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AIR MASS FREQUENCY DURING PRECIPITATION EVENTS IN THE NORTHERN PLAINS OF THE UNITED STATES

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ABSTRACT

Since 1980, numerous billion-dollar disasters have affected the Northern Plains of the United States, including nine droughts and four floods. The atmospheric environment present during precipitation events can largely be described by the presiding air mass conditions since air masses characterize a multitude of meteorological variables at one time over a large region. The goal of this research is to add knowledge to current understandings of the factors responsible for precipitation in the Northern Plains through an assessment of synoptic air mass conditions. The Spatial Synoptic Classification is used to categorize 30 years of daily surface air mass types across the region alongside precipitation from the United States Historical Climatological Network. Annual and seasonal air mass frequencies are examined for all precipitation events. Precipitation days are also examined by intensity. Results indicate that the Transitional air mass, associated with changing air mass conditions commonly related to passing fronts, is not the leading producer of rainfall in the region. All moist air mass varieties are generally more dominant during precipitation events and the Moist Moderate (MM) and Moist Polar (MP) air masses are frequently responsible for half of all rainfall in the region. MM and MP tend to be particularly prominent during the winter season. The MM and Moist Tropical air masses dominate around 65% of summer precipitation events. Interestingly, there is a tendency for precipitation while dry air masses are present to the north and west within the study region.

KEY WORDS: atmospheric environment, droughts, floods, meteorology, transitional air mass, U.S. Historical Climatological Network, moist moderate air masses, moist polar air masses, moist tropical air masses, spatial synoptic classification

INTRODUCTION

The 2011-12 winter season was exceptionally mild in the United States Plains (Fig. 1a). Across the region, the entire 2012 year was associated with near record low precipitation values (Fig. 1b). In January, many sites within the region observed one of the top 10 driest months on record, with less than 25% of the average liquid equivalent precipitation received at a number of locations (NCDC, 2013a). This worsened the developing drought conditions and diminished snow packs across the region. What followed was the devastating year-long drought that still persists in southern central U.S. states. Much of the northern plains region remains abnormally dry, or in moderate to severe drought (CPC, 2014). Failing regional soybean and corn crops and near record low levels of the Mississippi River are perhaps some of the most notable impacts (NCDC, 2013a). Just one year prior, regional snow packs were above average with record flooding ($2 billion in damages) observed alongside the springtime melt (Maximuk and Nadolski, 2012). This extreme intra-annual variability was reflected throughout the region and in other seasons.

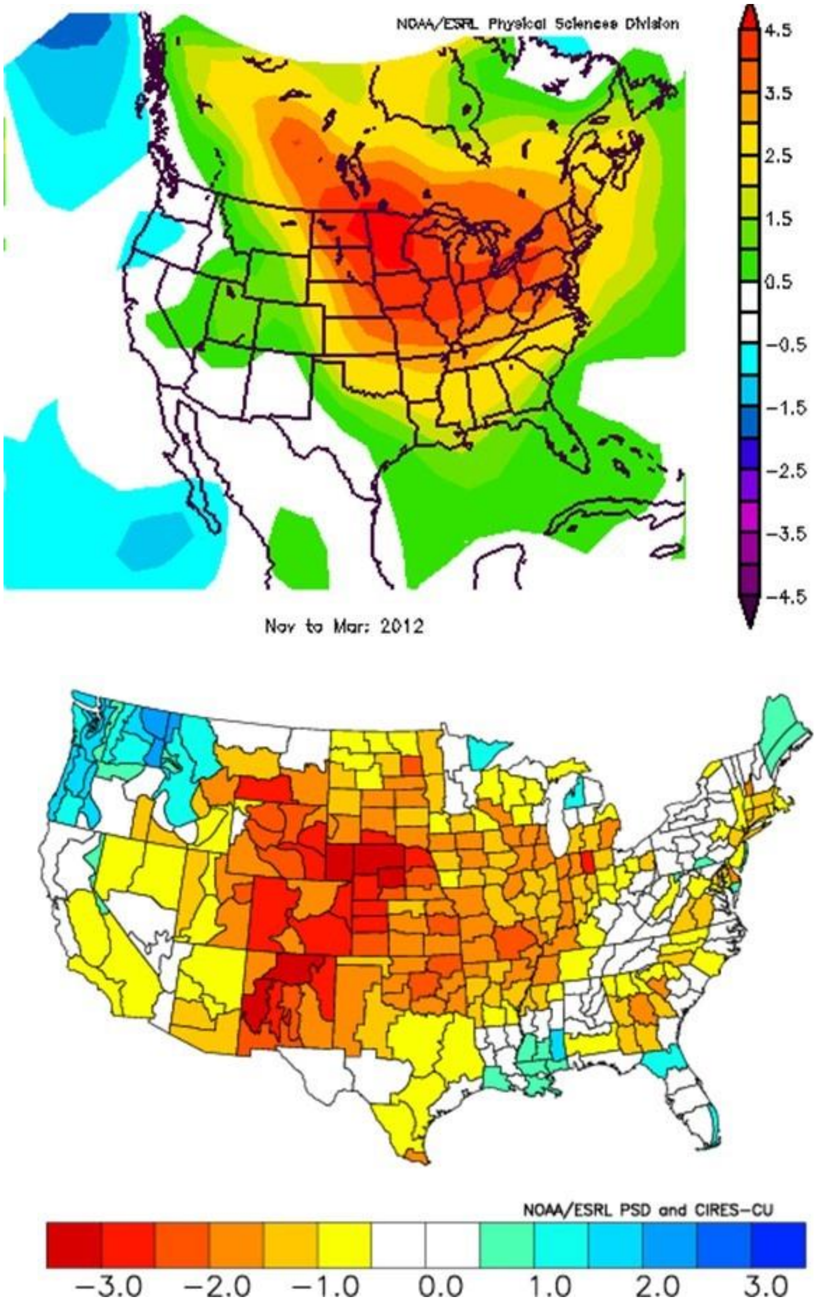

Figure 1. **(a)** November 2011-Marych 2012 surface air temperature anomalies (°C, from 1981-2010 climatology) and **(b)** January-December 2012 standardized mean precipitation anomalies (cm, from 1981-2010 climatology) (Created at ESRL PSD 2014).

Substantial precipitation surpluses and deficits can have extreme societal implications for everything from food prices to unemployment rates, morbidity and mortality. The Midwest flood of 1993 caused nearly $15 billion in damage and claimed the lives of 50 Americans (Larsson, 1996). The drought of 2012 also resulted in billions of dollars of economic loss (NCDC, 2013b). Since 1980, nine droughts and four floods have impacted the Northern Plains, each associated with over $1 billion of damages (NCDC, 2013b). With over 450,000 farms in the Northern Plains, developing a better understanding of regional precipitation variability is an issue of major importance to many (Table 1). This is especially true as the region's climate and topography are conducive to severe weather and all U.S. locations depend on the region's livestock and agricultural exports.

State	Number of Farms	Final Agricultural Sector Output ($1,000)
North Dakota	31,900	8,238,287
South Dakota	31,300	10,834,958
Nebraska	46,800	23,766,964
Kansas	65,500	17,311,843
Minnesota	79,800	19,777,224
Iowa	92,300	32,657,493
Missouri	106,500	11,064,111
Total	**454,100**	**123,650,880**

Table 1. 2011 agricultural statistics for the Northern Plains states (USDA, 2012).

In recent decades, rain and snowfall variability related to evident global change has received a great deal of attention in the atmospheric science literature. A recent global finding from Sun, *et al.* (2012) determined that land precipitation variability has decreased with time as drier regions of the planet have become wetter and moister land areas have become drier. In the Northern Plains, precipitation also varies with changes in natural climate oscillation patterns and with natural modifications of jet stream flow patterns. More wavy, meridional jet stream patterns often produce the necessary conditions for regional air mass collisions along frontal boundaries. Therefore, understanding air mass dynamics can provide important information about where precipitation will occur and how much rain and snow will fall over the Plains states. The prediction of air mass advections may be a useful tool for improving the prediction of short-term precipitation variability. Knowledge of these relationships may also aid farmers with agricultural planting and harvest times, along with advanced mitigation efforts to minimize economic and social losses related to extreme weather.

There are several air mass classification systems used for identifying dominant air mass types across the U.S. The Bergeron Classification, based on North American source regions, is the most popular and well known system (Bergeron, 1930). However, the Spatial Synoptic Classification (SSC) is perhaps the most unique and practical of all weather type schemes available for meteorological research since daily air mass calendars of seven air mass types can be accessed for download on a website for over 300 North American locations dating back to the early 1900s for most stations (Sheridan, 2002). The SSC is also unique because it is based on surface weather characteristics (*e.g.*, temperature, dew point depression, cloud cover, mean sea level pressure observations and diurnal temperature and dew point ranges) detected at a location rather than the source region, since air mass modifications are prominent across the country as pure thermal and moisture characteristics diminish outside of the source region (Sheridan, 2002).

While the SSC utilizes various meteorological parameters to assign air mass days, this system does not explicitly use *precipitation observations* for characterizing the air over a region. Parameters such as dew point depression account for the moisture content in the local air mass, but there is no confirmation that moist air masses are indeed wet enough to produce rain or snow. Further, there is no way to distinguish whether all moist air masses are *moist enough* to produce precipitation or even if dry air masses might be present during times of precipitation. Certain air masses may be related to more precipitation (higher recorded totals) than others. Perhaps more intriguing is that the classification scheme identifies a transitional (TR) category that occurs while air masses change from one dominant type to the next over a location. These conditions may well be associated with passing surface fronts and related frontogenetical rainfall, though this has also yet to be established. Since it cannot be discerned whether TR air masses or moist varieties are most often associated with precipitation this means that, to date, the relationship between air mass frequency and precipitation is unknown for the Northern Plains (and all other regions of the U.S.).

With this in mind, the primary goal of this research is to evaluate the relationship between air mass frequency and precipitation over the Northern Plains for the past three decades. More specifically, annual and seasonal SSC air mass frequency will be examined since the dominant precipitation-producing air masses may vary throughout the year. Precipitation amounts will be assessed alongside air mass frequency with total precipitation thresholds to see if certain air masses are related to more rainfall than others. The results should add information to current meteorological understandings of the relationship between air masses, circulation patterns (as one can then surmise the advection pattern of an air mass) and precipitation. A sensible initial hypothesis is that TR air masses are the most dominant type during days with rain but that different precipitating air masses will be prominent in different seasons (*i.e.*, more cold, moist types found in winter and warmer, moist types in summer).

BACKGROUND AND LITERATURE REVIEW

Northern Plains Precipitation Variability

High seasonality characterizes the Northern Plains region with most precipitation falling during warm months. Precipitation variability in this region is demonstrated with strong annual and semi-annual signatures (Yang, *et al.* 2007). In the warm seasons, Ashley, *et al*. (2003) observed that the Great Plains receives 8 - 18% of the region's total annual rainfall from Mesoscale Convective Complexes (MCCs). MCCs tend to form under conditions with ample warm air advection and abundant moisture in the immediate atmosphere; conducive of a southerly jet flow. Wang and Chen (2009) identify a late spring/ early summer maximum in rainfall over the Plains states and that the concentration of precipitation is related to positioning of an extant low level jet. The low level jet is found to contribute to 60% of the rainfall at this time but it becomes hindered as summertime anticyclones develop over the region. Niño 3.4 region sea surface temperatures also correlate well to summertime precipitation, particularly with a one month lead time on the precipitation (Yang, *et al*., 2007). Subsequently, the ENSO teleconnection relation to summer rainfall on the Plains is strong and typically defined by more (less) rain from El Niño (La Niña) events. Generally, the increase in summer precipitation in the Plains is connected to convergence of southerly flow patterns and northerly flow patterns from Pacific warming. The Northern Plains situate within the northerly flow at this time. (Yang, *et al*., 2007). To demonstrate inter-seasonal linkages, Quiring and Kluver (2009) found that above (below) average precipitation in winter and spring months tend to be correlated with wet (dry) summers in the Northern Plains states.

Winters tend to be the driest season in the Northern Plains (HPRCC, 2013). Elguindi, *et al*. (2005) found that winter cyclone development leading to heavy cold season precipitation is dependent on established central U.S. snow packs, which contribute to the location of the steepest tropospheric temperature gradients. Additionally, Yang, *et al*. (2007) describe the importance of southwest moisture advections in the generation of cool season precipitation. Hu and Huang (2009) note that when ENSO and PDO are in-phase, the pattern supports anomalous winter and autumn precipitation over the Great Plains. However, the authors note this relationship produces greater springtime rainfall anomalies as well.

The spring season that preceded the 2012 Great Plains summer drought did not bring the conditions necessary for instability and rainfall over the region. Both deep moist convective processes and general cyclonic activity leading to severe weather development, including MCCs, and strong precipitation was greatly reduced (Hoerling, *et al*., 2013). Chang and Smith (2001) explained the dynamical features responsible for similar drought patterns with large-scale mean subsidence. The work verifies that strong anticyclones over the central U.S. are related to weakened mid-tropospheric westerlies that situate south of the thermal low, drawing the Bermuda high west toward the Plains and triggering feedbacks that strengthen the heat low. In the 2012, State of the Climate report, Blunden and Arndt (2013) indicate that the year's winter snow packs and snow cover extent in this region were well below average which also impacted drought persistence.

With ongoing global climate change, precipitation patterns are expected to change over this region. At present, annual precipitation values in the Northern Plains generally exhibit a range between 38 cm in the north (*e.g.*, northwest North Dakota) and 102 cm in the south (*e.g.*, southern Kansas and Missouri) (HPRCC, 2013). Northwestern (southeastern) locations can record mean low precipitation values around 1 cm (5 cm) in winter to mean high values near 7.5 cm (12.5 cm) in summer (ESRL PSD, 2013). To place this in perspective with observed climate change, data from the Midwest Regional Climate Center (MRCC) show that the easternmost states of the Northern Plains have observed general trends of increased annual precipitation, on the order of approximately 5 to 10 cm per century, between 1895 and 2010 (MRCC, 2014). It is probably worth noting that the authors could not reproduce this finding with data from this analysis due to many missing data at the beginning of the station record collections in the early 1900s.

The Spatial Synoptic Classification

The SSC is a weather-type classification system that depends on near-surface weather observations to define air masses at a location from twice-daily collected records. The SSC provides air mass classifications for the past 60 years for many sites across the United States, Canada and Europe. The SSC classifies six air mass types: Dry Moderate (DM), Dry Polar (DP), Dry Tropical (DT), Moist Moderate (MM), Moist Polar (MP), and Moist Tropical (MT).

A seventh air mass, Transitional (TR) is defined for days in which a station is transitioning from one air mass type to another. One air mass is assigned to a site each day. The parameters utilized to determine air mass type are temperature, dew point depression, mean cloud cover, mean sea level pressure, diurnal temperature range, and diurnal dew point range. Diurnal dew point range, diurnal mean sea level range, and diurnal wind shift are used to identify the TR days (Sheridan, 2002).

DM is typically a dry and mild air mass; according to Sheridan (2002) the air mass is typical with zonal flow, and does not have a traditional source region. DP is similar to the cP air mass in the Bergeron Classification, with its traditional source region being northern Canada. DP is associated with the driest and coldest days at a station. DT is best described as the cT air mass in the Bergeron (1930) Classification, characterized with very hot and dry air, with a source region over the Mexican Plateau or the southwestern U.S. MM is characterized by mild temperatures, but more humid conditions. MP is similar to the mP air mass from the Bergeron (1930) classification, with cold and cloudy weather common. MT is similar to the mT air mass, and often characterized as a humid and muggy summer day, with a source region over the Gulf of Mexico (Sheridan, 2002).

Applications of the SSC are far-reaching and have included investigations on pollution and ozone, heat waves and urban convection, human health, and snow cover variability and ablation (Bentley, *et al.*, 2010; Davis, *et al.*, 2012; Green, *et al.*, 2011; Hanna, *et al.*, 2011; Kalkstein, *et al.*, 1996; Knight, *et al.*, 2008; Leathers, *et al.*, 2004). Precipitation studies focused on the central U.S. include Walker, *et al.* (2012), who found that the DT air mass is associated with persistent, intense drought in the region (one that overlaps areas of the Northern Plains region assessed here). Hondula and Davis (2011) connected TR air masses with the passage of cold fronts and warm fronts and detected decreases (increases) in cold (warm) front advections with time over the Midwest. A decreasing trend in the overall amount of TR days was detected and, since 1951, a shift toward a more northerly position of the jet stream and associated storm tracks was identified. While outside the central U.S., Labosier (2012) conducted a study of precipitation and air mass frequency for Birmingham, AL. The most prominent precipitation producing air mass for the city is the MM, with significant contributions from MT and TR.

METHODS AND ANALYSIS

Study Region and Data

For spatial cohesion, the geographical extent of the Northern Plains region of study is established using the latitude and longitude criteria of 37- 49°N and 94 - 104°W (Fig. 2). This provides a westernmost boundary is established at the North Dakota - Montana state line so that areas in closest proximity to the Rocky Mountains are excluded given major topographical variations. Similarly, the eastern boundary assures that stations nearest the Great Lakes are avoided. The confines include the states of North Dakota, South Dakota, Nebraska, Kansas, and portions of Missouri, Iowa, Minnesota, and Colorado. This region is generally void of major elevation changes, with the exception of the Black Hills in the southwest corner of South Dakota.

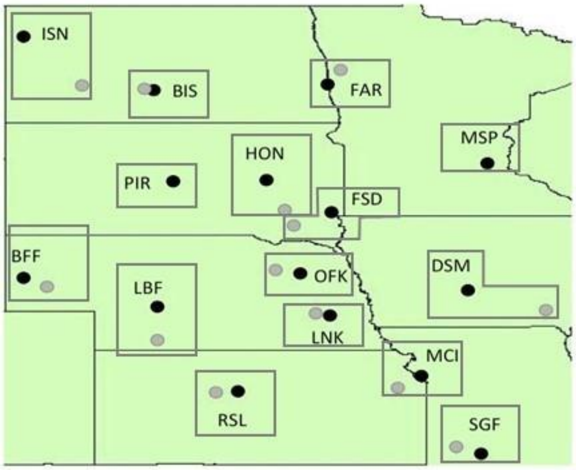

Figure 2. The NorthernPlains region (37-49°N, 94-104°W) with 15 selected SSC stations (black circles) and the paired 15 selected USHCN stations (gray). When station locations overlap only the SSC is identified.

Daily precipitation and air mass data are collected for 30 stations within the region for three decades, from 1981 - 2010. Daily station data from the SSC are used to represent daily air mass conditions at 15 stations across the region (Sheridan, 2013).

Precipitation data (rainfall, in mm) are gathered for 15 stations from the United States Historical Climate Network (USHCN). The USHCN is a subset of the U.S. Cooperative Observer Network, and is subject to the same data quality standards as the National Climatic Data Center's Global Historical Climate Network (USHCN, 2013). Each precipitation station is chosen for the closest proximity to the selected SSC stations given a high-quality record with less than 6% missing data. For instance, the nearest USHCN to an established SSC site is preferred but not always chosen if too many missing data are identified. Whenever possible, a site with both a SSC and USHCN station is used (*e.g.*, at Pierre, South Dakota). The SSC and USHCN sites are paired to represent the amount of rainfall each day and the air mass present at the time of precipitation. As air masses are spatially expansive across wide regions at any given time, it is expected that significant overlap occurs at multiple stations across the region. Nevertheless, the boundaries of air masses between stations can be captured using these station selection methods to capture the best possible coverage of the entire study region with a high degree of accuracy.

Annual Air Mass Frequency Analysis

Initial analyses are aimed at identifying the air masses present at the time of precipitation on the Northern Plains. A *baseline* for which to compare precipitation tendencies between air masses is established with annual air mass frequencies at each station set (hereafter simply deemed 'stations' to more easily declare each pairing as an individual site). The baseline is rather representative of a normal station condition, regardless of precipitation, as it includes all days of a station record (Fig. 3). Together, the mean of these values represent normal air mass conditions across the region. Annual *rain day frequencies* are then found for all stations with daily precipitation across the 30 year period. Figure 4 displays an example of annual frequencies for seven stations in the southeast part of the region (stations at Springfield, MO, Russell, KS, Kansas City, MO, Norfolk, NE, Des Moines, IA, Lincoln, NE and Sioux Falls, SD). At these sites, the MM and MT air masses are the most prominent during days with rain, with frequencies ranging from around 27 - 28% and 20 – 28%, respectively. Frequency *differences* (%) are also acquired for each station (as rain day minus baseline percentages) (Fig. 5). The values used to calculate the departures are tested for statistical significance using a two sample test of two proportions. Z-values are identified and examined at the 95 and 99% confidence levels to pinpoint the air masses with the most prominence during precipitation events.

Annual air mass frequencies are also quantified with precipitation thresholds. This allows for the intensity of rainfall associated with each air mass to be examined. The *rainfall categories* and thresholds used are shown in Table 2, rounded to the nearest hundredth of a millimeter, following limits defined by the Midwest Regional Climate Center (which the center established in inches versus the metric units displayed here). Figure 6 shows an example of results from Minneapolis/ St. Paul MN, where most of the days with rain

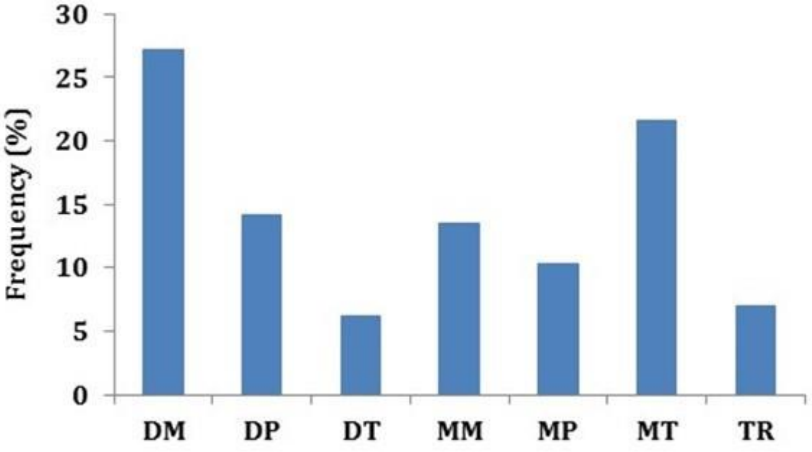

Figure 3. Annual air mass frequency (%) for all days on record at Springfield, MO.

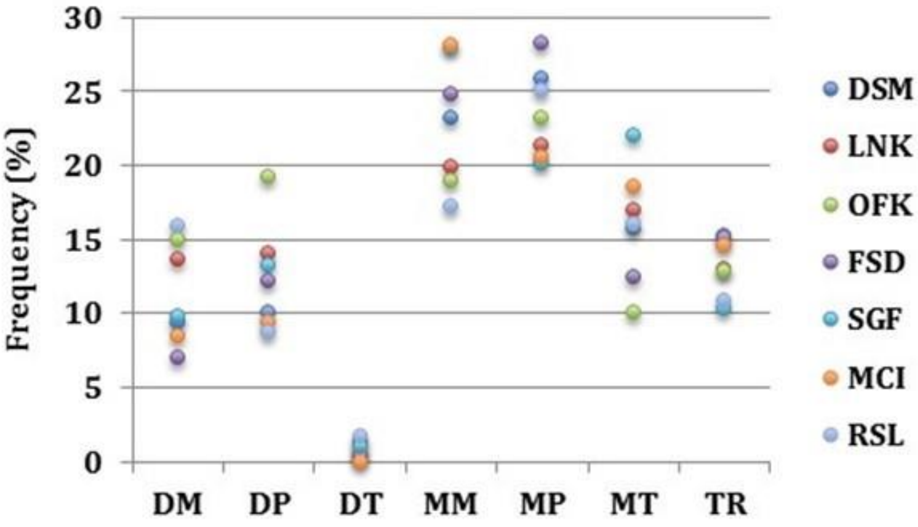

Figure 4. Annual air mass frequency (%) for seven station pairs in the southeast portion of the Northern Plains.

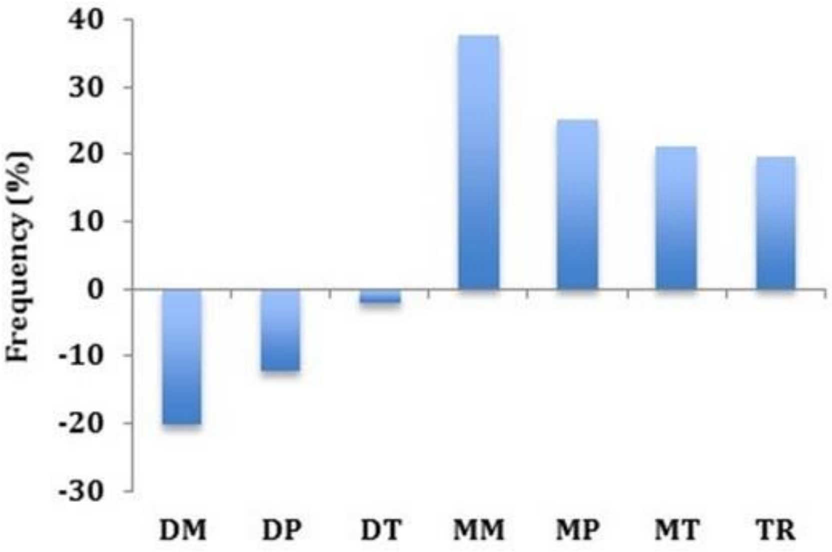

Figure 5. Annual rain day air mass frequency differences (%) from annual baseline frequencies for Sioux Falls, SD.

Precipitation Category	Rainfall Threshold (mm)
Category 1	0.25 - 2.53
Category 2	2.54 - 12.69
Category 3	12.70 - 25.39
Category 4	> 25.40

Table 2. Definition of Category 1-4 precipitation thresholds.

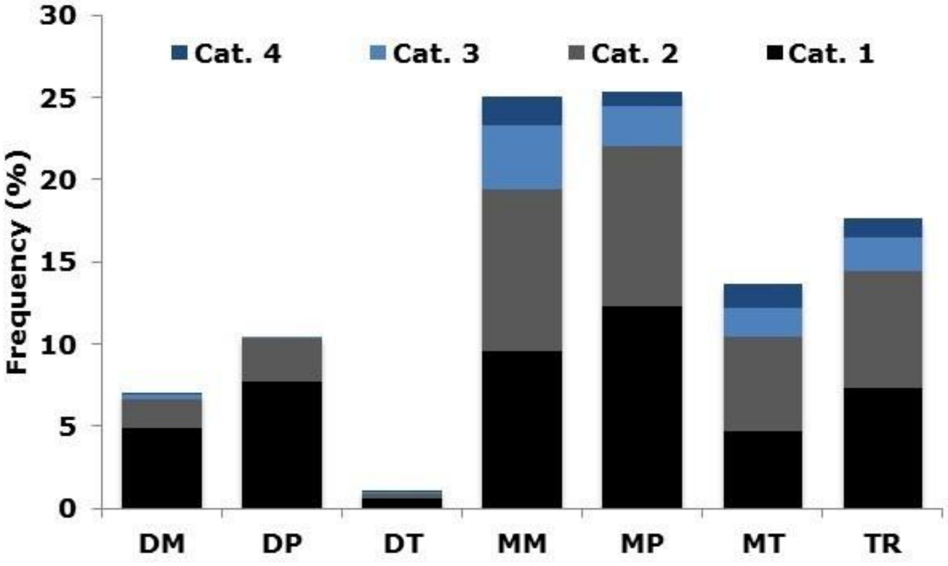

Figure 6. Annual rain day air mass frequency (%) for Minneapolis/ St. Paul, MN with Category 1-4 precipitation thresholds.

are classed as categories 1 and 2. At this site, most category 4 rain days are associated with the presence of an MM air mass. It can be seen that very few DT days produce rain from any category at this location.

Seasonal Air Mass Frequency Analysis

Seasonal air mass frequency analyses are performed to determine how the air masses most associated with precipitation may be variable throughout the year. Meteorological seasons are used so that three months define each season (winter is DJF, spring is MAM, summer is JJA and autumn is SON). Rain day frequencies are calculated at stations for each season (Fig. 7). Then, seasonal frequencies are obtained for all rain days within the precipitation threshold categories. Figure 8 displays the fall Category 4 rain day percentages across the region, which are low, given fewer days with heavy rainfall. Across the region it makes sense that colder air masses would be more related to winter precipitation than warm types and that warm varieties would dominate summer season rainfall. It is less intuitive what the transitional season frequencies should reveal, though with more air mass collisions at this time it is expected that the TR air mass should be more prominent in the spring and fall.

For purposes of comparing a seasonal finding to that of the annual analysis, Figure 9 shows an example of summer rain day air mass frequencies at North Platte, NE. The percentage of MT rain

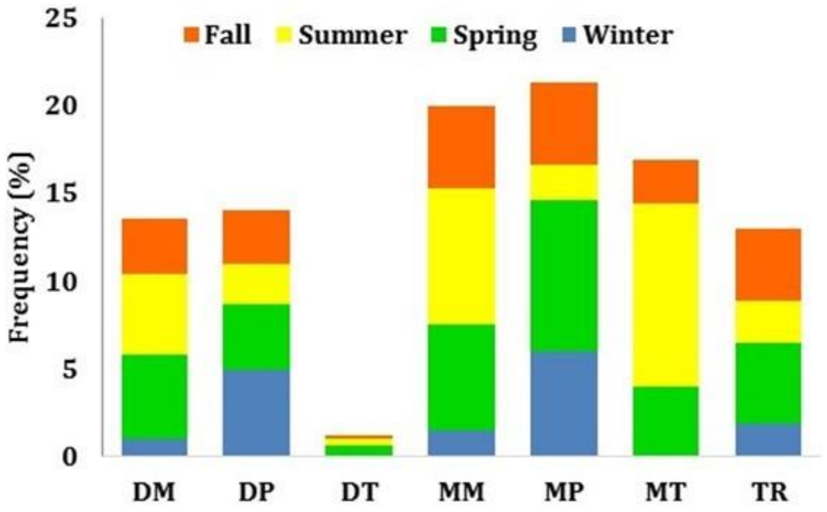

Figure 7. Seasonal rain day air mass frequency (%) for Lincoln, NE.

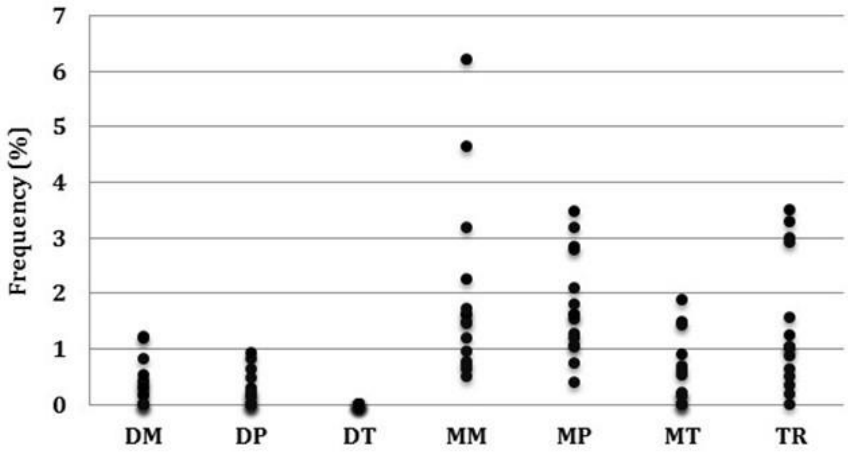

Figure 8. Fall rain day air mass frequency (%) at all 15 Northern Plains stations with Category 4 precipitation.

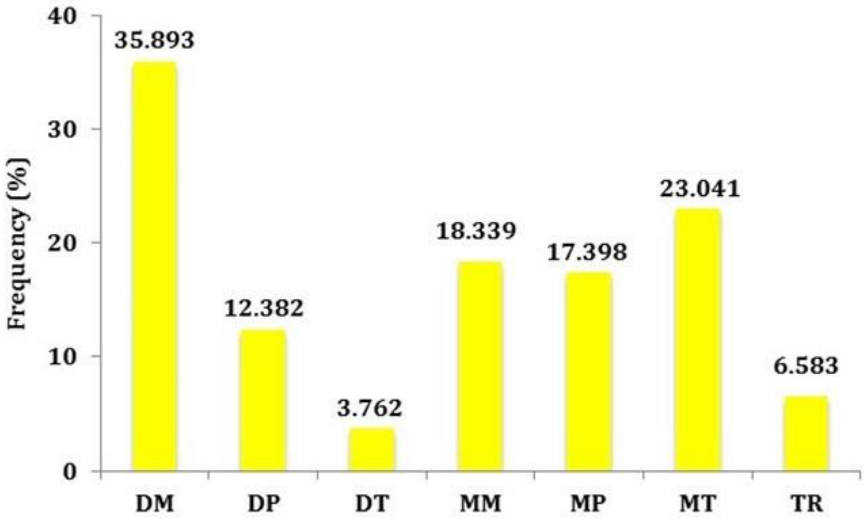

Figure 9. Summer rain day air mass frequency (%) for North Platte, NE.

days in this season are relatively high compared to those found in the annual analysis (23%, versus that for most stations between 10 - 20% annually; *compare to Fig. 4*). An even greater decrease in MP rain day frequencies is observed in summer from the annual rain day percentages (7% versus > 25%).

RESULTS AND DISCUSSION

Annual Air Mass Frequency

Baseline Frequency

The baseline frequencies, or standard synoptic weather type situation of the Northern Plains, reflect the prevalence of the dry air mass types on all days examined (with and without precipitation). For all but two stations (Kansas City and Springfield, MO), the DM and DP are the two most frequent air masses across the region, respectively (Fig. 10). DM is generally present from 25 - 37% of the time. DP days typically occur 15 -25% of the time. For stations situated further north and west, the presence of DP can exceed DM, as seen at Pierre, SD. As both types represent low moisture conditions, the general synoptic character of the region can be described as dry which reflects the geographical positioning at the center of the continent. The two exceptions are in the southeast of the region and demonstrate the spatial variability of weather across this expansive region. At both Missouri sites, MT days replaced the DP as the second most dominant weather type set up (mean frequencies near 20%) which shows a closer proximity to moisture sources and most jet stream activity can increase annual moisture conditions in an air mass for a location. The values obtained here correspond well to the information provided by Sheridan (2013) of the air mass frequency for four months out of the year (representing each season).

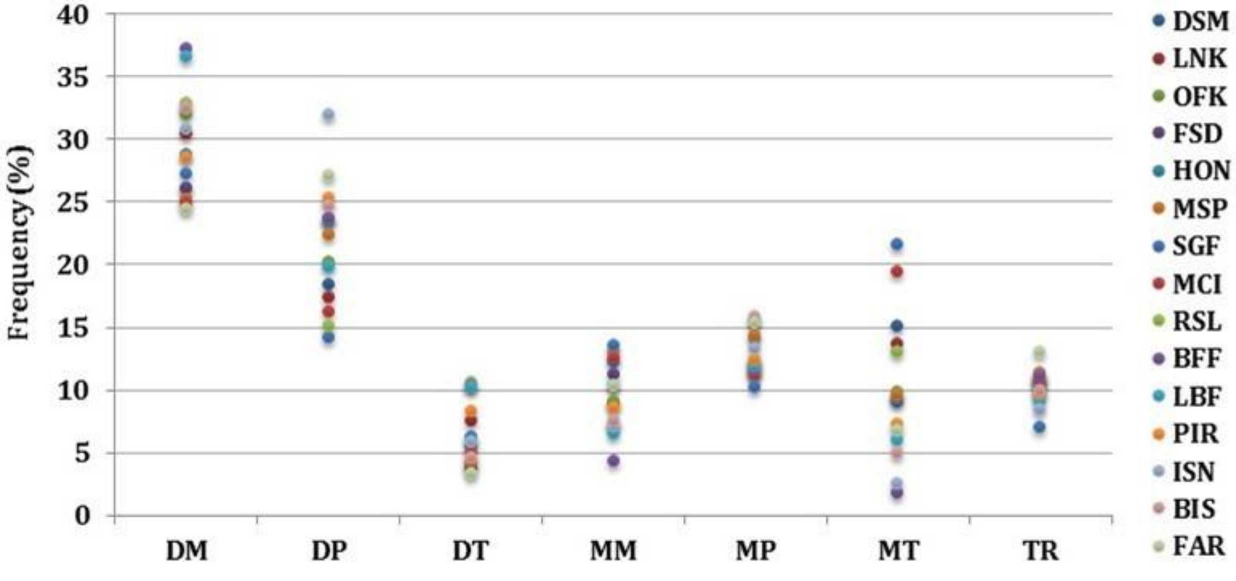

Figure 10. Annual air mass frequency (%) for 1981-2010 at all stations.

Following these air masses, some variability between stations can be identified. At most locations across the region MP and TR represent the next most frequent annual types (with mean values near 10 - 13%). The MM and MT air masses can be nearly as common across the region, though concentrations are more variable with mean frequencies from 2 - 15%. MT air masses become increasingly less prominent at northwest stations. Most stations have values between 6 and 11%. For nearly all stations the air mass with the least presence in the region is the DT (generally 1 - 6% mean frequency). These air masses are more common in the south, a finding that reflects the annual temperature gradient across the region. Typically, all stations located further north (south) have more (less) warm air mass types.

Rain Day Frequency

For the 30 year period, regional air mass frequencies during times of precipitation display some spatial variability. These data are displayed here so that stations in the northwest (NW) portion of the region (Fig. 11) are isolated from stations in the southeast (SE) of the region (see Fig. 4 and previous section for station list) based on similarities detected in the analysis. NW stations include Williston, ND, Bismarck, ND, Fargo, ND, Scotts Bluff, NE, Huron, SD, Minneapolis, MN, Pierre, SD and North Platte, NE. Generally, NW stations exhibit more variation in air mass tendencies than the SE stations. In other words, SE stations have more similar frequencies regardless of type. Across the entire region, moist air masses tend to be the most related to annual precipitation. MP and MM types are present most often when rainfall occurs. All moist air mass types tend to exhibit the highest frequencies at SE stations. In the NW, mean frequencies of the MP (21 - 34%) and DP types (10 - 34%) show these air masses are most related to precipitation. The further north and west a location is, the more precipitation is produced alongside dry air masses. This is exemplified in the northernmost stations of Bismarck, Fargo, and Williston. DP source regions are close to the NW but the finding is practically significant as very dry air masses are not often associated with precipitation. These days may have moist advections of air flow aloft, which could better be identified with an upper-air synoptic index. Essentially, moist air masses may get advected aloft, over what is being reported as a dry air mass at the surface. MM is the third most prevalent air mass during NW rain days (10 - 25%). With the strong presence of MP and MM types it can be seen that, at most stations, around half of all rain days may be related to these two air masses alone.

MM and MP are the two most common synoptic air masses related to precipitation in the SE (17 - 28 and 20 - 28% mean frequencies, respectively). MT is the third most prevalent (10 - 22%), indicating that rain in the SE is more often associated with moist air masses than any other type, and more so than in the NW. DP has fewer, but generally similar frequencies to MT in the SE.

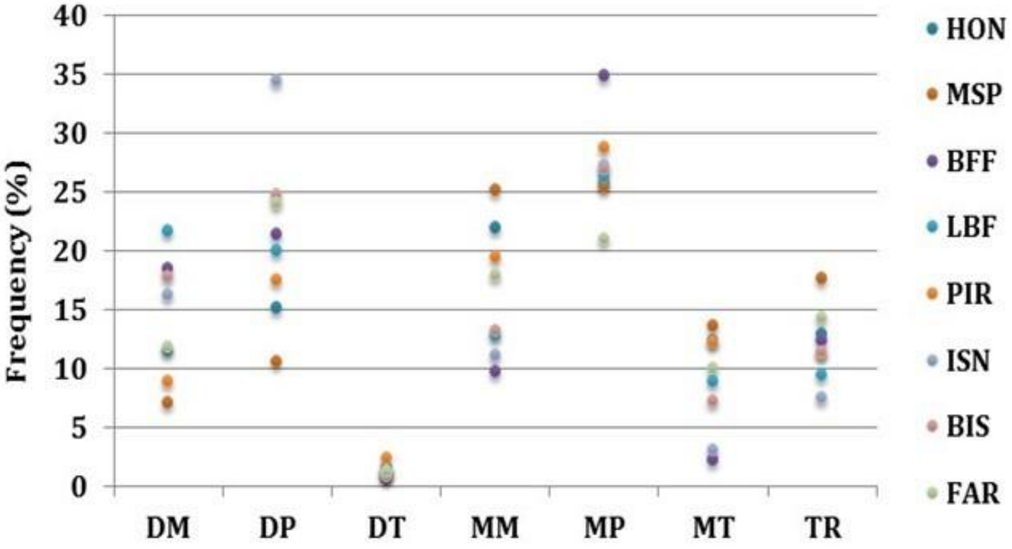

Figure 11. Annual air mass frequency (%) for eight station pairs in the northwest part of the Northern Plains.

Both the DM and TR are related to frequencies between approximately 7 - 20% in the NW and SE. These findings are rather unexpected for TR. TR are allocated to locations changing from one air mass to another over the course of the day, sometimes indicative of a frontal passage. It seems the day of the frontal passage is likely to be considered within the air mass ahead of the front, while the day after the front is what gets designated TR. This would result in more of the frontal precipitation occurring the day before the TR is recorded. TR may then mostly be present the day immediately following precipitation. Additionally, the SSC does not specify how the thermal or moisture properties of the TR air mass changes (*e.g.*, moist to dry, warm to cold). This means transition days from dry-to-dry air masses, which lack enough moisture to produce precipitation, are still defined TR. Labosier (2012) did find the TR air mass to be a significant producer of precipitation in Birmingham, AL. This finding would support the idea that precipitation is occurring along the boundary between two air masses. However, in the case of the Northern Plains region, the precipitation appears to be better described as occurring within one air mass, perhaps further from the boundary between the two air masses.

The MT is often less dominant in the NW than these other types, which is unsurprising given that upper-level flow patterns that bring moist, Gulf air north to this part of the country is infrequent and requires an easterly component. Warmer air masses are more likely to hold more water vapor than cooler air masses, which could make the MT more likely to not only produce precipitation in general, but also produce more intense precipitation. However, based on these results, MM and MP are primarily responsible for the precipitation production. Even with the Northern Plains wettest time of year observed in the warm season, MT is too infrequent to be related to this region's rainfall. DT frequencies are all less than 2% showing that this variety is not conducive to rainfall. The SE station findings are identical for DT. This supports the findings of Walker, *et al.* (2012) that found DT connected to extreme drought.

Frequency Departures

The differences between air mass frequencies during rain days and normal conditions (the baseline) highlight the results of the previous two sections. When examining these findings it becomes clear that rain days are related to an increase of all moist air masses rather than one particular type (Figure 12). All stations have at least a 5% increase in the MM and MP types. The increase is generally 5 - 20% across the region. All station increases in MM and MP frequency are statistically significant at the 99% confidence level (CL). MT types also increase from the norm though with less magnitude, 0 - 7%. Most stations (10 in number) exhibit a statistically significant increase (99% CL) in MT from the baseline during rain days. Des Moines, Norfolk, Scotts Bluff and Springfield display increases as well, but without statistical significance. Only Kansas City displays a statistically insignificant decrease in MT frequency.

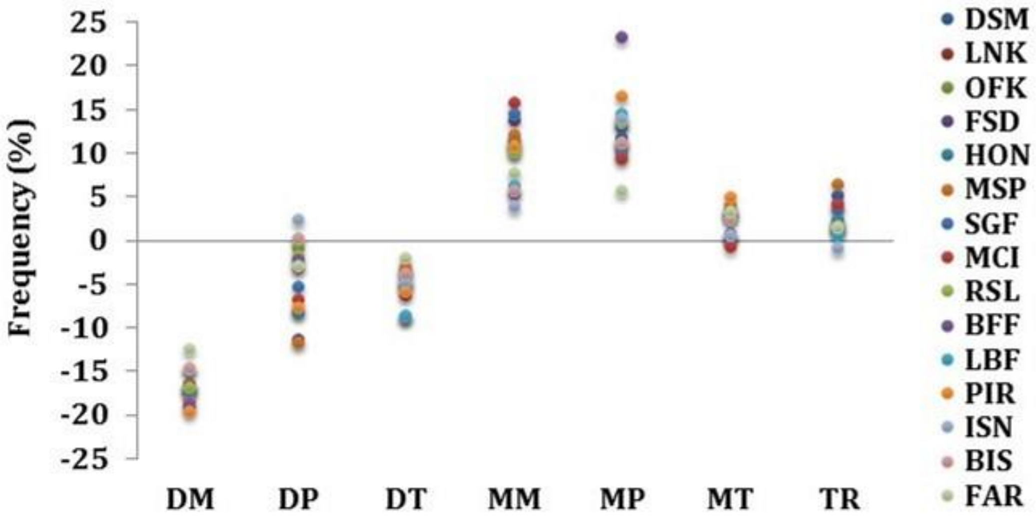

Figure 12. Annual air mass frequency differences (%), rain day minus baseline, for all station pairs.

TR air masses are 0 - 10% more frequent during rain days in the Northern Plains. Eleven stations exhibit increases in TR frequency that are statistically significant at the 99% CL. The other four locations (Bismarck, North Platte, Scotts Bluff and Williston) have insignificant increases.

Altogether, this likely means that rain days on the Northern Plains are linked to the advection of moist air from source regions like the Great Lakes and Atlantic Ocean. To a lesser extent this seems to also be attributed to Gulf of Mexico moisture (with lower percentages of MT increases observed) and transitioning air mass days (e.g., TR or from MT to MM). These are important findings as it highlights the kinds of synoptic patterns that must be present during rain days. Figure 13 provides two maps that illustrate potential ways that MP and MM air can reach the region to be present during rain events.

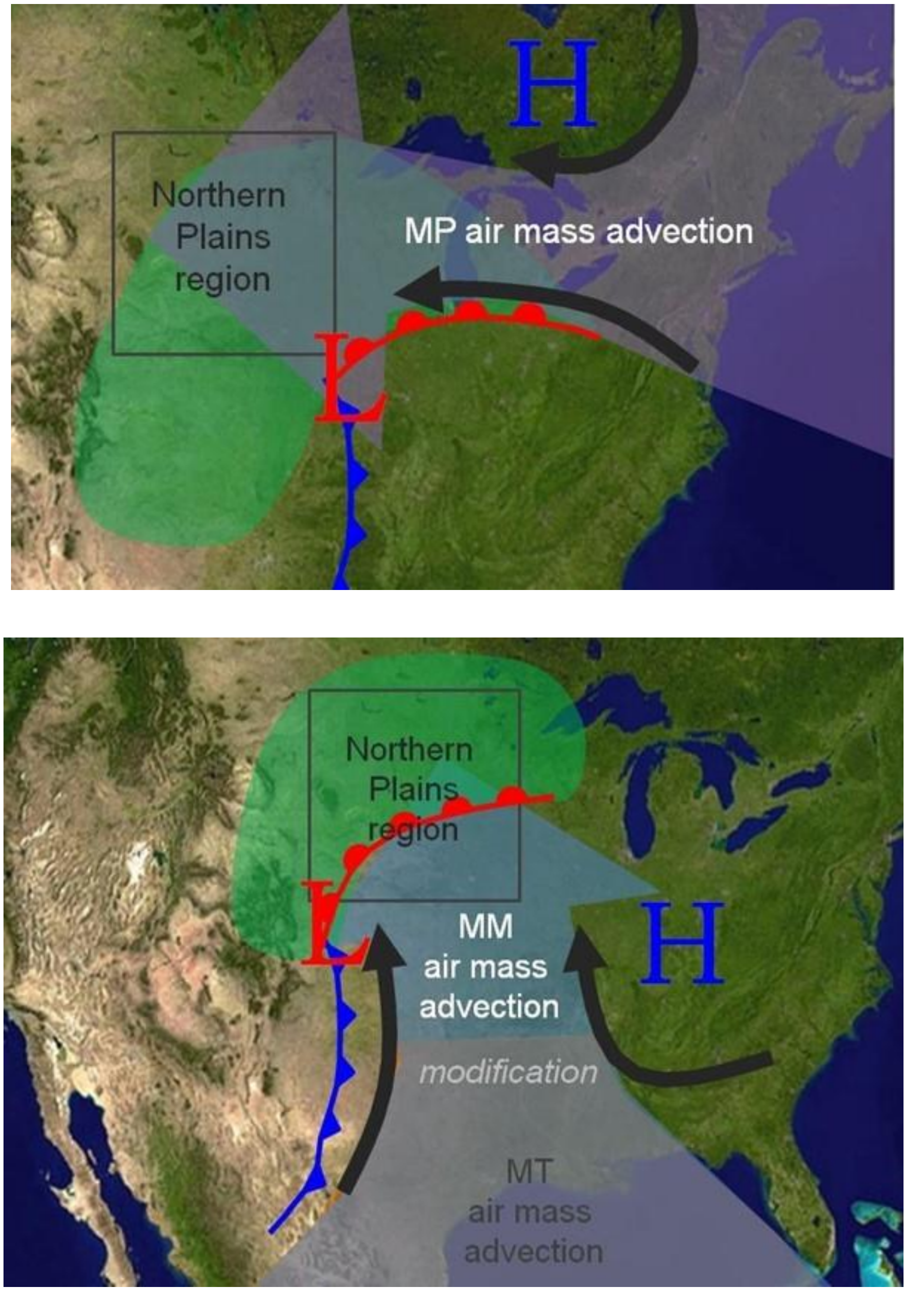

Figure 13. Maps showing how MP (a) and MM (b) air masses may be advected into the region during rain day events.

The departures also depict characteristic decreases in all dry air mass types rather than an individual variety. While the previous section shows that it is possible to have dry types present during rainfall, most rain days are associated with the replacement of a dry type from the region with any one of the moist air masses. The two most dominant types in the baseline, DM and DP, have decreased frequencies by as much as -20%. All stations have 10 - 20% fewer DM days during rain events. These departures from the baseline are significant at the 99% CL. Scotts Bluff is one exception, where fewer DM days are detected but the departures are without statistical significance. For DP, two stations (Bismarck and Norfolk) display insignificant decreases from normal during rain days. North Platte has a tendency for increases in the DP type, but without statistical significance which highlights that the result cannot be weighted with much credence. All other stations show decreases in DP from the baseline. Of those stations, all are statistically significant at the 99% CL but Russell (significant at the 95% CL). DT days are associated with negative, statistically significant departures (99% CL for all stations) that range from -1 to -10%.

Rain Day Frequency: Precipitation Categories

Category 1 rainfall represents the lightest precipitation that falls in the Northern Plains. By examining Figure 14 the data indicate that most light rain received is related to the dry DM and DP air masses as often as MM and MP, with generally 5 – 15% frequencies each. This explains the earlier findings that rainfall is associated with dry air masses which was an unexpected result. It turns out that the result is influenced by the fact that, naturally, far more category 1 precipitation is received than heavier rainfall. In other words, while light rains are so frequent these low totals can be produced by moist types and even dry types. This may occur as the moist types have just moved out or preceding their advection into the region. The amount of TR types are around the same frequency as the others, which may be capturing these transitional time frames. Stations can only record one type per day so it is likely that the dry air masses present during rain actually represent the *moistest* dry days of the air mass. An air mass character assessment would reveal whether or not this is true and should be performed in the future.

Category 2 rainfall represents the totals between category 1 and 12.69 mm. Days with these light to moderate rains are associated more with moist types than category 1, though dry air masses are also a factor in these conditions. More TR types (up to 10%) are also related to these rain days. As for all other rainfall categories, DT is very rarely related to rain in this region.

Category 3 rainfall is more intense than category 2 but less than 25.4 cm. Fewer days with rain produce these kinds of totals compared to category 1 and 2. Nevertheless, when these moderate to heavy rains are observed the MM, MP, MT and TR are responsible. Dry air masses are less frequent at most stations meaning that heavier precipitation tends to fall when either a moist air mass or transitional day is experienced. It is likely that the TR days represent a transition from one moist type to another (*e.g.*, MM to MP or MP to MM). If so, then moist air masses would really be displaying an even stronger connection to this type of rainfall than the results are able to highlight.

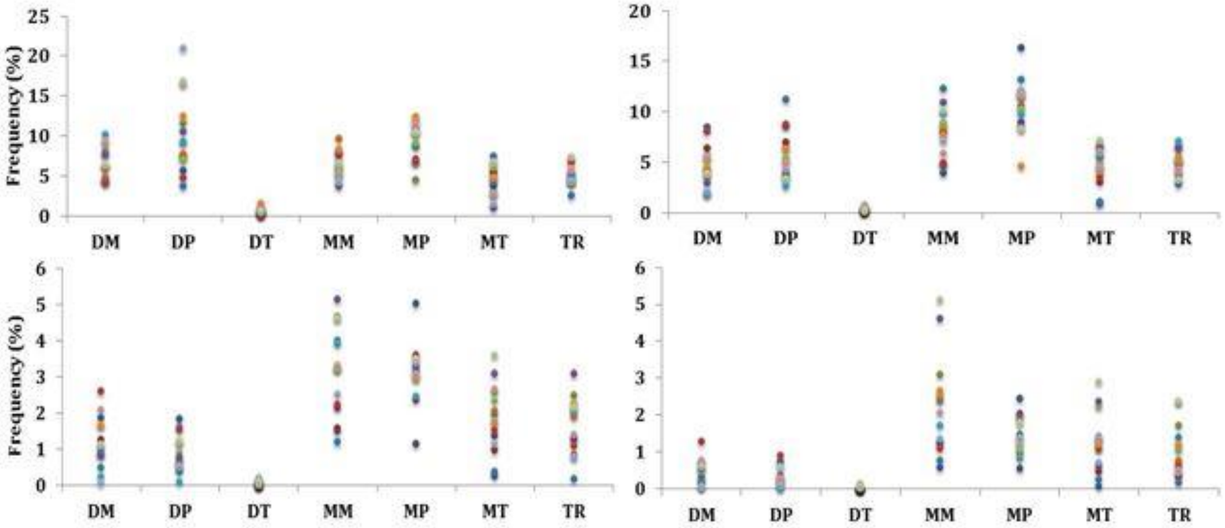

Figure 14. Rain day frequency (%) by precipitation category for all stations: Category 1 (upper left); Category 2 (upper right); Category 3 (lower left); and Category 4 (lower right).

Category 4 rainfall constitutes any precipitation that falls with totals over 25.4 cm. When this heavy precipitation occurs, all moist air masses and the TR variety are present (much more so than the dry types). The finding is intuitive in that such heavy rainfall should be indicative of a very wet day at the surface, with high dew points and relative humidity at 100%. Even if these high totals fall quickly, it would make sense that the surface and near-surface levels are saturated, as one would find with the moist air masses. Alternatively, if a TR is present this could represent a front over the region, like a stationary front, that may characteristically stall. If so, stations could receive larger rainfall totals.

Seasonal Air Mass Frequency

This section describes the major findings produced when air mass frequency during rain days is discriminated by season (Figure 15). In addition, the results obtained from studying different total precipitation categories is presented by season (Figure 16 and reference Figure 8). It is useful to compare these findings to the frequencies identified for the annual period of record during rain days across the region as well as those in the baseline (all days regardless of any precipitation falling).

Winter

The winter months have MP air masses dominating during most winter precipitation (see Figure 15). This is expected as MP represents the coolest, most moist days in the SSC classification scheme. DP air masses are also fairly common, though variable by station (frequencies from 3 - 11% across all stations). As noted in the annual discussion, this result is partly due to an extreme prevalence of this air mass at all times, especially at NW stations, during the winter season. This is also a time where rainfall is less common than snowfall and more light rain days are observed in winter. Note that the scope of this research did not extend to include snowfall though the authors expect that this result would be different if snow days were included. MM and TR (both with around 2 - 6% frequency) are the next two most dominant air masses in winter rain events.

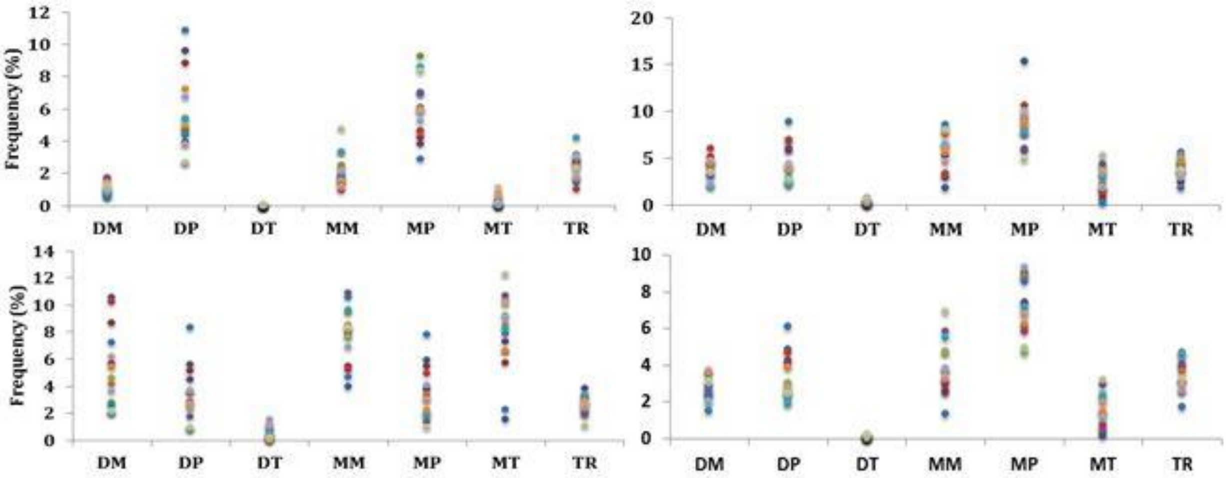

Figure 15. Seasonal rain day frequency (%) for all stations: Winter (upper left); Spring (upper right); Summer (lower left); and Fall (lower right).

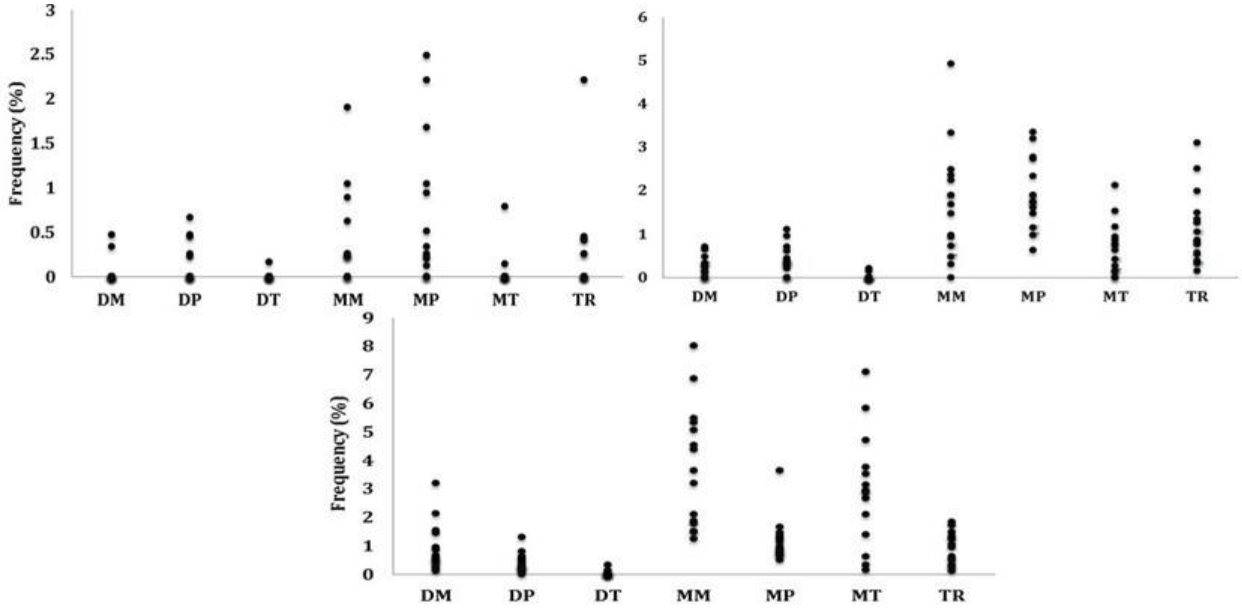

Figure 16. Seasonal rain day frequency (%) examples by precipitation category for all stations: Winter category 4 (upper left); Spring category 4 (upper right); and Summer category 4 (bottom). Note that Fall category 4 values are displayed in Figure 8.

When examining winter category precipitation, the same general findings found for all seasons is detected here. When category 1 and 2 precipitation is recorded, MP (occurring 10 - 25% of the time in category 1) and DP (occurring from 11 - 44% of the time in category 1) are the most prevalent. The larger percentages are recorded at NW stations where DP is always a more regular synoptic regional feature. For categories 3 and 4, however, dry air masses are nearly entirely absent in winter (see Figure 16). DP percentages drop to less than 2%. Instead, MP becomes dominant in producing winter rainfall with up to 10% frequency in category 3 days. As this magnitude rainfall is less common, the result becomes more important from a practical forecasting perspective. MM follows with high prominence during winter rains; up to 6% frequencies observed in category 3. While not many days are category 4 in winter, these are nearly all MM, MP or TR. The other air mass types do not feature more than 5% occurrence at any station, with the majority of stations experiencing other air masses less than 3% of the time. A lack of tropical air masses and a reduced presence in moderate air masses is rather expected as the northern location of the region experiences strong polar influences with Alberta clippers and Arctic high pressure systems throughout the winter season.

Spring

During the spring season, the MP air mass dominates the seasonal precipitation in frequency over other air mass types, occurring between 5 and 15% of the time (see Figure 15). DP and MM are the next most prevalent, both occurring between 2 and 10% of the time. It should be noted that while the spread of the smallest and greatest frequency for each air mass is similar, the DP air mass is skewed more heavily toward a less frequent occurrence. MT and TR air masses account for up to 6% of the spring frequencies. During spring, atmospheric pattern changeability seems to account for variations in values from winter. The air masses that were subdued in the cold season, like the moderate MM and tropical MT types, become more frequent at this time of year. The dominant winter air masses, most notably DP, become less frequent.

This addition of moderate and tropical air to the region is also reflected in the spring category frequency analyses. For instance, MM and MT become nearly as frequent as MP in category 4 rainfall (see Figure 16). This reflects the warmer conditions of spring, but not entirely one without some cold days. TR air masses are more commonly associated with heavy rain at this time of year, too. Interestingly, the range in frequency is greater at this time of year than observed in winter. This may be attributed to more rainfall in general at this time of year. It is also an indication that the winter-to-summer pattern is evolving with more frontal passages. All dry types occur less than 1% of the time during category 4 rain events and less than 2% of the time in category 3 events.

Summer

The summer season experiences the most variability in terms of what air mass is present during precipitation events. MT is one of the most dominant air masses, with up to 12.5% seasonal frequency (see Figure 15). The MT air masses may migrate from the Gulf region with less modification at this time which explains why they are most dominant in southern stations. Only the far northern stations experience an insignificant number of MT days, sometimes as low as 2% of the total air mass range. Other moist air masses, as well as DM, are prominent; usually more so than other dry varieties. The DT air mass is very rarely a precipitation producer in the summer with less than 2% frequency. TR occurrence decreases from the previous season in summer, indicative that this season resembles winter with fewer synoptic pattern changes (that would produce TR air masses). The general summer surface heating across the study region is sufficient to trigger and support air mass thunderstorms if conditions forcing vertical ascent align. Such conditions are less frequent during dry air mass dominance, but possible nonetheless. DT days would typically be expected to bring some of the greatest heat to the region, encouraging thunderstorm development even if those outbreaks occur with other air masses. This means their presence may actually be important for Great Plains rainfall. Summer is probably the best season in which the climate allows for such development to happen.

Air mass thunderstorms are likely responsible for the higher precipitation totals detected in the category analyses. MM and MT air masses are at the surface most of the time when heavy, category 4 precipitation falls (see Figure 16). The frequency of both types generally ranges from 2 - 9% during these days. MT and DP tend to be the most related to light rains in summer. MM becomes more prominent as the amount of rain increases. Behind MM and MT, the MP, DM and TR are all the next types most associated with heavy rain. As seen with all rain days in the Northern Plains, it appears that in summer heavier precipitation falls while moist conditions prevail at the surface. Dry air masses may be around during lighter rains, perhaps as summer thunderstorms are quickly swept across the region with strong winds.

Fall

Fall rain day frequencies most resemble those of the springtime. All air mass frequency ranges are closer together in this season. MP is the most dominant air mass during the fall, as in spring. MP air masses occur 5 - 10% of the time. MM, DP and TR also have stations that identify over 5% dominance during fall rain events. DP air masses increase slightly from the summer months, which are probably related to the cooling seasonal conditions, regardless of precipitation. DM decreases (from between 2.5 and 11% in summer) to having 2 - 6% autumn frequency. Similarly, MM decreases (from between 4 and 11% in summer) to 2 - 7% fall frequency. TR is more common than in summer, with 3.5 - 6% occurrence. As with spring, this can be attributed to more frequent synoptic weather pattern changes. DT values are below 1% at all stations, and altogether absent at most stations. One of the largest changes between this and the last season occur with the MT air masses which have less prominence (<

4% values) across the region in fall precipitation events.

These tendencies are also represented in category rainfall examinations, particularly with categories 1 – 3. Again, drier types tend to be related to low totals and moist types tend to occur with higher totals. In category 4 rain days, the MM, MP and TR types are the strongest autumn rain day features (see figure 8).

SUMMARY

The Northern Plains is a region rich with agriculture, meaning the productivity of farms throughout these states is inevitably tied to precipitation. The skillful prediction of annual and seasonal precipitation influences not only the region's state economies but those throughout the country. This research provides the kind of spatial and temporal information about seasonal precipitation that can aid farmers in better understanding the synoptic conditions present during rain (and varying rainfall intensity events). The primary research objective is successful in determining the most prevalent air mass types on days with precipitation. This is the first time that such quantitative information about the connection between air masses and rainfall has been investigated for this region. While regional spatial variability is influential, MM and MP are the statistically most dominant types during rain days across the region. This varies from the regional norm which shows that DP and DM air masses are regularly dominant, especially at NW stations. Dry air masses of any type rarely produce precipitation but when this happens it is mostly during light, category 1 rains. As rainfall intensity increases, more moist and TR air mass types become more prevalent.

The early hypothesis that TR air masses days are related to the greatest number of precipitation days is essentially incorrect. This result does not follow the findings of Labosier (2012) in the southeast U.S. (although the station examined there may not be representative of the whole region). In the Northern Plains region, the TR does tend to be more prominent in spring and fall when the MP air mass dominates seasonal rainfall. In spring, DP frequency declines while MT rises, especially in the south. MM and MT days result in nearly as much heavy, category 4 rainfall as MP in this season, spotlighting more moisture flow from the Gulf of Mexico. In the fall, MP becomes more frequent as cooler weather sets in the region. MM, DP and TR (as mentioned earlier) also maintain a strong presence in autumn.

Matching early hypotheses, the thermal nature of an air mass is reflected in frequencies identified during the cold and warm seasons. DP and MP dominate winter rainfall, with the most precipitation falling during MP days. DP occurs more at NW stations, closer to the air mass source region. Warmer, Gulf-advected MT air masses are the leading producer of summertime precipitation, especially light rains which account for most rain days. Finally, the fact that this study finds DT days to be so evidently, and statistically, unrelated to rainfall on the Northern Plains verifies the results of Walker et al. (2012) that pinpoints this air mass as one connected to drought and a vigorously dry central United States.

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