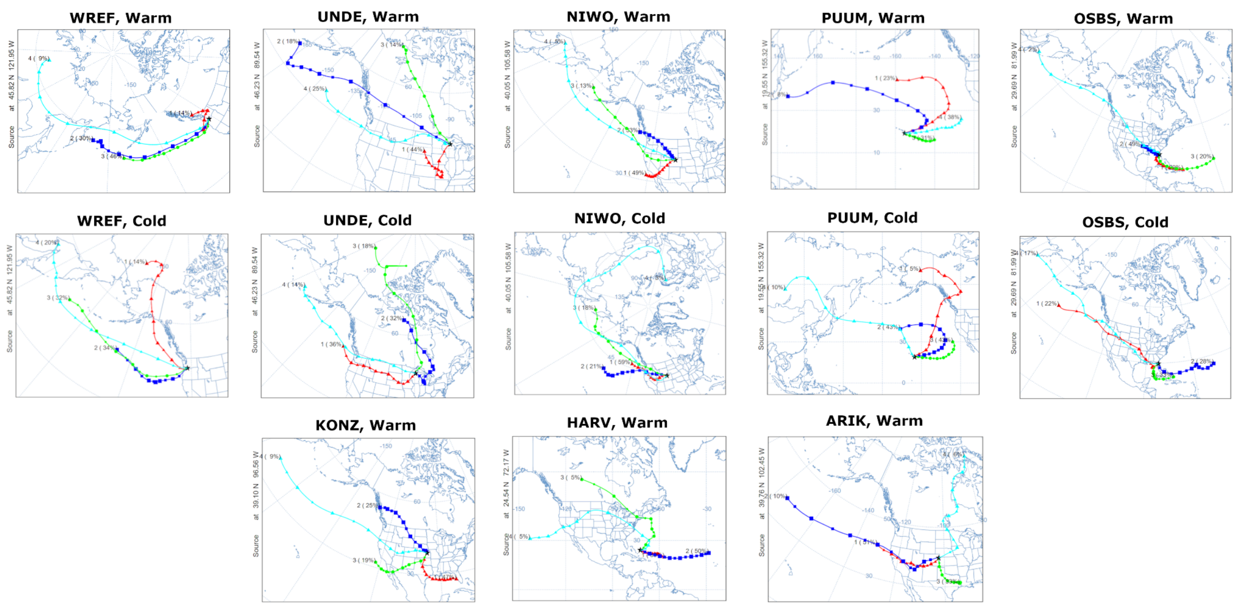
The back trajectories calculated from the University of Notre Dame Environmental Research Center (UNDE) under NEON. The two figures show how during the cold season, the majority of moisture is coming from the Pacific Ocean near the North American coast, as well as the northern portion of mainland Canada. This changes during the warm season, however, as it can be seen that the majority share of moisture tends to originate from the CONUS, and generally it appears that moisture is coming from sources further south than was seen in the cold season.

This correlates with how isotopic signatures tend to be transported due to changes in temperature; during warm seasons, moisture can be evaporated from the continental, isotope-poor fresh water and recycled into the continental mainland. During the cold season, moisture must come from the isotope-rich ocean waters, and is carried over to the mainland (while still depleting in δ^{18}O and Deuterium due to the rainfall effect). As a result of these trends, we can see similar results in the other figures produced moisture source varies seasonally as well; the NIWO station located west of Boulder, Colorado, shows an increased amount of moisture coming from within the continental boundary during the warm season, and more moisture sourced from the Pacific Ocean during the cold season.





Furthermore, a composite image of all of the HYSPLIT back-trajectories was produced comparing all spatial-temporal variations in back-trajectories across different NEON sites in the CONUS and Hawaii, in order to directly compare warm and cold season movements of air masses. In addition, three warm-season only sites were included in order to give a more complete understanding of how moisture sources are linked to seasonal change.



3.3: Data Sources

NEON Data

The National Ecological Observatory Network, also known as NEON, is an institution funded by the United States National Science Foundation (NSF). NEON acts as an ecological observatory network that currently collects ecological, airborne, and meteorological data from 81 field sites across the contiguous United States, Alaska, Hawaii, and Puerto Rico (Spatial and Temporal Design).

Precipitation data collected from NEON was categorized by secondary precipitation and primary precipitation and then warm and cold seasons. Each site has several different rain gauges/collectors in various places. Some rain gauges are labeled as ‘through fall’ sensors which measure the precipitation data that ‘falls through’ the canopy. These gauges are at ground level and serve to measure the rain that falls through the tree canopy. At sites with little to no tree canopy, there exist Dual Fence Intercomparison Reference sensors (DFIR). These sensors are at ground level, but elevated off the ground to prevent obstructions from hindering precipitation falling on said sensor. These sensors record primary precipitation data. Sites also have sensors at the top of each tower. These are deemed 'secondary precipitation' data.

Using python code to filter NEON data for this research's scope, information was sorted on the basis of domain identification, collect dates, and measurements of $\delta^{18}O$ and $\delta^{2}H$ in water. After filtering the two sets of data for said research needs, d-excess values were then calculated. The relationship between $\delta^{18}O$ and d-excess values were then assessed using a linear regression model.

GDAS Data

The data acquired in order to produce the HYSPLIT back-trajectory figures was collected and compiled through the Global Data Assimilation System (GDAS). The main purpose for the existence and continuity of the GDAS program is to collect data for use in the Global Forecast System (GFS), which can be used to predict and analyze weather events (Global Data Assimilation System, 2023).

The data collected through GDAS included metrics, but is not limited to: temperature at 2m AGL, temperature at surface, U and V components of wind with respect to grid and at 10m AGL, amount of cloud cover, categorical classification of precipitation (rain, ice, freezing rain, etc.), pressure at surface, pressure vertical velocity, and relative humidity. The data is compiled into an archive and is run 4 times a day at 00, 06, 12, and 18 UTC which allows for 3, 6, and 9-hour forecasts (Air Resources Laboratory, 2024)

4) Results and Discussions

- **4.1 Spatial Variation**:

The spatial variation of isotopic values vary across the CONUS. The results from our study concluded that lower $\delta^{18}O$ values were found in locations with a higher latitude. Higher latitudes in the CONUS generally have lower temperatures and moisture sources from more polar regions. Warmer temperatures generally enhance evaporation, leading to a higher concentration of isotopes like oxygen-18 and deuterium in the remaining water vapor, which subsequently impacts the isotopic signature of precipitation (Gat, 2010). In cooler temperatures, the concentration of oxygen-16 is higher because it is lighter and takes less energy to evaporate. In figure 2 and 3 the higher δ18O values are located near the Gulf of Mexico which is a large moisture source for the CONUS. These higher values are due to the higher temperatures in the region and increased precipitation. Additionally, temperature gradients can create distinct climatic zones, each with unique precipitation patterns and isotopic characteristics. For instance, areas experiencing significant seasonal temperature fluctuations may exhibit greater variability in isotopic ratios, reflecting changes in evaporation and condensation dynamics throughout the year (Tian & Wang, 2019). More Oxygen-18 is evaporated into the atmosphere and more oxygen-18 falls in the form of precipitation. This creates a region with higher $\delta^{18}O$ values. As that same parcel of air travels further inland the oxygen-18 values will become lower as the heavier isotopes fall first. This leaves the parcel of air with a lower $\delta^{18}O$ value. In the same figures 1 and 2 the Western region of the CONUS has lower values of $\delta^{18}O$. This is caused by the moisture source from more polar regions and the lower atmospheric temperatures. There are lower $\delta^{18}O$ values due to lower evaporation energy. Oxygen-16 isotopes are the first to evaporate and the last to fall in precipitation. Given the Western region's climate the $\delta^{18}O$ values are lower due to less Oxygen-18 isotopes present.

Figure 4.1.1

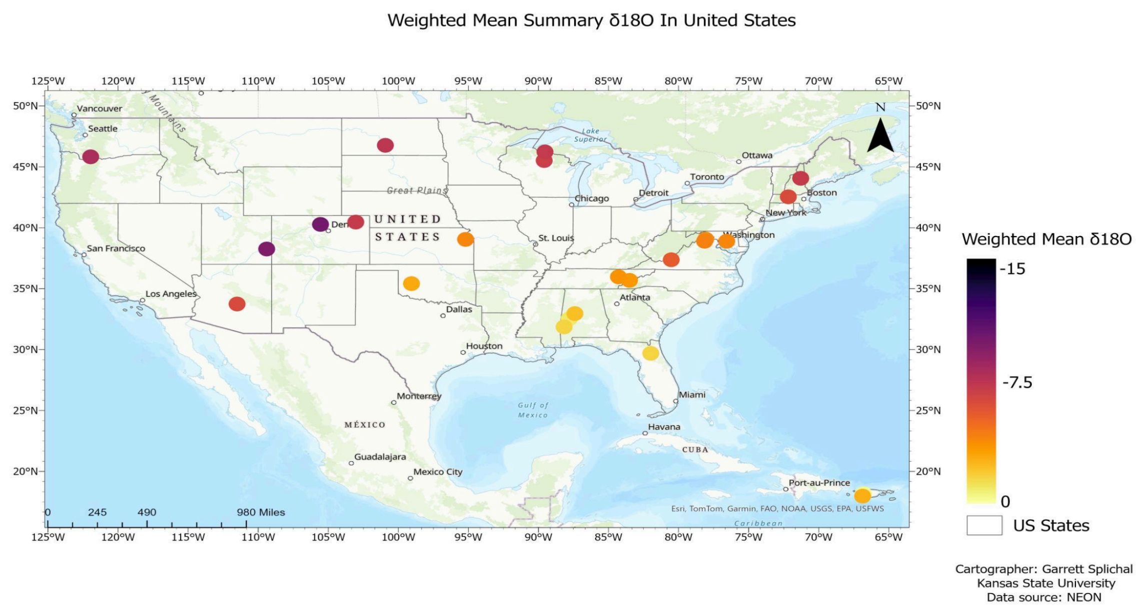
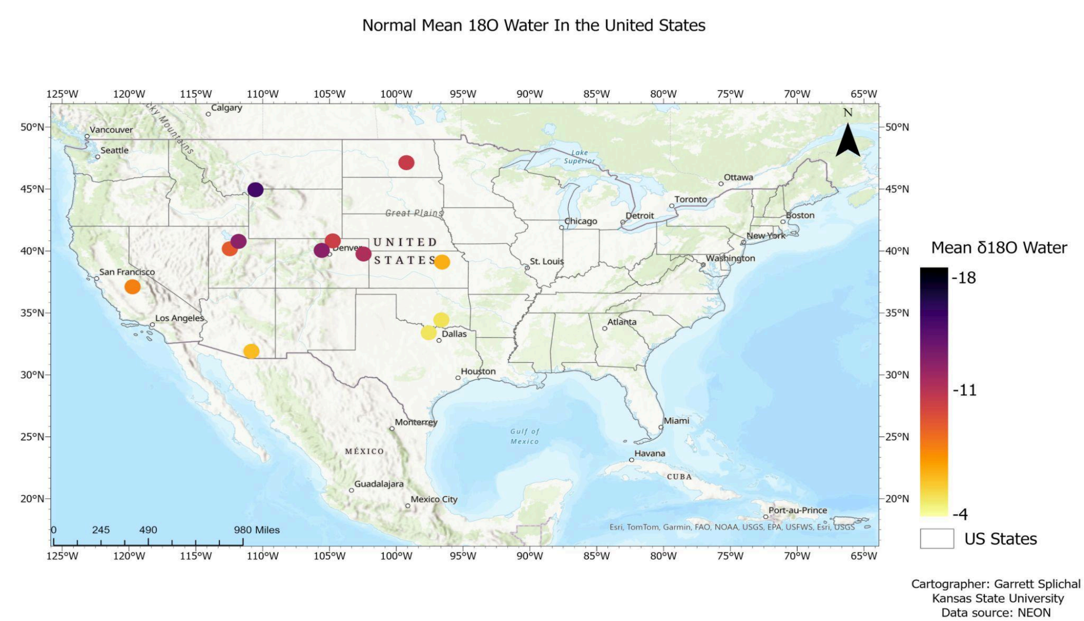


Figure 4.1.2



The spatial variation in d-excess is represented similarly to the δ18O values. As represented in Figures 4 and 5 the lower d-excess values are shown in the Northern latitudes of the CONUS with the Rocky Mountains showing the lowest values. One key influence is elevation in the Western U.S.. Elevation is a key factor influencing the spatial variation of isotopic composition in precipitation, primarily through its effects on temperature, pressure, and moisture dynamics. As air masses ascend a mountain range, they experience cooling, which leads to condensation and precipitation. This orographic effect typically results in isotopically lighter precipitation on the windward side of the range, as heavier isotopes tend to be removed first during the condensation process (Kendall & Coplen, 2001; Liu et al., 2010)The higher values are near the Gulf of Mexico and the Eastern region of the CONUS. The difference in temperatures, moisture sources, and precipitation creates a high variability of d-excess across the CONUS.

Figure 4.1.3

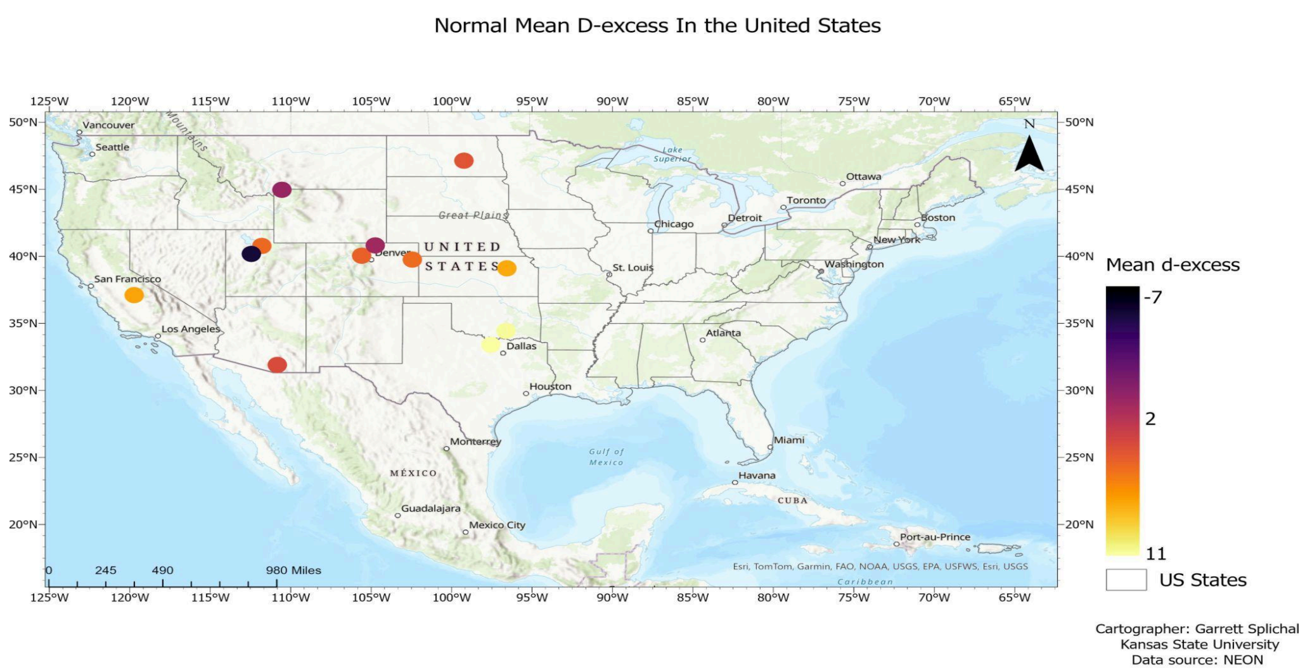
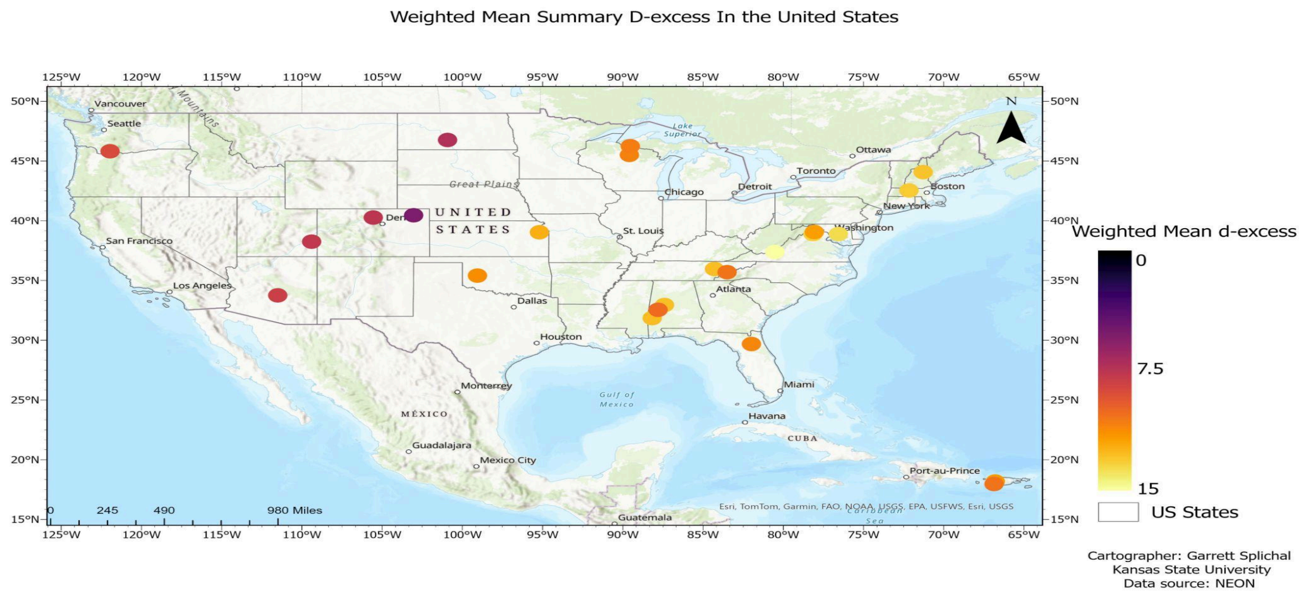


Figure 4.1.4



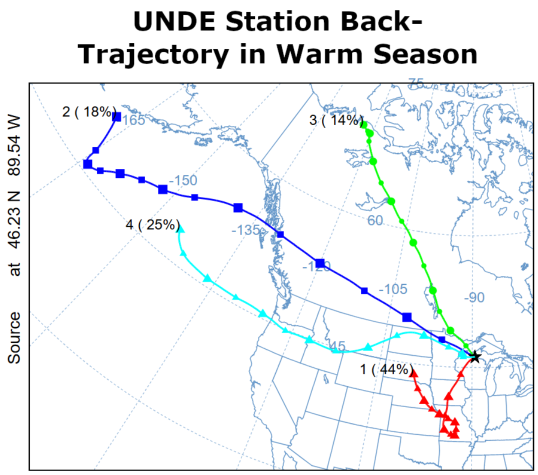
The variation of $\delta^{18}O$ and d-excess across the United States showcases significant geographic and climatic influences on isotopic composition in precipitation. These variations highlight the intricate interplay of climatic and geographical factors across the nation.

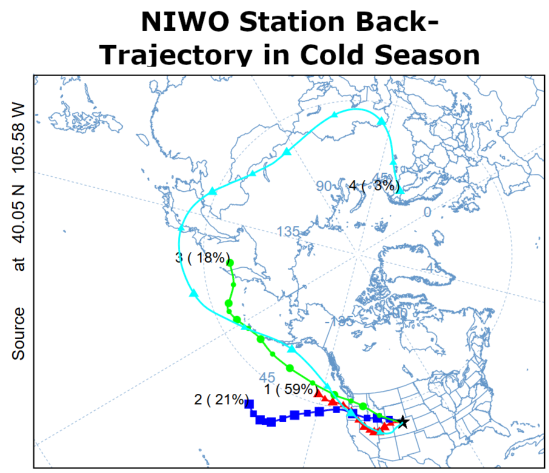
- **4.2 Influence of Moisture Sources**:

Moisture recycling is a necessary part of the water cycle in sustaining water resources. The isotopic composition of atmospheric moisture is greatly influenced by maritime evaporation which is thus affected by moisture recycling and precipitation. Understanding moisture sources, atmospheric processes, and isotopic compositions relationship to climate variability, namely relative humidity and temperature, help provide better foundational understandings of the hydrological cycle and origins or moisture within the cycle (Gat, 2000).

A study conducted in the Apuan Alps of Italy from 2019 to 2021 found that significant variation with d-excess occurred both spatially and temporally. A positive linear relationship between d-excess and these variations stated sub-cloud evaporation is responsible for variability in d-excess values. With these findings, researchers determined that d-excess is a reliable tool in determining moisture sources (Natali et al, 2022).

Moisture sources play a crucial role in hydrometeorological processes, as these sources are the main contributors of water vapor to the atmosphere. This water vapor drives weather events such as cloud formation and precipitation events. These moisture sources play a vital role in the hydrological cycle by determining local water availability and ultimately influence the overall climate of a large-scale region (Wallace and Hobbs, 2006).





Moisture Sources for NEON site UNDE for Warm and Cold Seasons

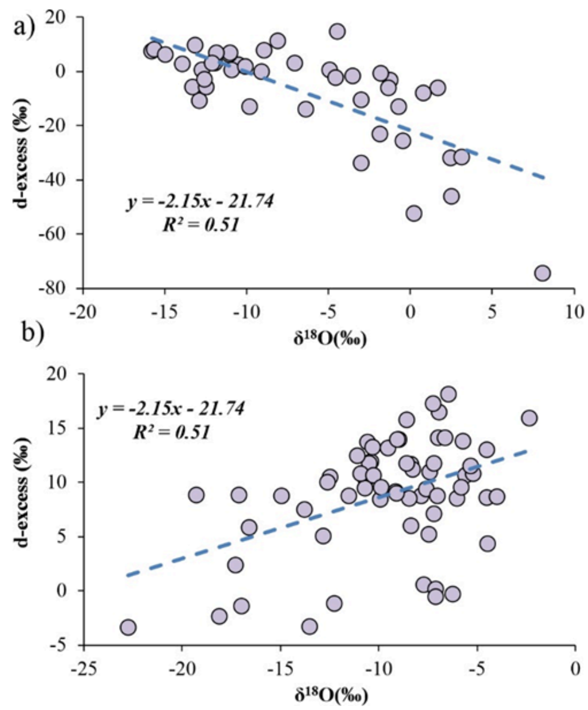
These two figures above demonstrate the influence cold and warm season weather patterns have on moisture sourcing patterns. During the cold season months, as stated previously, the majority of moisture is coming from the Pacific Ocean near the North American coast, as well as the northern portion of mainland Canada. This, however, changes during the warm season months as the majority of moisture tends to originate from the continental United States, and generally it appears that moisture is coming from sources further south than was seen in the cold season.

- **4.3 Role of Sub-Cloud Processes**:

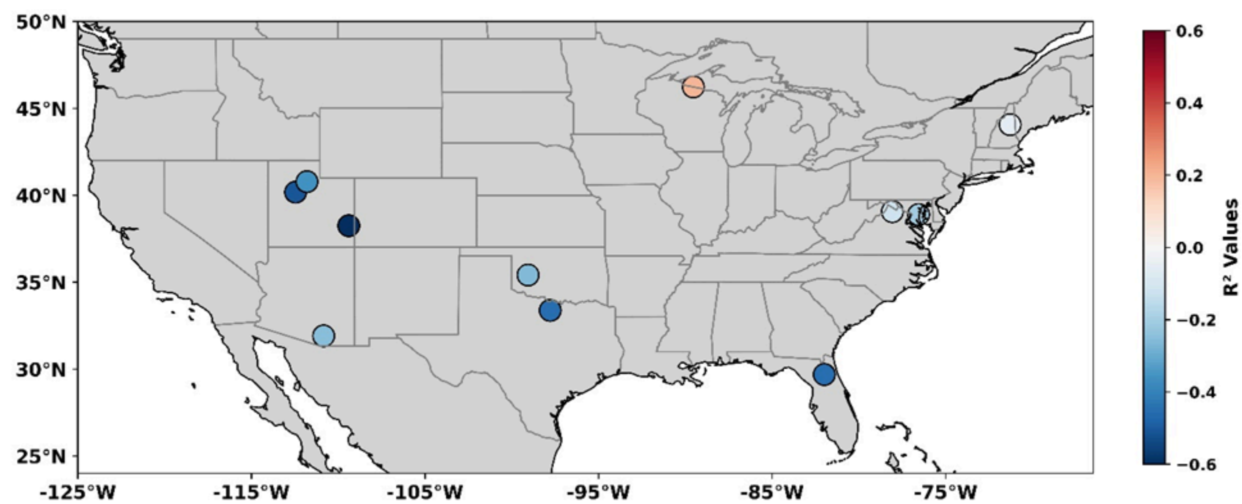
Sub-cloud evaporation occurs as precipitation falls from some saturated air mass (i.e. a cloud) in the atmosphere to earth's surface. Before hitting the ground, an individual water molecule may experience evaporation in the process. During this process, molecules attached to lighter isotopes like ^{16}O or H, will evaporate at a higher rate leaving a more concentrated amount of ^{18}O and deuterium (^{2}H) behind in the water molecules that are not evaporated. The most common isotopes occurring in the hydrosphere are H and ^{16}O. Hydrogen occurs at a 99.985% abundance rate and ^{16}O has a mass abundance of 99.762%. Their counterparts, ^{18}O and ^{2}H, have an average abundance of 0.2% and 0.015% respectively (Gat, 2000). While deuterium and ^{18}O are still decreasing in value from the original amount the larger water molecule began with, the d-excess value increases which allows for more efficient tracking of moisture sources (Zhu et al, 2016). The relative abundance of isotopic water is as such: $H_2{}^{16}O$ has an atomic mass of 18 and is 99.78% abundant, $H_2{}^{18}O$ has an atomic mass of 20 and has an abundance of 0.20%, $H_2{}^{17}O$ has an atomic mass of 19 and is 0.03% abundant, $HD^{16}O$ has a weight of 19 and is 0.0149% abundant, and $D_2{}^{16}O$ has a weight of 20 and occurs at a rate of 0.022 ppm (Gat, 2000).

Sub-cloud evaporation plays an important role in providing accurate observations of isotope water cycles. A study conducted in different regions of China concluded that there exists a strong inverse relationship between relative humidity and secondary evaporation. When relative humidity was high, secondary evaporation was less. In other words, when the atmosphere is fully or near-fully saturated, sub-cloud evaporation occurs less (Zhu et al, 2016).

The negative relationship between δ18O and d-excess is observed during warm seasons and is prominent in humid, semi-arid regions. However, one site from the NEON database exhibited a positive relationship between δ18O and d-excess. This is most likely a result of continental moisture recycling and sub-zero temperature-driven fractionation processes in the atmosphere (Deshpande, 2013). Data results from the HYSPLIT back trajectory analysis shows this pattern is due to air parcels from the continental United States combined with higher latitudes. From the stations observed from NEON data, ten stations had an observed negative relationship while two showcased a positive relationship during the warm season, indicating the significant role of secondary processes like sub-cloud evaporation, moisture recycling, and in-cloud supersaturation events.

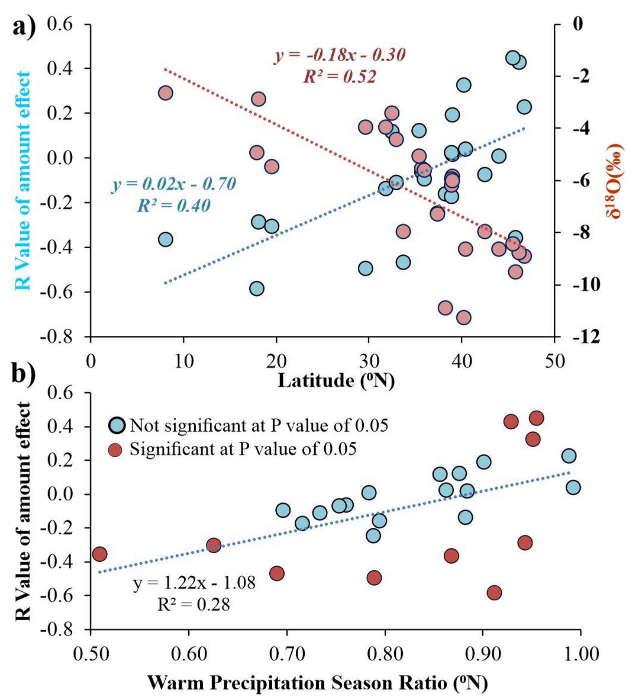


Figures a) δ18O and d-excess relationship showing presence of sub-cloud evaporation process and b) δ18O and d-excess relationship showing moisture recycling or in-cloud supersaturation driven fractionation signatures

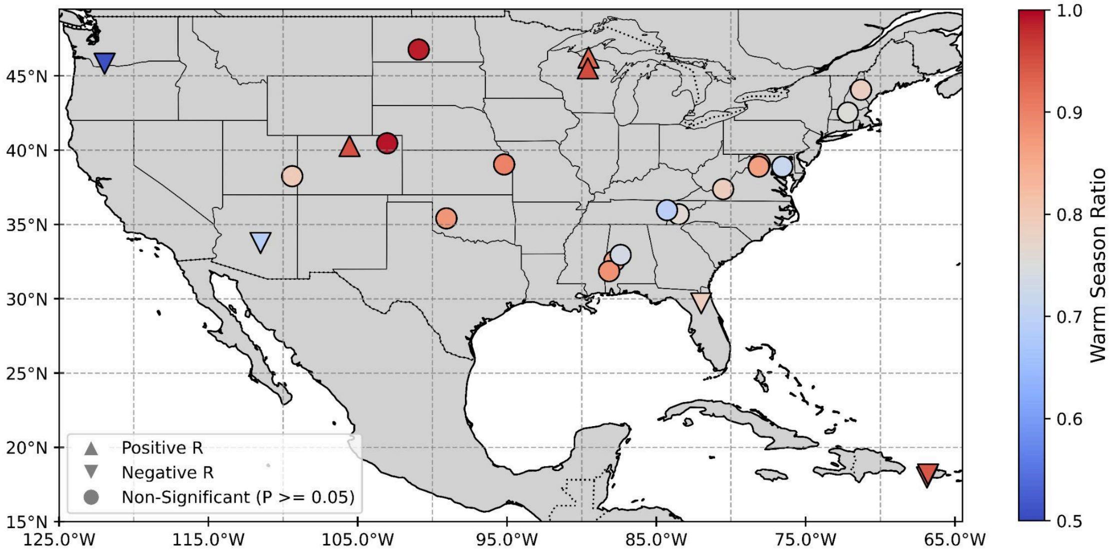


Spatial distribution of R^2 values of δ18O and d-excess linear regression ($P<0.05$)

Based on the negative relationship of δ18O and d-excess signifying sub-cloud processes, latitude and warm season precipitation ratios were taken into account to determine the significance of secondary processes (sub-cloud evaporation and in-cloud supersaturation). To summarize, a negative relationship between δ18O and d-excess signifies sub-cloud evaporation while a positive relationship indicates supersaturation. Accounting for amount effect, the relationship of $\delta^{18}O$ and precipitation amount, can help determine at a particular site, how much control or influence amount effect has on $\delta^{18}O$. Thus, amount effect illustrates the relationship of isotope values helping indicate secondary processes and providing more insight on rainfall events. The figures below indicate that as latitude increases, amount effect increases while $\delta^{18}O$ decreases.



Figures a) relationship of latitude and amount effect R value and b) relationship of warm precipitation season ratio based on latitude to amount effect R value



Spatial variability of amount effect and warm season precipitation ratio

The figure above demonstrates the spatial variability of amount effect and influences of warm season precipitation ratio. The intensity of saturation of each plot shows a strong warm season precipitation ratio. The triangles indicate significant amount effect values. Inverted triangles show a negative relationship of amount effect while upright triangles indicate a positive amount effect relationship. As shown above, all inverted triangles are situated near coastal regions. Stations located more inland have a positive relation of amount effect.

5) Conclusions

In summary, the variation of $\delta^{18}O$ and d-excess in precipitation across the United States provides valuable insights into the complex interplay of climatic, geographic, and hydrological factors influencing water cycles. By examining specific isotopic values from diverse regions—ranging from the isotopically lighter precipitation in the Pacific Northwest to the more enriched signatures in California and the Southeast—researchers can better understand the mechanisms behind precipitation sources and processes. Factors such as temperature, elevation, and evaporation significantly shape these isotopic landscapes, reflecting local and regional climatic conditions. As the impacts of climate change continue to alter precipitation patterns and hydrological processes, understanding $\delta^{18}O$ and d-excess variations will remain crucial for water resource management, paleoclimate reconstruction, and climate science as a whole.

Secondary processes like sub-cloud evaporation, moisture recycling, and in-cloud supersaturation-driven fractionation play a significant role in hydrometeorological processes across the continental United States and Puerto Rico. Observing the relationship of $\delta^{18}O$ and d-excess, amount effect and latitude and warm precipitation ratios, indicated strong presence of sub-cloud evaporation and in-cloud supersaturation events by positive and negative relationships, respectively.

6) Scope for Future Work

Due to the importance of $\delta^{18}O$ and $\delta^{2}D$ tracking in the United States, there are multiple routes of analysis and data collection that would be beneficial to pursue in order to gain a greater understanding of how stable water isotopes can be used to illuminate the fields of paleoclimatology and meteorology, as well as climate change research as a whole. The continued collection of seasonal $\delta^{18}O$ and Deuterium samples across the United States is of utmost importance, as an overall increase in data would allow for an overall increase in analysis to better understand hydrologic systems. Not only is further data collection useful for understanding climate within the United States, but in addition to analysis compiled from global databases it supports future climate models for the earth as a whole.

7) References

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