SHIFTS IN THUNDERSTORM OCCURRENCE AND SPATIAL SYNOPTIC AIR MASS CLASSIFICATIONS IN THE MID-ATLANTIC UNITED STATES, 2003 TO 2012

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ABSTRACT: *Atmospheric science literature establishes a heightened probability of thunderstorm activity occurring in instances of increased atmospheric instability. Convective available potential energy (CAPE), a measure of atmospheric instability, increased over the timeframe of 2003 to 2012. Thunderstorm occurrence and Spatial Synoptic Classification (SSC) air mass classifications were used to further investigate the atmospheric instability of the Mid-Atlantic United States over the meteorological summer season (June, July, and August) from 2003 to 2012. Thunderstorm occurrence data were separated into two categories, early (2003 to 2007) and late (2008 to 2012), and the Wilcoxon Signed-Ranks Test was used to test for changes between the timeframes. Similarly, SSC data were split into the same categories for each of the seven classifications and tested for changes between the timeframes, using Wilcoxon Signed-Ranks or Matched Pairs T-tests depending on the normality of the data. The analysis of thunderstorm occurrence data yielded a significant increase in frequency from the early to late timeframes. The analysis of SSC data yielded significant results for five of the seven SSC classifications suggesting that the prevalence of these air masses has led to increased thunderstorm occurrence.*

Keywords: *climatology, thunderstorm, synoptic, air mass, climate change*

INTRODUCTION

Increased thunderstorm occurrence in a warming climate has been generally agreed upon in the ensemble of climate literature (Brooks, 2013; Diffenbaugh et al., 2013; Allen et al., 2014; Seeley and Romps, 2015). These thunderstorms can disrupt social and economic patterns with flash flooding (Kermanshah et al., 2017), crop loss in agricultural regions of the northeast and Mid-Atlantic (Tomasek et al., 2017; Wolfe et al., 2018), and have negative impacts on ecosystems (Spooner et al., 2011; Jones et al., 2013). One parameter that factors into the potential instability in a warming environment is convective available potential energy (CAPE). In previous work, CAPE was seen for the summer seasons from 2003 to 2012 in the Mid-Atlantic United States (Andrews and Davis, 2017). CAPE is a measure of atmospheric instability that provides a numerical value (J/kg) for energy released from a parcel of air as it ascends in the atmosphere, with high values of CAPE signifying an unstable atmosphere. Scientific literature generally agrees that severe weather has a higher probability of occurring when there is increased CAPE (Brooks, 2013; Diffenbaugh, Scherer, & Trapp, 2013). Diffenbaugh et al. (2013) also found that further warming from anthropogenic climate change has been linked to increased instances of severe thunderstorm environments in the eastern United States, along with a greater risk of thunderstorm-related damage.

Unfortunately, there is a lack of recent literature on the topic of thunderstorm occurrence. An early study yielded results in which there was a high occurrence in afternoon thunderstorms in the Northeast United States, as well as a generally high frequency of thunderstorms during the day in summer months (Wallace 1975). One study that was conducted by Hurlbut and Cohen (2014) suggested that severe weather events in the northeast United States are largely determined by lapse rates in the mid and lower levels of the atmosphere. Precipitation associated with these northeastern United States storms have been found to have observed a sharp increase in extreme precipitation (Howarth et al., 2014). This was followed by a study done by Araghi et al (2016) in Iran analyzed the trends in thunderstorm days over five decades. Using the Mann-Kendall Trend Test they found that for the entire time series, trends were positive and significant (or non-significant) for more than 90% of the country (Araghi et al., 2016). Though the mostly arid or semi-arid climate of Iran is different from the temperate Mid-Atlantic United States, it provides inspiration for conducting a similar analysis of thunderstorm occurrence in the Mid-Atlantic United States. Similar studies have depicted a two to three day increase in thunderstorm days in the eastern United States due to 21st century warming by the end of the century, particularly in the spring and summer (Trapp et al., 2007; Trapp et al., 2009; Diffenbaugh et al., 2013). These findings were consistent with a later study focused on severe weather events derived from CAPE values in Australia (Allen et al., 2014). Thunderstorm trends in Africa have also been examined (Harel and Price, 2020) along with correlation with lightning frequency (Lavigne et al., 2019). Thunderstorm frequency in a warming climate was a central topic to a recent study (Taszarek et al., 2021) that also evaluated whether North American trends could be assumed for other continents.

In addition to thunderstorm occurrence, the type of air mass present over a region can provide greater clarity to the behavior of the atmosphere. The first iteration of the Spatial Synoptic Classification (SSC) was created in the 1990s with the intention of creating a scheme in which subtle patterns, too subtle to affect the whole climate record, could be recognized (Kalkstein, Sheridan, & Graybeal, 1998). When Kalkstein et al. (1998) published this paper using the first SSC, they intended for it to be used as a synoptic climatological tool for climate change research. Thus, the SSC appears to be a great tool for assessing climatic trends in the Mid-Atlantic United States. The SSC provides an air mass-based approach to assessing atmospheric instability in the Mid-Atlantic United States. It classifies air masses based on surface observations of temperature, dew point, wind, pressure, and cloud cover (Kalkstein et al., 1996; Sheridan, 2002). Araghi et al. (2016) noted that most of the thunderstorm occurrences in Iran took place in regions that were the main pathways for synoptic pressure systems to enter the country.

The SSC has been utilized previously, primarily to understand the characteristics of the air or to supplement cross-disciplinary research in relation to climate science (Dixon et al., 2016). Hondula and Davis (2011), using the SSC, found a decrease in winter transition (TR) frequency patterns in the United States and further noted that transition frequency patterns can be associated with cyclonic (low pressure) and anticyclonic (high pressure) activity. Vanos and Cakmak (2014) similarly found significant decreases in transition (TR) air mass frequencies in Canada for both winter and summer seasons. Vanos and Cakmak (2014) also found an increase in moderately moist (MM) and dry moderate (DM) air mass types in all climate zones for summer and winter, as well as a large increase in the moist tropical (MT) air mass in the summer. Even after years with the SSC, Dixon et al. (2016) note that the SSC provides a great opportunity for climate-change research through the lens of synoptic climatology, yet it is “under-utilized”.

This paper aims to assess how the atmosphere over the Mid-Atlantic region of the United States has evolved over in terms of atmospheric instability and trends in prevalence of air masses which, in turn, would lead to increased thunderstorm frequency.

METHODS

Thunderstorm Occurrence

Summer (June, July, August) average days with thunderstorms data was collected from the National Oceanic and Atmospheric Administration’s Local Climatological Data Reports for each of 18 weather stations in the Mid-Atlantic United States from 2003 to 2012 (National Centers for…, 2018). Mean monthly CAPE data was collected from the National Center of Atmospheric Research Earth Systems Research Laboratory from 2003 to 2012. This ten-year period was utilized due to the limitations in CAPE availability. While the ten-year window is not ideal, the authors hope it will show trends in atmosphere instability over this important region of the United States. While other variables have a robust range and with the spirit of examining CAPE data in this research, that was the motivation for facilitating the reduced temporal period. The Mid-Atlantic was defined as New York, Pennsylvania, New Jersey, Delaware, and Maryland. The 18 weather stations were divided among the states as follows: seven in New York, seven in Pennsylvania, two in New Jersey, one in Delaware, and one in Maryland (Figure 1). Table 1 shows the list of weather stations and the data after being processed into two groups: early (2003 to 2007) and late (2008 to 2012). This step was to ensure the data were in a proper format for a matched-pairs test later in the analysis.

A Shapiro-Wilk test was run in SPSS to test the dataset for normality, with significance accepted at $p < 0.05$. The dataset showed significant difference from normality, seen in Table 2, so the Wilcoxon Signed-Ranks test was used to determine any changes in the dataset. The null hypothesis (H_0) for the test was the early (2003 to 2007) frequencies of days with thunderstorms did not differ significantly from the late (2008 to 2012) frequencies of days with thunderstorms. The alternative hypothesis (H_A) for the test was that the early frequencies of days with thunderstorms differed significantly from the later frequencies of days with thunderstorms for the Mid-Atlantic United States. Significance of results was accepted at $p < 0.05$.

Spatial Synoptic Classification

The SSC data was collected from Sheridan’s online SSC archive. Daily SSC data was collected over the period of 2003-2012 based on surface observations of temperature, dew point, wind, pressure, and cloud cover and yields the following breakdown of air masses/weather types:

The temporal period aligned with the CAPE data and provided additional insight into the instability with the prevalent air mass. These SSC types were compared against days with thunderstorm data from the National Ocean and Atmospheric Administration’s Local Climatological Data Reports for each of 18 weather stations in the Mid-

Atlantic United States from 2003 to 2012. Counts of days with each of the seven air mass types were collected for the meteorological summer season for each station from 2003 to 2012 (Table 3).

Figure 1. Station locations for the Mid-Atlantic region.

Table 1. Averaged days with thunderstorms values for early and late subgroups for each weather station in the Mid-Atlantic United States: 2003 to 2012.

Station	Early (2003 to 2007)	Late (2008 to 2012)
Allentown [ABE]	8.4	5.8
Erie [ERI]	12.0	13.2
Harrisburg [MDT]	4.2	20.8
Philadelphia [PHL]	19.6	17.8
Pittsburgh [PIT]	21.6	19.0
Wilkes-Barre [AVP]	7.2	7.6
Williamsport [IPT]	14.6	17.4
Atlantic City [ACY]	4.2	5.8
Newark [EWR]	15.2	18.2
Wilmington [ILG]	11.8	14.0
Baltimore [BWI]	17.8	19.4
Albany [ALB]	11.6	16.8
Binghamton [BGM]	13.2	14.4
Buffalo [BUF]	16.0	19.6
Islip [ISP]	11.6	16.0
New York [JFK]	13.6	15.8
Rochester [ROC]	16.6	19.8
Syracuse [SYR]	14.4	18.0

Table 2. Shapiro-Wilk normality test for days with thunderstorms data for the Mid-Atlantic United States: 2003 to 2012.

	Statistic	df	p
Days with Thunderstorms	0.934	36	.034

Table 3. Breakdown of the weather types specified in the Spatial Synoptic Classification scheme (Sheridan, 2002)

Dry Polar (DP)	Cool or cold, dry air with little to no cloud cover	Northern Canada and Alaska
Dry Moderate (DM)	Mild and dry	No conventional source region
Dry Tropical (DT)	Associated with the hottest, sunniest, and driest conditions	Deserts of southwestern USA and northwestern Mexico
Moist Polar (MP)	Cool, cloudy, and humid	North Pacific and North Atlantic Oceans
Moist Moderate (MM)	Cloudy, but warmer and more humid than MP air	No conventional source region
Moist Tropical (MT)	Warm and very humid, partly cloudy in the summer	Gulf of Mexico and tropical Atlantic Ocean
Transition (TR)	indicates when one weather type changes to another	N/A

For each weather station, counts of each air mass type were separated into two subgroups, Early (2003 to 2007) and Late (2008 to 2012), and then averaged. This resulted in each weather station having a single value for each subgroup for each of the seven air mass types. A Shapiro-Wilk test for normality was conducted on the data associated with each air mass category (Table 4). The test indicated that the data for Moist Tropical (MT), Moist Moderate (MM), Moist Polar (MP), and Dry Moderate (DM) air masses followed the normal distribution. With significance accepted at $p \leq 0.05$, the data for the Dry Tropical (DT), Dry Polar (DP), and Transition (TR) types did not follow the normal distribution.

Table 4. Shapiro-Wilk test for normality for each of the seven air mass types from 2003 to 2012 in the Mid-Atlantic United States

	Statistic	df	p
Moist Tropical (MT)	0.971	36	.464
Moist Moderate (MM)	0.972	36	.488
Moist Polar (MP)	0.955	36	.145
Dry Tropical (DT)	0.807	36	**.000**
Dry Moderate (DM)	0.954	36	.142
Dry Polar (DP)	0.928	36	**.022**
Transition (TR)	0.885	36	**.001**

A Matched-Pairs T-test was used to analyze the normally distributed data. The null hypothesis (H_0) was that there is no change in the counts of days for MT, MM, MP, or DM air mass types from the Early to the Late years of the timeframe. The alternate hypothesis (H_A) for MT, MM, MP, and DM air was that there is a difference in the counts of days with these air masses from the Early to the Late years of the timeframe. Significance of results was accepted at $p \leq 0.05$.

The Wilcoxon Signed-Ranks Test is a nonparametric equivalent to the Matched-Pairs T-test and was used to analyze the data that did not fit the normal distribution. The null hypothesis (H_0) was that there is no change in the counts of days with DT, DP, or TR air mass types from the Early to the Late years of the timeframe. The alternate hypothesis (H_A) was that there is a difference in DT, DP, and TR air mass types from the Early to the Late years in the timeframe. Significance of results was accepted at $p \leq 0.05$.

RESULTS

CAPE

Surface based CAPE plots are presented in Figure 2. There appears to be a general increase in CAPE values over West Virginia, Delaware, and Maryland suggesting that atmospheric profiles in the southern peripheries of the study area could be more unstable. Especially high values across these states can be observed in 2003, 2009, and 2012. Other years, such as 2004, 2005, and 2010 contain rather steep gradients in CAPE across these states. There was no large discernable trend in CAPE values across Pennsylvania and New York, most likely due to lower temperatures further north. In New Jersey, CAPE seemed to be higher toward the southern end of the state and higher toward the northern end of the state. It's possible the state's proximity to the ocean could be having this effect.

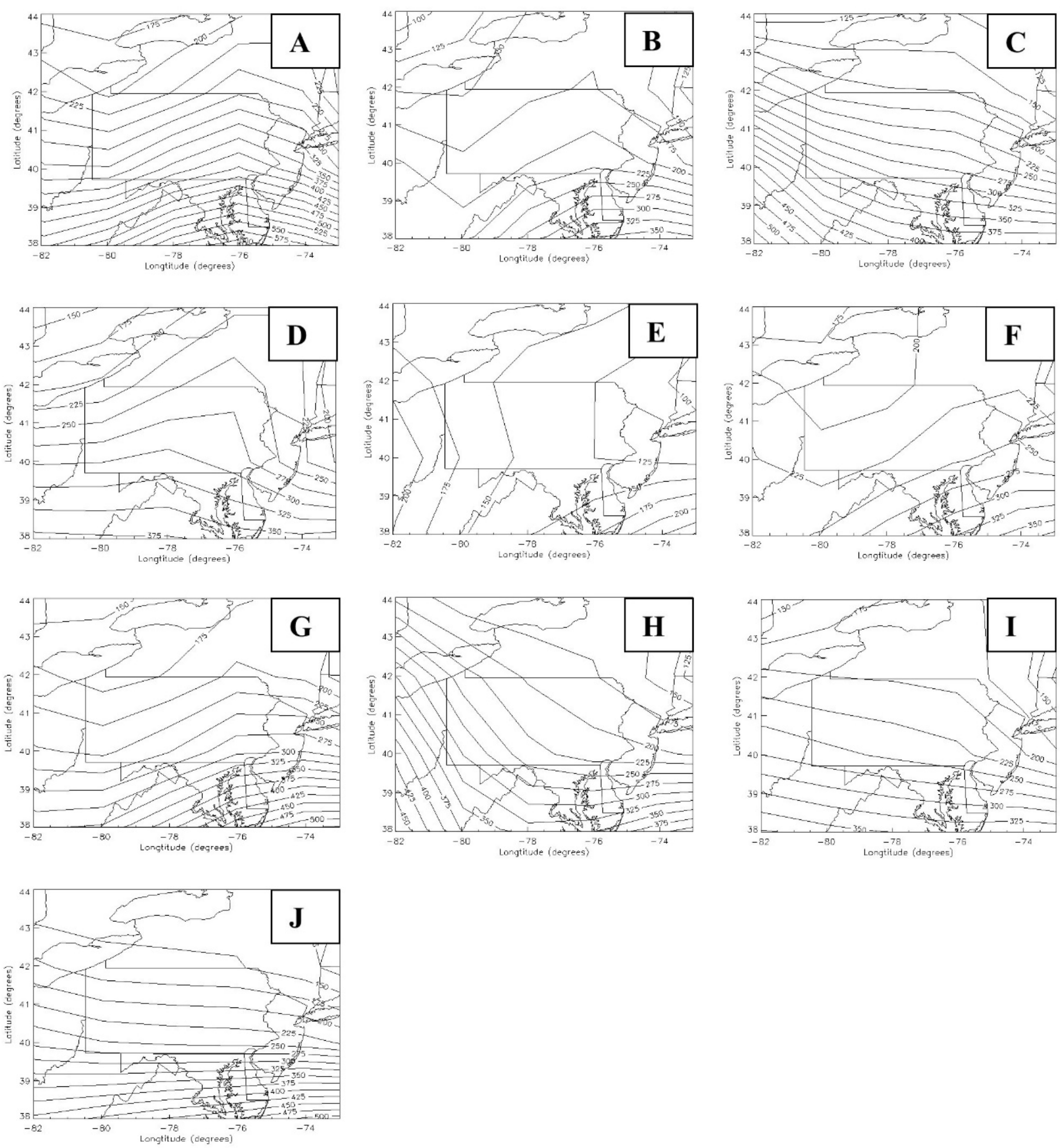

Figure 2. *Summer surface-based CAPE plots for a) 2003, b) 2004, c) 2005, d) 2006, e) 2007, f) 2008, g) 2009, h) 2010, i) 2011, and j) 2012.*

Generally low observed values of surface-based CAPE were found during the 2007, 2008, 2010, and 2011 summers. These summers correspond with La Nina events suggesting a possible link between the lack of instability present in the Mid-Atlantic with this global scale oscillation. While it is generally agreed that La Nina causes more severe weather in the continental United States (Heaton et. al, 2011; Mannshardt and Gilleland, 2013; Gilleland et al., 2013), our result would suggest the environment is not conducive for deep convection during these years. It is possible that some other synoptic scale phenomenon may influence the observed pattern.

Thunderstorm Occurrence

The Wilcoxon Signed-Ranks Test yielded significant results for the days with thunderstorms data. There were significantly more days with thunderstorms in the Late timeframe than the Early timeframe (Z = -2.636, p < .01, Table 5).

Table 5. Wilcoxon Signed-Ranks Test on the Late (2008 to 2012) - Early (2003 to 2007) categories for days with thunderstorm data in the Mid-Atlantic United States.

	N	Mean Rank	Sum of Ranks	Z	p (2-tailed)
Negative Ranks	3	8.33	25.00	-2.636	**.008**
Positive Ranks	15	9.73	146.00		

Spatial Synoptic Classification

The Matched-Pairs test results were not significant for the MT air mass type (t = -1.218, df = 17, p = .240, Table 6). The results for the MM air mass type were also not significant (t = -1.628, df = 17, p = .122, Table 6). There were significantly fewer days with the MP air mass type in the Late timeframe than in the Early timeframe (t = -7.231, df = 17, p < .01, Table 6). Lastly, there were significantly more days with the DM air mass type in the Late timeframe than the in the Early timeframe (t = 5.165, df = 17, p < .01, Table 6).

Table 6. Matched-Pairs T-test on the Early (2003 to 2007) and Late (2008 to 2012) categories for MT, MM, MP, and DM air mass types.

	t	df	p (2-tailed)
MT Late - MT Early	-1.218	17	.240
MM Late - MM Early	-1.628	17	.122
MP Late - MP Early	-7.231	17	**.000**
DM Late - DM Early	5.165	17	**.000**

The Wilcoxon Signed-Ranks Test yielded significant results for the DP, DT, and TR air mass data. There were significantly fewer days with the DP air mass type in the Late timeframe than in the Early timeframe (Z = -3.628, p < .01, Table 7). There were significantly more days with the DT air mass type in the Late timeframe than in the Early timeframe (Z = -3.238, p < .01, Table 7). There were also significantly more days with the TR air mass type in the Late timeframe than in the Early timeframe (Z = -2.168, p = .030, Table 7).

DISCUSSION AND CONCLUSION

The Wilcoxon Signed-Ranks test yielded significant results for thunderstorm occurrence; thus, the null hypothesis of no change was rejected. The sum of positive ranks was much larger than the sum of negative ranks, suggesting an increased frequency in days with thunderstorms from the Early timeframe to the Late timeframe. While a different method was employed in the Araghi et al. (2016) study, similar results were found in that thunderstorm occurrence was increasing over the timeframe studied. It is interesting that increased thunderstorm occurrence was found in two different climates.

Table 7. Wilcoxon Signed-Ranks Test on the Early (2003 to 2007) and Late (2008 to 2012) categories for DT, DM, and TR air mass categories.

	N	Mean Rank	Sum of Ranks	Z	p (2-tailed)
DT Late - DT Early					
Negative Ranks	1	3.00	3.00	-3.238	**.001**
Positive Ranks	14	8.36	117.00		
DP Late - DP Early					
Negative Ranks	17	9.00	153.00	-3.628	**.000**
Positive Ranks	0	0.00	0.00		
TR Late - TR Early					
Negative Ranks	3	6.00	18.00	-2.168	**.030**
Positive Ranks	11	7.91	87.00		

The Matched-Pairs T-test yielded non-significant results for the MT air mass type, thus the null hypothesis of no change was not rejected. It would appear that the number of days with the MT air mass type were consistent over the entire timeframe for the Mid-Atlantic United States. With the agreement in scientific literature that severe weather has a higher probability of occurring when there is increased CAPE, and that warmer and more humid air are associated with higher CAPE, it is interesting that there were no significant results for the MT air mass, which provides the warm and humid air that can perpetuate high CAPE environments (Brooks, 2013; Diffenbaugh et al., 2013). Vanos and Cakmak (2014) found a large increase in MT air masses in the summer for Canada, especially over large population centers. While the Mid-Atlantic United States it nowhere near as far north, the data for this study focused on the summer season and came primarily from weather stations located within large population centers. Perhaps looking at the individual factors used to classify the MT air mass type would yield more information than simply looking at its frequency. Kalkstein et al. (1998) found that the MT air mass type had statistically significant increases in summer mean daily dew point changes in the northeastern United States. Since the SSC scheme utilizes surface observations of temperature, dew point, wind, pressure, and cloud cover, more information may be gleaned from looking at observational data and comparing it to the thresholds used to classify particular air mass types, such as Kalkstein et al. (1998) did when developing the SSC.

Similar to the MT air mass type, the Matched-Pairs T-test yielded non-significant results for the MM air mass type which means the null hypothesis of no change was not rejected. Interestingly, Vanos and Cakmak (2014) found an increase in summer MM frequencies in Canada for all climate zones. Though not as extreme as the MT air mass type, the MM air mass type is warm and humid which also makes it influential in heightening CAPE, and therefore increasing atmospheric instability. Understanding the MM air mass type in relation to atmospheric instability and climate change may require analysis of the surface observations, as was suggested for the MT air mass type.

The Matched-Pairs analysis of the MP air mass type yielded significant results in which the MP type was less frequent in later years (2008 to 2012), which supports the alternate hypothesis. This conclusion is supported by Vanos and Cakmak (2014), in which the MP air mass type was found to be declining in Canada in the summer season. With anthropogenic climate change and its link to heightened CAPE, it makes sense that such a cool air mass type would not be as common, especially when a decrease in this type was found in Canada, both further north than the Mid-Atlantic United States and closer to the MP air mass's source region (Andrews and Davis, 2017; Diffenbaugh et al., 2013; Kalkstein et al., 1998). Overall, these results are supported in scientific literature.

The Matched-Pairs analysis also yielded significant results for the DM air mass type, in which DM days were more frequent in the later years of the time frame. This result supports the alternative hypothesis. Vanos and Cakmak (2014) observed something similar; the DM air mass type was becoming more frequent in all climate zones for the summer season in Canada. Similarly, the Wilcoxon Signed-Ranks Test yielded significant results for the DT air mass type where the air mass type was more frequent in the later years. This air mass is associated with the sunniest, driest, and hottest conditions, which is not as conducive as the MT or MM air mass types to the observed increase in CAPE in recent work and the above findings of increased thunderstorm occurrence (Andrews and Davis, 2017). With the general increase in CAPE values across the southern peripheries of the region, it would appear as increased instability in these locations would promote enhanced uplift for thunderstorm potential. With anthropogenic climate change, the increase in air masses that are warm/hot is not surprising, but the increase in dry air mass types may lead to avenues for future research. It is worth considering not only the air masses in place during thunderstorm days, but at the air masses in place a few days before and/or after the thunderstorm day. Abundant middle-latitude precipitation is found along boundaries of air masses rather than in the center, and, in Iran, a lot of thunderstorm occurrences were in pathways for synoptic pressure systems (Hondula and Davis, 2011; Araghi et al., 2016). This indicates that the movement and mixing of such air masses may be just as crucial to the formation of severe thunderstorm environments as the conditions associated with the air mass itself.

The Wilcoxon Signed-Ranks analysis also yielded significant results for both TR and DP air mass types. The TR air mass type was more frequent in the later years of the timeframe while the DP air mass type was less frequent. The alternate hypothesis is supported by these results; there is significant change in the frequency of these air masses from the early years to the later years of the timeframe. The results for the TR air mass ties in with the importance of mixing air to the formation of environments conducive to severe weather and precipitation. Recent literature seems to point to a decreasing trend in TR days (Hondula and Davis, 2011; Vanos and Cakmak, 2014). Additionally, Hondula and Davis (2011) indicate that TR frequency patterns can be linked to cyclonic and anticyclonic activity. This significant increase in TR days in the Mid-Atlantic United States may have something to do with the significant increase in thunderstorm days as well as the heightened CAPE seen from 2003 to 2012. Lastly, Vanos and Cakmak (2014) observed a strong significant decrease in the DP air mass type in both winter and summer seasons in Canada, which is consistent with the findings of this study.

From these results, there are two avenues for continuing this research in the future. Looking into the air masses in place on a thunderstorm day as well as the air masses that were present in days prior to and after that thunderstorm day may indicate what air masses are contributing more to the formation of severe weather environments. Another avenue for future research is comparing observed conditions to the thresholds used to classify air mass types. For example, a day may be classified MT, but how far is the observed temperature to the minimum temperature associated with classifying this air mass? If there is a large difference, and if a larger difference is becoming more frequent, it may be a way to assess warming. Additionally, Wallace (1975) primarily looked at the time of day for thunderstorm occurrence, not the change over a timeframe, so it would be interesting to expand the timeframe for these analyses and see how the results may change when looking at a larger range of years. Understanding climate change at the synoptic scale can provide a much more localized view to such a large, global problem.

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