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AIR MASS FREQUENCY, TRENDS, AND STAGNATION IN THE SOUTHERN APPALACHIAN REGION OF THE U.S.A., 1965–2014

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I am submitting herewith a thesis written by Shannon Lynn Woolfolk entitled "AIR MASS FREQUENCY, TRENDS, AND STAGNATION IN THE SOUTHERN APPALACHIAN REGION OF THE U.S.A., 1965–2014." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

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ABSTRACT

Recent research suggests that accelerated Arctic warming reduces the thermal gradient between polar and tropical regions and weakens the mid-latitudinal jet stream. A weakened jet produces deep troughs and synoptic-scale blocking, which results in the persistence of air masses in the high- to mid-latitudes of the northern hemisphere. Studies across the United States and Canada have documented a decline in the frequency of air mass transition (TR) days. This study analyzes air mass frequency, trends, and stagnation in the Southern Appalachian region of North America. This study places particular emphasis on the persistence of life-threatening air mass types, defined as those that contribute to extreme weather and poor air quality days. Analyses are conducted using 50 years of daily synoptic weather-type classifications (Spatial Synoptic Classification, SSC) from four study locations in Southern Appalachia. No such study has previously been conducted for the Southern Appalachian region. Results of this study show some significant frequency trends in air masses. Most notably, dry polar (DP) days are declining, and dry tropical (DT) days are increasing. Though expected to change significantly, the frequencies of moist tropical (MT) days and TR days show no distinct trend. Changes in the stagnation frequency of potentially oppressive types MT and DP vary by location, and stagnation duration has slightly increased at all stations for the two types. Overall, it seems as though the region is trending toward a warmer, drier climate with more frequent, longer stagnation events. This study serves as a foundation for future studies concerning the impact of climate change on the southeastern United States, Great Smoky Mountains National Park, and residents and visitors in the region.

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CHAPTER ONE

INTRODUCTION

The effect of anthropogenic forcing on the climate of the southern Appalachian region is still largely unknown. Unlike many places around the world, the southeastern United States has not experienced the extreme and rapid warming associated with anthropogenic forcing, partly because the availability of moisture cools the region (Portmann et al. 2009); however, evidence suggests that climate change is affecting the climate of the Southeast. The diurnal temperature range for most areas in the Southeast has been decreasing since 1948, with a warming of extreme minimum temperatures and cooling of extreme maximum temperatures (Powell and Keim 2015). Extreme precipitation events have increased in frequency, magnitude, and intensity in the past half-century, and winters in the Southeast have fewer extreme cold days and snowstorms (Ingram et al. 2013, Francis and Vavrus 2015, Powell and Keim 2015).

Many studies link the vanishing cryosphere to extreme mid-latitude weather (Francis and Vavrus 2012, Wang et al. 2013, Tang et al. 2013, Cohen et al. 2014, Francis and Vavrus 2015). The lessening of the thermal gradient between the poles and the tropics is weakening the jet stream, causing it to slow and take a meandering path (Cohen et al. 2014, Francis and Vavrus 2015, Ballinger and Sheridan 2015). This meandering path is characterized by a flow with a higher amplitude trajectory that results in a “blocking” or stalling pattern (Francis and Vavrus 2012). Blocking creates stagnation events, which have been described in three ways: (1) times of light low-level winds produced by a stable lower atmosphere that does not allow for horizontal or vertical dispersion; (2) times of light upper-level winds corresponding to persistent or

slow-moving warm air cores associated with high-pressure systems; and (3) when a lack of precipitation causes air-borne particulates to remain in the atmosphere (Horton et al. 2012).

The changes in mid-latitude circulation are affecting the frequency of air mass transition days in the United States. An air mass transition day is a day of atmospheric instability that occurs as one air mass shifts to another. Over the last 50 years in the United States, the number of air mass transition days has declined, resulting from a change in the synoptic flow (Knight et al. 2008, Hondula and Davis 2010, Vanos and Cakmak 2014). This decline may indicate an overall trend toward fewer frontal passages (Knight et al. 2008). Consequently, stagnation days are expected to increase by 12–25% in the eastern United States through this century, with the largest change occurring in the autumn and winter seasons (Horton et al. 2012). Stagnation affects people by contributing to poor air quality and producing life-threatening meteorological conditions as oppressive air masses persist. Ozone and particulate matter concentrations increase as air stagnation increases because, without winds or precipitation, the atmospheric particulates cannot escape the region (Horton et al. 2012). Stagnant air masses are also linked to extreme weather (e.g., cold spells, storms, heat waves, and droughts) (Francis and Vavrus 2015). Through the end of the 21st century, the southern Appalachian region is expected to experience an increase in the number of annual extreme precipitation events, extreme summer heat events and extreme winter weather events, all of which could be devastating for the region (Cohen et al. 2013, Ingram et al. 2013, Tang et al. 2013).

An understanding of past, present, and potential future air mass trends can unlock critical information for human health and environmental stability. Studies that evaluated changing air mass trends in the United States have expanded greatly within the past five years because understanding such trends is an important and pressing topic. This study uses air mass data from the Spatial Synoptic Classification (SSC) because of its wide acceptance among climate scientists as a viable system for characterizing air masses, especially for research on synoptic climatology, air quality, plant growth, and human health (Hondula et al. 2013). The SSC has been used in more than 75 publications as of 2015. The SSC provides a daily air mass type for locations across the United States and other parts of the world by characterizing air masses by moisture content and temperature. Analyzing the frequency trends of the air mass types should provide more information about the effects of climate change, especially when coupled with meteorological observations (Knight et al. 2008, Hondula and Davis 2010).

Objectives and Research Questions

This work provides a regional analysis of air mass frequencies, trends, and stagnation for the southern Appalachian region. Special attention was paid to potentially life-threatening air mass types as defined by the SSC. These potentially oppressive air mass types are identified as Dry Polar, Moist Tropical, Moist Tropical Plus, and Moist Tropical Double Plus (Sheridan 2002). These air masses can be associated with extreme cold or heat, and are especially dangerous when they persist for several days. The study region is the southern Appalachian Mountains and foothills, with a particular emphasis on Great Smoky Mountains National Park (GSMNP). No previous study had been conducted for this region at this scale, only for the broader Southeast region. The

objective of this work is to assess the temporal and spatial patterns of air mass frequencies, trends, and stagnation for the southern Appalachian region from 1965–2014. Special attention will be paid to potentially life-threatening air mass types. The work is centered around three main questions:

Question 1

What is the frequency of each air mass type observed in the southern Appalachian region?

Question 2

Are the frequencies of air masses in the southern Appalachian region changing over time?

Question 3

Are the durations of potentially oppressive air masses changing over time in the southern Appalachian region?

CHAPTER TWO
LITERATURE REVIEW

2.1 Arctic Amplification

One effect of anthropogenic greenhouse-gas forcing is Arctic amplification, the phenomenon of the polar region warming twice as fast as the mid-latitudes (Cohen et al. 2014). This is phenomenon is perpetuated by a strong feedback loop—Arctic amplification is both an outcome of and an instigator behind Arctic sea-ice loss (Cohen et al. 2014). Sea ice cover for the month of September, the culmination of the summer melt season, has declined 12.4% every decade since 1979, exposing ocean waters that have a lower albedo than snow or ice (Cohen et al. 2014). The ocean absorbs more radiant energy, causing a 4–5 °C increase in sea surface temperature (Francis and Vavrus 2015). Additionally, the melt season for sea ice is expanding. Satellite imagery since 1970 shows that melt occurs earlier and the onset of sea ice occurs later in the year (Ballinger and Sheridan 2015). Delayed sea-ice cover in the Arctic corresponds to warmer, more humid air masses present over the Arctic and nearby continents, and the lower troposphere is especially warmer in autumn (Cohen et al. 2014, Ballinger and Sheridan 2015). A warmer lower troposphere disturbs the traditional temperature gradient, decreasing the pressure difference between the high and middle latitudes (Ballinger and Sheridan 2015).

2.2 Changes in the Jet Stream

The jet stream is a fast, narrow current of westerly winds in the upper troposphere that influences storm development in the mid-latitudes (Archer and

Caldeira 2008). Arctic amplification may be changing the jet stream in two ways. First, it may be increasing the north-south amplitude of the jet stream flow, causing deeper ridges and troughs (Francis and Vavrus 2012, Cohen et al. 2014). A slower, more exaggerated meridional (i.e., north-south) flow will make instances of “blocking” more likely, causing weather patterns to persist in a given region (Francis and Vavrus 2015). This is a concern because persistent weather patterns cause more extreme weather events, especially in the mid-latitudes (Francis and Vavrus 2015). Additionally, the increased meridional flow allows cold polar air to reach increasingly lower latitudes more frequently (Cohen et al. 2013). This was exemplified recently when the Arctic experienced record-low sea ice coverage in September 2012, and the mid-latitudes, including the southern Appalachians, experienced a severe winter (Cohen et al. 2013). The second way Arctic amplification affects the jet stream is by decreasing upper-level wind speeds (Cohen et al. 2014). Slower jet stream movement also favors persistent weather patterns. Since 1979, the jet stream has weakened, shifted to a higher altitude, and moved poleward (Archer and Caldeira 2008, Horton et al. 2012).

2.3 Air Masses

An air mass is a large volume of air with relatively homogenous characteristics (e.g. temperature, humidity, cloud cover) that occurs over large geographic regions and persists for several days (Hanna et al. 2011). The SSC was developed by Larry Kalkstein and Scott Greene in the mid-1990s, with a newer version now maintained by Scott Sheridan. The system uses an algorithm that categorizes daily weather data to identify the following six air masses: Dry Polar (DP), Dry Moderate (DM), Dry Tropical (DT), Moist Polar (MP), Moist Moderate (MM), and Moist Tropical (MT) (Sheridan 2002).

Additionally, the transition category (TR) marks a day when one air mass replaces another, such as when warm or cold frontal passages move into the region (Hondula and Davis 2010). Moist Tropical Plus (MT+), Moist Tropical Double Plus (MT++), and Dry Tropical Plus (DT+) are sub-categories for extreme examples of their respective parent air mass. The SSC is commonly used in applied climate research to characterize meteorological conditions in terms of air masses (Knight et al. 2008, Hanna et al. 2011). The air masses are categorized by temperature, pressure, dew point, wind velocity, and cloud cover (Sheridan 2002).

The most common air mass type in the southern Appalachian region is DM, which is present through the year and dries and warms as it passes from west to east over the mountain range (Hanna et al. 2011). The most oppressive air masses for the region include DP, MT, MT+, and MT++. The DP is associated with very cold temperatures and dry conditions (Hanna et al. 2011). The MT, MT+, and MT++ are especially dangerous for people because they produce oppressive warm, humid conditions (Hondula et al. 2013).

2.4 Air Mass Trends

The jet stream controls the presence of mid-latitude air masses, thus it is reasonable to expect changes in air mass trends with changes in the jet stream. Some air mass frequencies in the contiguous United States have changed significantly since 1948, with increases in moist, warm air masses and decreases in cold, dry air masses (Knight et al. 2008). In this same period, moist tropical air mass days in the summer months increased significantly (Knight et al. 2008). Similar results were observed in

Canada, where moist, warm air masses have significantly increased in the summer, and cold, dry air mass frequency has decreased (Vanos and Cakmak 2014).

Not only have changes in air mass frequency been observed, but the duration of these air masses also appears to be changing. In the past 50 years, air mass transition days have declined (Hondula and Davis 2010, Tang et al. 2013). Frontal passages have weakened because of increasing moisture content in the driest polar air masses and a poleward shift of the circumpolar vortex in the western United States (Hondula and Davis 2010, Tang et al. 2013). Winter months show the most significant decline in the frequency of transition days, especially in the Rocky Mountains (Hondula and Davis 2010). Declining transition days indicate that stagnation is increasing. Through this century, stagnation days are expected to increase 12–25%, or three to 18 days per year in the eastern United States, with autumn and winter being the most stagnant seasons (Horton et al. 2012).

In stagnant air mass conditions, weather patterns are more likely to persist in any given mid-latitude region (Francis and Vavrus 2015). This will likely lead to more frequent extreme weather events such as droughts, floods, heat waves, stormy periods, and cold spells (Francis and Vavrus 2015). Understanding trends in stagnation is key to meeting future clean air objectives because more stringent regulations will be needed to offset the increase of stagnation and the resulting poor air quality (Horton et al. 2012).

2.5 Human Impacts

Located in the southern Appalachians, GSMNP is the most visited national park in the United States with more than nine million visitors per year (Souza et al. 2006). With air quality and scenic views compromised by stagnation days, visitor health and

enjoyment are at risk. An increase in air mass stagnation could have devastating effects on the visitors and residents of this region.

Oppressive air masses bring winter storms, heat, and humidity to an area, and affect human health, especially the health of those unable to acclimatize or seek proper shelter. For example, early-season heat waves, generated by stagnant DT and MT+ air masses in particular, increase mortality dramatically when populations cannot acclimatize (Vanos and Cakmak 2014). Heat syncope, cramps, exhaustion, and stroke may also occur (Vanos and Cakmak 2014). The southern Appalachian region is inhabited by a rather vulnerable population. As of 1980, only about 43% of homes in the Appalachian region had some form of air conditioning (Black et al. 2007). This is a concern because the Southeast is expected to have more heat waves this century (Ingram et al. 2013). The frequency of maximum temperatures exceeding 35 °C is expected to increase, and these conditions are expected to persist for longer periods. Ingram et al. (2013) predicts a 97 to 207% increase in consecutive days of 35 °C or higher, constituting more heat waves.

Persistent oppressive air masses pose a threat to human health and wellness, especially when they coincide with high levels of air pollution (Hondula et al. 2013, Vanos and Cakmak 2014). Stagnant air conditions contribute to poor air quality (Horton et al. 2012). Ambient air quality is largely influenced by weather. Wind determines where emissions disperse, and cloud cover determines radiation intensity which, along with temperature and humidity, promotes chemical reactions of air pollutants (Yuval et al. 2012). For example, ozone is a primary health concern related to air masses. Ozone is elevated in North Carolina under DT, DM, and MT air masses and is linked to

cardiovascular and respiratory morbidity and mortality (Hanna et al. 2011). Hospital admissions for asthma and myocardial infections increase when these air masses are present (Hanna et al. 2011). Oppressive air masses of heat and high humidity, such as the MT+ and DT air masses, can cause mortality and morbidity, especially when they persist (Hondula et al. 2013, Vanos and Cakmak 2014).

2.6 Effects of Extreme Weather on the Natural Environment

In the past 20 years, the frequency of extreme precipitation events has increased in the Southeast (Ingram et al. 2013), and the annual number of extreme precipitation events is expected to increase in the next half-century for the southern Appalachian region (Wang et al. 2013). At the same time, the Southeast is also projected to experience more frequent, more intense droughts (Ingram et al. 2013). Mean annual temperatures in the Southeast inland areas could rise as much as 4.4 °C by the end of this century (Ingram et al. 2013). The freeze-free season is expected to expand 30 days by the mid-century (Ingram et al. 2013).

The frequency and intensity of extreme weather events affect the natural environment through various means (Francis and Vavrus 2012). In the southern Appalachian region, aquatic systems may be the most vulnerable natural system to climate change (Ingram et al. 2013). An increased frequency of warm air masses at the expense of cold air masses is projected to increase the number and scope of non-native, invasive species that have a broader environmental tolerance than native species (Ingram et al. 2013). Extreme heat waves in the southern Appalachian region cause stress for native trout because the trout suffer near their upper thermal limits and from a decrease in dissolved oxygen concentrations (Ingram et al. 2013). Rare

ecosystems such as Appalachian bogs may be negatively affected and should be considered in future climate change assessments (Ingram et al. 2013).

Long-term trends of warming waters and extreme rainfall, or lack thereof, will likely alter both aquatic and terrestrial ecosystems (Ingram et al. 2013). Extreme rainfall events can contribute to accelerated erosion (Ingram et al. 2013). Droughts may affect forest ecosystem dynamics by altering competition among tree species, shifting dominant species types, increasing tree vulnerability to disease and pests, and increasing tree mortality (Klos et al. 2009). A lack of regular precipitation can contribute to atmospheric deposition and air quality issues. Some species will not be able to adapt to a rapidly changing climate, and the National Park Service is specifically concerned about ozone impacts on plants in the parks (Neufeld et al. 2000). Acid rain, as well as gaseous pollutants such as ozone, threatens the abundance and diversity of flora and fauna at GSMNP. Ozone levels doubled here between 1990 and 1999, despite the national average decreasing (Souza et al. 2006). Over 95 species of plants show signs of ozone damage, including tall milkweed (Neufeld et al. 2000, Souza et al. 2006). With over 18,000 species of organisms within the park borders (*Smokies Species Tally* 2015), this brief list of possible impacts barely breaks the surface.

CHAPTER THREE
DATA AND METHODS

3.1 Data

The air mass data were obtained from the SSC, which categorizes air masses using surface-based meteorological data (Sheridan 2002). This system was originally developed by Larry Kalkstein and Scott Greene in the mid-1990s (Sheridan 2002). Climatologist Scott Sheridan of the Department of Geography at Kent State University improved the SSC in 2002, creating the SSC2, which is referred to as simply the "SSC" (Sheridan 2002). The revised SSC accounts for seasonality by incorporating sliding seed days, which more accurately represent the meteorological criteria of a particular type as it varies by season (Sheridan 2002, Knight et al. 2008). These sliding seed days keep the context of the season when defining the algorithm for each air mass type (Sheridan 2002). Therefore, an MT air mass in the summer does not have the same characteristics as an MT air mass in the winter, for example. Algorithms are built around data recorded over two-week periods four times a year, at the hottest, coldest points as well as two midway points in the year (Sheridan 2002).

The SSC system is technically a weather-typing system and does not directly assess synoptic air mass movement; however, correlations are strong between the ground-level readings and upper-level activity (Sheridan 2002). The SSC determines the daily air mass for a given region using weather observations made four times daily, specifically temperature, dew point, wind, pressure, and cloud cover (Sheridan 2002).

The study area of this project is the southern Appalachian region, defined by the four closest SSC stations to GSMNP. I obtained daily SSC data from 1965 to 2014 for

the four airports that service the southern Appalachian region (Figure 3.1): Asheville, North Carolina (AVL), Chattanooga, Tennessee (CHA), Knoxville, Tennessee (TYS), and the Tennessee Tri-Cities, including Kingsport, Bristol, and Johnson City (TRI).

3.2 Methods

3.2.1 Question 1

What is the frequency of each air mass type observed in the southern Appalachian region for the period 1965 to 2014?

I hypothesized that, being in a temperate climate, all stations would present a slightly higher frequency of warm, moist air mass types and a slightly lower frequency of cool, dry air mass types.

I used descriptive statistics to provide preliminary information about air mass frequencies for Asheville (AVL), Chattanooga (CHA), Knoxville (TYS), and the Tennessee Tri-Cities (TRI) for 1965–2014 (1966–2014 for AVL, because of missing data in 1965). Mean annual frequency and mean seasonal comparisons were assessed for each type. Seasons are defined by months as follows: spring as March, April, and May (MAM); summer as June, July, and August (JJA); fall as September, October, and November (SON); and winter as December, January, and February (DJF).

3.2.2 Question 2

Are the frequencies of air masses in the southern Appalachian region changing over time?

I hypothesized that, in the southern Appalachian region, the mean annual frequency of TR days has significantly decreased, cold and dry days have decreased,

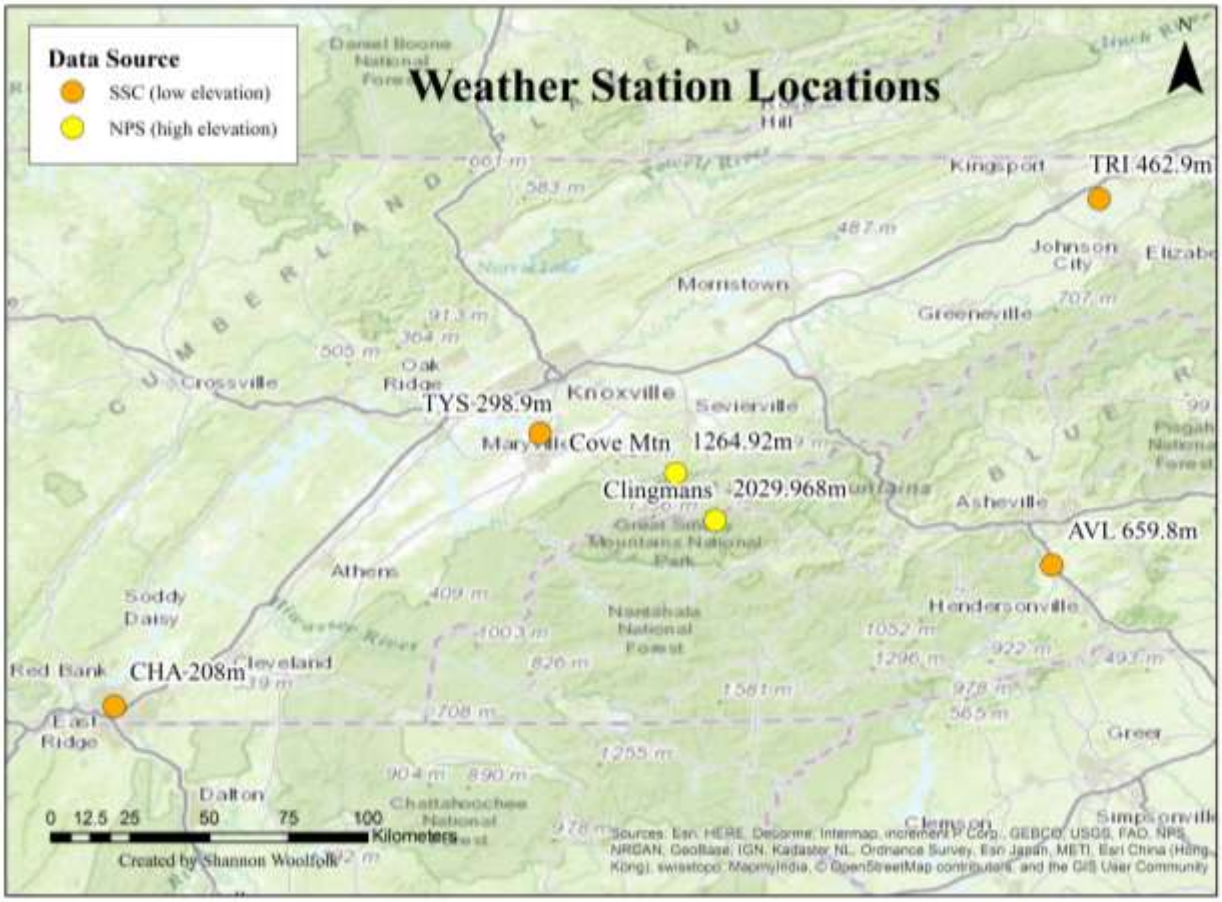

Figure 3.1 The low-elevation airport weather stations AVL, CHA, TRI, and TYS record hourly meteorological data used by the SSC. Two high-elevation weather stations exist in the study area (Cove Mountain and Clingmans Dome) and record daily weather observations; however, SSC data are not available here.

and moist and warm days have increased significantly.

I used R-Studio to conduct a generalized linear regression model using time as the independent variable and air mass frequency as the dependent variable for each air mass type to determine if air mass frequency is changing over time. I used Poisson methods of statistics because air mass occurrences are count data. The annual frequency trend, using the total number of times a particular type was present in one calendar year, was calculated for each air mass type at each data station for the years 1965–2014. The seasonal frequency trend identified any changes in frequency of a particular type over the 50 years during a specific season. Analyzing seasonal trends was particularly important in the cases of oppressive air mass types because oppressive types are typically only life-threatening in their dominant seasons. For example, DP air masses are most oppressive in the winter months, so the DP trend for the months of December, January, and February (DJF) were considered. Seasonal trends in MT types were analyzed for the summer months of June, July, and August (JJA).

In all cases, the null hypothesis states that the slope of the regression line is zero. The alternate hypothesis is that the slope of the regression line differs from zero. If the slope differs significantly ($p < = 0.05$) from zero, this indicates that frequencies of oppressive air mass types in this region have significantly changed (increased or decreased) since 1965.

3.2.3 Question 3

Are the durations of oppressive air masses changing over time in the southern Appalachian region?

I hypothesized that stagnation frequency and duration has increased for oppressive air mass types in the southern Appalachian region over the past 50 years.

The stagnation duration (i.e., number of consecutive days) and stagnation frequency (i.e., regularity of occurrence) for the oppressive air mass types Dry Polar, Moist Tropical, Moist Tropical Plus, and Moist Tropical Double Plus was tabulated per decade for the four stations AVL, CHA, TYS, and TRI from 1965–2014. In this study, a stagnation event is identified as the presence of the same air mass for two or more consecutive days. Stagnation frequency is a count of the number of stagnation events per decade. Stagnation duration is the mean length of days in a stagnation event per each decade. Seasonality was considered because air masses are not oppressive when warm (cold) air masses are present in the winter (summer). I analyzed air mass stagnation (persistence) using simple decadal descriptive statistics. No notable variability was observed, so no further analysis was conducted.

CHAPTER FOUR
RESULTS

4.1 Air Mass Frequencies

4.1.1 Annual Frequencies

At the Asheville location, Dry Moderate is the most common air mass type annually and the most variable year to year (Table 4.1). Averaging 31% of days in a year, it accounts for nearly twice as many days as the second most common type, Moist Moderate. All three dry air mass types (DM, DP, and DT) together account for an average of 50% of days annually, whereas the total percentage of all moist air mass types (MM, MP, MT, MT+, and MT++) together is 42%. Transition days make up the remaining 8%. Potentially oppressive air mass types (DP, MT, MT+, and MT++) are present one-third of the year, on average. Among the four stations, Dry Polar has the strongest presence in Asheville, and Moist Tropical has the weakest presence in Asheville.

At the Chattanooga location, Dry Moderate was also the most common air mass type, and was observed nearly 31% of days during the 50 study years (Table 4.1). All dry air mass types in Chattanooga account for 50.2% of annual days on average. The Moist Tropical and Moist Moderate air masses are the second and third most common types in Chattanooga, respectively. These air masses, along with the other moist air mass types, account for 42.3% of annual days. Potentially oppressive types constitute 33.3% of days in the year on average. Moist Tropical has the strongest presence in Chattanooga (18.5%), while Dry Polar has the weakest presence (11.3%) among the four stations. MT+ accounts for 3.5% of mean annual oppressive days.

Table 4.1 The mean annual frequency, standard deviation, and percent distribution of SSC types (1965–2014) for four locations in the southern Appalachian region.

	AVL			**CHA**			**TRI**			**TYS**		
Air Mass Type	**Mean**	**SD**	**%**	**Mean**	**SD**	**%**	**Mean**	**SD**	**%**	**Mean**	**SD**	**%**
DM	111.7	19.1	31.4	111.4	16.7	30.6	111.8	14.1	30.7	104.2	15.8	28.7
DP	53.0	13.3	14.9	41.1	10.8	11.3	49.5	12.0	13.6	46.1	11.5	12.7
DT	14.2	5.8	4.0	30.1	19.4	8.3	20.1	8.9	5.5	18.6	11.8	5.1
MM	60.0	16.6	16.9	48.7	12.5	13.4	60.4	13.9	16.6	62.7	14.6	17.3
MP	30.7	9.1	8.6	25.2	9.2	6.9	27.6	8.6	7.6	24.6	8.2	6.8
MT	52.2	13.0	14.7	67.5	15.5	18.5	58.0	13.3	15.9	64.2	12.0	17.7
MT+	6.5	4.3	1.8	12.6	7.5	3.5	5.8	4.0	1.6	11.6	6.2	3.2
MT++	0.0	0.2	0.0	0.2	0.5	0.0	0.0	NA	0.0	0.3	0.9	0.1
TR	27.5	7.5	7.7	27.2	6.8	7.5	30.7	6.4	8.4	30.6	6.9	8.4

At the Tri-Cities location, Dry Moderate was observed 30.7% of days during 50-year study period and was the most variable air mass type year to year (Table 4.1). The second most common air mass in TRI is Moist Moderate at 16.6% of days. Dry air masses average 49.8% days of a year, and all moist air mass types average 41.7% days of a year. Potentially oppressive types constitute 31.1% of days in the year on average. DP is present 13.6% of days, MT is present 15.9% of days, and MT+ accounts for 1.6% of days in a year.

The Knoxville location observed Dry Moderate an average of 28.7% of annual days during the 50-year study period, and Dry Moderate was the most variable of all air mass types (Table 4.1). Dry air mass types are present 46.5% of days annually. The Moist Tropical and Moist Moderate air masses are the second and third most common types, respectively, both appearing nearly 18% of days. In total, moist air mass types are present 45.1% of annual days. Transition days account for the remaining 8.4%. Potentially oppressive types constitute 33.7% of days in the year on average.
Of the four locations in this study, MT++ occurred most frequently in Knoxville (0.1% of annual days).

4.1.2 Seasonality

At the Asheville location, Dry Moderate is the most common air mass type and is fairly evenly distributed through the year, showing little seasonality (Table 4.2). Dry Polar is most frequent in winter and has low summer frequency. Dry Tropical, a rare air mass for the region, shows strong seasonality and is most common in spring.

The most common moist air mass in Asheville, Moist Moderate, is twice as common in the summer than any other season (Table 4.2). This is the same for the

Table 4.2 The mean seasonal frequency and percent distribution of SSC types (1965–2014) for AVL.

	MAM		**JJA**		**SON**		**DJF**	
Air Mass Type	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**
DM	29.5	26.3	26.0	23.3	30.6	27.4	25.6	22.9
DP	13.1	24.7	5.1	9.6	15.0	28.3	19.8	37.4
DT	6.3	44.3	1.1	7.9	3.1	22.0	3.7	25.9
MM	13.2	22.0	24.1	40.1	13.6	22.6	9.1	15.2
MP	6.3	20.4	2.2	7.3	7.2	23.5	15.0	48.9
MT	11.5	22.0	26.5	50.8	10.7	20.4	3.5	6.7
MT+	2.3	36.4	1.2	18.8	0.9	14.6	1.9	30.3
MT++	NA	NA	0.04	100%	NA	NA	NA	NA
TR	7.7	27.8	3.1	11.3	7.6	27.5	9.2	33.4

Moist Tropical air mass. Moist Tropical has the strongest seasonal preference of all of the air mass types recorded in Asheville. Meanwhile, nearly half of Moist Polar occurrences are in the winter.

From a seasonal perspective, Asheville is dominated by Dry Moderate air masses for all seasons except summer, during which Moist Tropical is slightly more frequent (Table 4.2). Transition days in Asheville are fairly evenly distributed through spring, fall, and winter, and less frequent in the summer.

At the Chattanooga location, the most common air mass type is not as evenly distributed. Dry Moderate most often occurs in the fall and is less frequent in summer (Table 4.3). Dry Polar is most frequent in winter and has low summer frequency. Dry Tropical is most frequent in spring.

The moist air mass Moist Moderate is fairly evenly distributed through spring, fall, and winter (Table 4.3). Moist Moderate is most frequent at Chattanooga in summer. Moist Polar, a rare air mass type for the site, occurs in winter twice as often as any other season. Moist Polar experiences great seasonality, with over half of its mean annual days occurring in winter. Moist Polar is least frequent in summer. Moist Tropical, a common air mass in Chattanooga, has strong seasonality, with over half of its mean annual days occurring during summer. MT+ is most frequent in spring but occurs almost as frequently in summer. MT+ is not common in fall and winter. MT++ has only occurred nine times in the 50-year study span in Chattanooga, all occurring in the spring and summer.

A seasonal perspective emphasizes that Dry Moderate air masses are dominant in every season except summer in Chattanooga (Table 4.3). Summer is largely

Table 4.3 The mean seasonal frequency and percent distribution of SSC types (1965–2014) for CHA.

	MAM		JJA		SON		DJF	
Air Mass Type	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**
DM	27.5	24.7	22.7	20.4	34.3	30.8	26.9	24.1
DP	9.7	23.6	1.2	3.0	11.4	27.7	18.8	45.8
DT	12.5	41.7	7.5	25.0	5.7	18.8	4.4	14.5
MM	11.5	23.7	15.5	31.8	11.6	23.9	10.1	20.6
MP	5.0	20.0	1.1	4.5	5.6	22.3	13.4	53.3
MT	12.6	18.6	35.9	53.3	13.9	20.6	5.1	7.5
MT+	5.0	39.4	4.1	32.4	1.3	10.7	2.2	17.5
MT++	0.1	33.3	0.1	66.6	NA	NA	NA	NA
TR	7.7	28.3	3.4	12.5	7.1	26.0	9.0	33.2

characterized by Moist Tropical air masses. Transition days are most frequent in winter and also frequent in spring and fall. Transition days have a low frequency in summer.

Dry Moderate, the most common air mass type in the Tri-Cities, occurs most frequently in fall, but it is fairly frequent through the year (Table 4.4). Dry Polar is most frequent in winter and least frequent in summer. Dry Tropical, a rare air mass type for the region, has a strong seasonality and is most frequent in spring. Nearly half of the mean annual Dry Tropical days occur in spring.

Moist Moderate, the second-most common air mass type in the Tri-Cities, is most frequent in summer with strong seasonality, because 42.4% of Moist Moderate mean annual days occurred in summer (Table 4.4). MT, the third most frequent type in TRI, has an even stronger seasonality with 48.9% of its mean annual days occurring in summer. MT+ is most frequent in spring, followed by winter, summer, and fall.

Seasonally, spring and fall in the Tri-Cities is notably dominated by Dry Moderate which occurs twice as frequently as any other air mass type (Table 4.4). In summer, Dry Moderate, Moist Moderate, and Moist Tropical have similar frequencies. Winter is also dominated by Dry Moderate, but Dry Polar is a close second. Transition days are fairly frequent in all seasons except summer, which has less frequency. On average, roughly nine transition days occur per spring, fall, and winter, whereas only 2.68 days per summer.

At the Knoxville station, Dry Moderate, the most common air mass type, is most frequent in fall (Table 4.5). Summer experiences the lowest frequency of Dry Moderate. Dry Polar is most frequent in winter. Summer has the lowest frequency of Dry Polar. Dry Tropical, a rare air mass type for the region, is most frequent in spring.

Table 4.4 The mean seasonal frequency and percent distribution of SSC types (1965–2014) for TRI.

	MAM		JJA		SON		DJF	
Air Mass Type	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**
DM	26.6	23.8	26.0	23.3	33.8	30.2	25.5	22.9
DP	11.4	23.0	4.7	9.5	14.0	28.2	19.4	39.2
DT	10.0	49.9	1.8	8.8	5.0	24.8	3.3	16.6
MM	11.9	19.7	25.6	42.4	12.3	20.3	10.6	17.6
MP	7.0	25.4	1.3	4.6	5.5	20.1	13.7	49.6
MT	13.3	23.0	28.4	48.9	11.3	19.4	5.1	8.7
MT+	2.4	41.6	1.2	20.6	0.6	10.6	1.6	27.2
MT++	NA	NA	0.02	100%	NA	NA	NA	NA
TR	9.1	29.5	2.7	8.7	8.3	26.8	10.7	34.9

Table 4.5 The mean seasonal frequency and percent distribution of SSC types (1965–2014) for TYS.

	MAM		JJA		SON		DJF	
Air Mass Type	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**	**Mean**	**%**
DM	25.2	24.2	20.6	19.8	32.6	31.2	25.8	24.8
DP	12.0	26.1	2.9	6.4	11.7	25.4	19.5	42.2
DT	7.9	42.8	3.6	19.3	4.2	22.8	2.8	15.1
MM	13.2	21.0	20.7	33.1	14.8	23.7	13.9	22.2
MP	5.9	24.0	1.1	4.4	5.5	22.4	12.1	49.2
MT	13.1	20.5	34.2	53.2	13.0	20.2	3.9	6.1
MT+	3.3	28.4	4.8	41.7	1.7	14.4	1.8	15.6
MT++	NA	NA	0.3	100.0	NA	NA	NA	NA
TR	9.6	31.3	3.6	11.6	7.3	23.9	10.2	33.2

Moist Moderate, the third most common air mass type present in Knoxville, is most frequent in summer (Table 4.5). The lowest frequency of Moist Moderate is in spring. Moist Polar has a high winter frequency. Meanwhile, Moist Tropical, the second most common air mass type at TYS, has a strong seasonal preference for the summer. MT+ days at TYS most frequently occur in summer. The MT++ air mass has been recorded 17 times in the 50-year study period. TYS has the greatest frequency of MT++, and 100% of those days occurred in summer.

Spring and fall in Knoxville are dominated by Dry Moderate air masses, the frequency of which is nearly double that of the second most frequent air mass type, Moist Moderate (Table 4.5). The summer season is dominated by Moist Tropical. Moist Tropical air masses are present 34.2 days of summer on average, followed by Moist Moderate and Dry Moderate. Winter months are also predominated by Dry Moderate air masses. The highest mean seasonal frequencies for transition days occur in winter, but the highest average monthly frequency of transition days is in March.

4.2 Frequency Trends

At the Asheville location, the mean annual frequencies of five air mass types have significantly changed over time (Table 4.6). Dry Moderate and Dry Tropical have significantly increased in frequency over the 50 year study period. Dry Polar, Moist Moderate, and Moist Polar as well as transition days are decreasing in frequency over time. Changes in mean annual frequencies of Moist Tropical types (MT, MT+, and MT++) are not significant, nor is the trend in summer seasonal frequency significant. The seasonal frequency trend of Dry Polar in winter is also not significant.

Table 4.6 Trends of mean annual frequencies of SSC types (1965–2014) for AVL.

Air Mass Type	**Slope**	**Std. Error**	**Significance**
DM	0.0078	0.001	<0.01
DP	–0.0051	0.001	<0.01
DT	0.0067	0.003	0.01
MM	–0.0097	0.001	<0.01
MP	–0.0070	0.002	<0.01
MT	0.0020	0.001	0.14
MT+	0.0005	0.004	0.90
MT++	–0.0460	0.056	0.41
TR	–0.0059	0.002	<0.01

At the Chattanooga location, the mean annual frequencies of seven air mass types have significantly changed over time (Table 4.7). Dry Tropical, Moist Tropical, and MT+ mean annual days are becoming more common over time. The seasonal frequency trend for Moist Tropical types in the summer is also significant. Dry Polar, Moist Moderate, and Moist Polar mean annual frequency is decreasing. The seasonal frequency trend for Dry Polar in winter is also significant. Transition days and Dry Moderate air masses have also decreased in frequency. Of the significantly trending types at Chattanooga, Dry Tropical has changed the most dramatically. The least dramatic change occurred with Dry Moderate.

At the Tri-Cities location, the mean annual frequencies of only four air mass types have significantly changed over time (Table 4.8). Dry Moderate is trending positively, as well as Dry Tropical. While mean annual days of Moist Tropical types have not changed significantly, mean summer days of Moist Tropical types have increased significantly. Mean annual Dry Polar days have significantly declined, and Moist Moderate days have declined as well. Mean winter days of Dry Polar have also significantly declined. Of the significant types at the Tri-Cities, the most dramatic change in mean annual days occurred with Dry Tropical. The least dramatic change occurred in Dry Moderate.

Table 4.7 Trends of mean annual frequencies of SSC types (1965–2014) for CHA.

Air Mass Type	Slope	Std. Error	Significance
DM	–0.0021	0.001	0.02
DP	–0.0106	0.002	<0.01
DT	0.0276	0.002	<0.01
MM	–0.0059	0.001	<0.01
MP	–0.0102	0.002	<0.01
MT	0.0044	0.001	<0.01
MT+	0.0136	0.003	<0.01
MT++	–0.0148	0.023	0.53
TR	–0.0052	0.002	0.01

Table 4.8 Trends of mean annual frequencies of SSC types (1965–2014) for TRI.

Air Mass Type	Slope	Std. Error	Significance
DM	0.0022	0.001	0.02
DP	–0.0069	0.001	<0.01
DT	0.0122	0.002	<0.01
MM	–0.0029	0.001	0.02
MP	–0.0020	0.002	0.29
MT	0.0008	0.001	0.52
MT+	0.0058	0.004	0.16
MT++	NA		
TR	–0.0032	0.002	0.07

At the Knoxville location, the mean annual frequencies of only four air mass types have changed significantly (Table 4.9). Dry Moderate and Dry Tropical frequencies are increasing, whereas Dry Polar and Moist Moderate frequencies are decreasing in mean annual counts. Dry Polar is also decreasing in mean winter frequency. Of the significant types at TYS, Dry Tropical experienced the greatest change in the annual frequency and Dry Moderate experienced the least.

Overall, the Dry Tropical air mass changed the most with a significant increase in number of annual days. Dry Tropical has the greatest absolute slope among all air mass types and transition days at three out of four stations.

4.3 Stagnation

The stagnation frequency of the Dry Polar air mass type in Asheville in winter has undulated through the five decades of the study period, ranging from 50 to 65 events per decade, with an overall net increase of 12 events (Table 4.10). The mean duration of these stagnation events ranged from 2.8 to 3.0 days, and has not notably changed, with a net increase of 0.018 days. The stagnation frequency of the Moist Tropical air mass types in Asheville in summer is similar across the decades, ranging from 56 to 68 events, with an overall net increase of 9 events. The four most recent decades show there may be a slight decreasing trend. The mean duration of these stagnation events is also very similar, ranging from 3.1 to 3.4 days with a net increase of 0.3 days.

At the Chattanooga location, the frequency of Dry Polar air mass stagnation events in winter has ranged from 46 to 63 events per decade with an overall net decrease of 11 events (Table 4.11). The mean duration of these events has remained relatively steady and ranges from approximately 2.6 to 2.8 days, with a net decrease

Table 4.9 Trends of mean annual frequencies of SSC types (1965–2014) for TYS.

Air Mass Type	Slope	Std. Error	Significance
DM	0.0030	0.001	<0.01
DP	–0.0068	0.001	<0.01
DT	0.0177	0.002	<0.01
MM	–0.0050	0.001	<0.01
MP	–0.0028	0.002	0.16
MT	–0.0011	0.001	0.39
MT+	0.0045	0.003	0.12
MT++	0.0084	0.017	0.62
TR	0.0002	0.002	0.93

Table 4.10 Seasonal stagnation event frequency (number of events per decade) and mean duration (number of days) for the potentially oppressive SSC types DP and MT, MT+, and MT++, 1965–2014 at AVL.

	Decade	1965–1974	1975–1984	1985–1994	1995–2004	2005–2014
DP	**Frequency**	51	65	52	50	63
	Duration	3.020	2.785	2.827	2.900	2.762
	Std. Dev.	1.615	1.157	1.051	1.285	1.281
	Std. Error	0.226	0.143	0.146	0.182	0.161
MT	**Frequency**	56	68	67	66	65
	Duration	3.054	3.235	3.284	3.167	3.354
	Std. Dev.	1.469	1.808	1.464	1.420	1.740
	Std. Error	0.196	0.219	0.179	0.175	0.216

Table 4.11 Seasonal stagnation event frequency (number of events per decade) and mean duration (number of days) for the potentially oppressive SSC types DP and MT, MT+, and MT++, 1965–2014 at CHA.

	Decade	**1965–1974**	**1975–1984**	**1985–1994**	**1995–2004**	**2005–2014**
DP	**Frequency**	57	63	53	46	46
	Duration	2.772	2.825	2.642	2.783	2.761
	Std. Dev.	1.155	0.968	0.892	1.020	1.025
	Std. Error	0.153	0.122	0.123	0.150	0.151
MT	**Frequency**	58	83	86	89	78
	Duration	4.069	3.807	4.570	4.371	4.590
	Std. Dev.	2.377	2.357	3.101	3.092	2.857
	Std. Error	0.312	0.259	0.334	0.328	0.324

of 0.011 days. The frequency and duration of stagnation events for Moist Tropical types have undulated through the study period. Frequency has ranged from 58 to 89 events per decade, with an overall net increase of 20 events. Duration ranges from approximately 3.8 to 4.6 days, with a net decrease of 0.481 days.

The frequency of Dry Polar air mass stagnation events at the Tri-Cities location ranges from 43 to 67 events per decade (Table 4.12). A notable, steady decrease in stagnation event frequency has occurred in the four most recent decades, and frequency has decreased by a net 19 events over the 50-year period. The change in mean duration of Dry Polar stagnation events across the decades is not dramatic and ranges from approximately 2.6 to 2.9 days, with a net gain of 0.021 days. The frequency and duration of Moist Tropical type stagnation events has undulated over the study period, with no strong trends. Frequency ranges from 61 to 76 events, with a net gain of 10 events. Duration ranges from approximately 3.2 to 3.7 days, with a net gain of 0.322 days.

The frequency and duration of Dry Polar and Moist Tropical stagnation events at the Knoxville location are not highly variable (Table 4.13). The frequency of Dry Polar stagnation events has ranged from 46 to 65 events per decade, with a net decrease of 12 events. The duration of these events has ranged from approximately 2.7 to 3.0 days with a net decrease of 0.074 days. The frequency of Moist Tropical stagnation events has ranged from 71 to 94 events, with a net decrease of 5 events. Duration of events has ranged from approximately 3.6 to 4.2 days, with a net increase of 0.564 days.

Table 4.12 Seasonal stagnation event frequency (number of events per decade) and mean duration (number of days) for the potentially oppressive SSC types DP and MT, MT+, and MT++, 1965–2014 at TRI.

	Decade	1965–1974	1975–1984	1985–1994	1995–2004	2005–2014
DP	Frequency	62	67	54	52	43
	Duration	2.677	2.940	2.574	2.558	2.698
	Std. Dev.	1.104	1.268	0.915	0.989	0.928
	Std. Error	0.140	0.155	0.125	0.137	0.142
MT	Frequency	61	67	76	70	71
	Duration	3.295	3.284	3.671	3.414	3.211
	Std. Dev.	1.986	1.619	2.191	1.517	1.735
	Std. Error	0.254	0.198	0.251	0.181	0.206

Table 4.13 Seasonal stagnation event frequency (number of events per decade) and mean duration (number of days) for the potentially oppressive SSC types DP and MT, MT+, and MT++, 1965–2014 at TYS.

	Decade	**1965–1974**	**1975–1984**	**1985–1994**	**1995–2004**	**2005–2014**
DP	**Frequency**	59	65	49	46	47
	Duration	2.797	2.738	2.878	2.957	2.723
	Std. Dev.	1.161	0.997	1.062	1.250	0.961
	Std. Error	0.151	0.124	0.152	0.184	0.140
MT	**Frequency**	76	94	89	90	71
	Duration	3.605	4.117	3.865	4.100	4.169
	Std. Dev.	2.033	2.705	2.045	2.650	2.573
	Std. Error	0.233	0.279	0.217	0.279	0.305

4.4 Results Summary

In the southern Appalachian region, moist air masses appear nearly as frequently as dry air masses. Dry Moderate air masses are prevalent through the year and dominate every season except summer, when Moist Tropical air masses are more frequent. Transition days are more frequent in winter than in summer. From 1965 to 2014, the mean annual frequency of Dry Polar and Moist Moderate air masses decreased (Table 4.14); Dry Moderate and Dry Tropical air masses increased; and Moist Polar air masses and transition days decreased in Asheville and Chattanooga. The seasonality of air masses has not significantly changed except for an increased mean seasonal frequency of Moist Tropical over Chattanooga and the Tri-Cities in the summer. There are no notable trends in the frequency or duration of air mass stagnation.

Table 4.14 Significant trends of mean annual frequencies of SSC types (1965–2014) for stations in the southern Appalachian region; Positive trends are represented by green arrows, and negative trends are represented by red arrows.

	AVL	CHA	TYS	TRI
DM	↑	↓	↑	↑
DP	↓	↓	↓	↓
DT	↑	↑	↑	↑
MM	↓	↓	↓	↓
MP	↓	↓	--	--
MT	--	↑	--	--
MT+	--	↑	--	--
MT++	--	--	--	--
TR	↓	↓	--	--

CHAPTER FIVE
DISCUSSION

5.1 Air Mass Frequencies

The four study sites (AVL, CHA, TRI, and TYS) have similar air mass climatologies. Similarities between the stations were expected, because all data stations lie in a low- to mid- elevation zone in the temperate climate of the southern Appalachian region. Though the stations share many geographic characteristics, some key differences exist between the sites.

At all four stations, Dry Moderate air masses are the most frequent annually. Dry Moderate air masses are characteristic of the temperate mountain climate (Hanna et al. 2011). These dry, moderate conditions help make the region popular for relocation and tourism (Ingram et al. 2013, Perkins 2016). Great Smoky Mountains National Park, in the heart of the southern Appalachian region, records greater than nine million visitors annually, making it the most visited national park in the United States (Souza et al. 2006).

Moist Moderate and Moist Tropical air masses are highly frequent in the region. Moist Moderate air masses are associated with cool, moist air, and Moist Tropical air masses are associated with warm, moist air (Hanna et al. 2011). This is characteristic of a temperate mountain climate, and moisture plays an important role in the mountains. The mountainous southwestern North Carolina is one of the wettest places in the Southeast and subsequently one of the most biologically diverse places in the world, which has helped earn Great Smoky Mountains National Park the titles of International Biosphere Reserve and World Heritage Site (Souza et al. 2006, Ingram et al. 2013).

Though annual air mass frequencies are largely similar among the four sites, some differences exist. This study found that, across the region Dry Polar air masses account for 11% to 15% of days in a year. These air masses, responsible for cold, dry air in the region, are slightly more frequent in Asheville and the Tri-Cities (Hanna et al. 2011). The greater frequency of Dry Polar in Asheville and the Tri-Cities may be attributed to various factors, including the higher elevations of Ashville and the Tri-Cities, the higher latitude of Tri-Cities, and the leeward location of Asheville. The leeward, or eastern side of the Appalachians typically experiences drier conditions as air dries while ascending over the mountain range (Hanna et al. 2011, Gaffin et al. 2012). These differing geographical characteristics of the stations may account for small, yet significant variations in the frequencies of other air masses including Dry Tropical, MT+, and MT++.

Though not very frequent at any of the four sites, Dry Tropical, MT+, and MT++ air masses have interesting patterns for particular locations, which supports the above notion that the slightly differing geographical characteristics account for small, yet significant variations in air mass frequencies. Dry Tropical, which is associated with dry, warm air from the Southwest (but not the Gulf of Mexico), is much more frequent in Chattanooga than at the other stations, likely because Chattanooga is southerly in latitude, low in elevation, and west of the mountains (Hanna et al. 2011). MT+ and MT++, associated with an easterly flow of extremely moist, warm air from the Gulf, are more frequent in Chattanooga and Knoxville, likely because of their low elevations and windward locations (Hanna et al. 2011). The frequencies of Dry Tropical, MT+, and MT++ are important to consider because Dry Tropical and Moist Tropical air masses

have been proven favorable for elevated levels of ozone and other conditions extremely hazardous for human health (Hanna et al. 2011, Hondula et al. 2013).

Overall, Chattanooga and Knoxville have similar annual air mass climatologies. The two have a notable frequency of moist, warm air masses. These results correspond to what might be expected from the geography of Chattanooga and Knoxville. Chattanooga, at only 208 m, is the lowest study site. Dry Tropical, one of the least likely air mass types to occur at Asheville, occurs with more frequency at Chattanooga. Moist Polar is the least common air mass, but somewhat frequent at Asheville. Asheville and the Tri-Cities have similar air mass climatologies. Asheville is the driest, coolest site. The two most frequent air mass types at Asheville include moderate temperature conditions (Dry Moderate and Moist Moderate), and the third most frequent type is Dry Polar. This distinction is likely attributable to the elevation of Asheville (660 m).

While annual air mass frequencies are helpful, understanding the effects of air masses, especially those that are potentially oppressive, only comes from assessing the seasonality of air mass frequencies. Sheridan (2002) considers Dry Polar, Moist Tropical, MT+, and MT++ to be potentially oppressive. This only holds true when they exist in their respective seasons of winter (Dry Polar) and summer (Moist Tropical, MT+, MT++). For instance, warm temperatures of a Moist Tropical air mass have a greater potential to harm human health in the summer than in the winter, because moist, tropical air is likely going to create an oppressively hot, poor air quality day in summer but a mild day in winter. The same is true for Dry Polar air, in that it may introduce oppressively cold air in winter, causing snowstorms and bitter cold, but a mild day in summer.

Though Dry Moderate is not considered an oppressive type by Sheridan (2002), Hanna et al. (2011) found that Dry Moderate air masses, like Dry Tropical and Moist Tropical, favor elevated levels of ozone in North Carolina. This is important because Dry Moderate air masses have a fairly steady, high frequency distribution through the year (Hanna et al. 2011).

In the winter, Asheville and the Tri-Cities are more likely to experience oppressive winter weather from Dry Polar air because they are located at mid-elevations and experience the coolest air masses. In the summer, Chattanooga and Knoxville are more likely to experience oppressive weather from a high frequency of Moist Tropical days, coupled with a relatively low occurrence of transition days. This is likely due to their geographical locations in the Tennessee Valley. At the Asheville and Tri-Cities locations, Moist Tropical is still dominant in the summer time, but Dry Moderate and Moist Moderate days are almost as frequent. At these higher elevation sites, roughly half of the Moist Tropical days occur in the summer, but this strong seasonality of Moist Tropical air masses is counteracted with the nearly equivocally frequent presence of Dry Moderate and Moist Moderate air mass types in the summer. Oppressive weather resulting from Moist Tropical is likely not such a concern for Asheville or Tri-Cities.

MT+ and MT++ are rare in the study area but are associated with extreme heat when they are present. At the Asheville and Tri-Cities locations, MT+ occurs most commonly in spring, and, interestingly, more commonly in winter than in the summer. At the Chattanooga location, MT+ most commonly occurs in the spring, but the summer is nearly evenly occupied by MT+ conditions. Knoxville is the only station to record MT+ at

a greater frequency in summer than the spring. The MT++ air mass has only occurred twice in Asheville in the 50 years considered in this study. MT++ has occurred nine times in Chattanooga and only in spring and summer months. A key characteristic of the Tri-Cities is the lack of MT+ and MT++ occurrences. Of the four stations, TRI had the lowest total frequency of MT++ for the 50 years, having only experienced one day of MT++ conditions. This is likely attributable to the latitude of the site. TRI is the farthest inland and farthest northward site. In Knoxville, MT++ has been recorded 17 times in 50 years, all within the summer months. This is the greatest total among the four sites, and equals more than all the totals at the other three sites combined.

Of the oppressive types, Dry Polar (Moist Tropical) air masses occur the least (most) frequently at Chattanooga when compared to the other three sites. Knoxville recorded the greatest percentage of total mean annual oppressive type days, followed closely by Chattanooga. This is largely due to the prevalence of the MT++, which has been recorded 17 times in 50 years. All of the MT++ occurrences were in the summer when transition days show the lowest mean seasonal frequency. The combination of MT++ air masses happening in the season with the lowest number of transition days is likely a formula for stagnant, oppressive weather. Therefore, it is important to consider whether these conditions are occurring more often over time.

5.2 Frequency Trends

Assessing air mass trends in the southern Appalachians is important for understanding the past and potential future climatology of the region. It is outside the scope of this project to predict future trends; however, significant trends of the past 50 years may provide insight into potential future climate changes.

In the US overall, air mass frequencies have changed significantly in the past 50 years (Hondula and Davis 2010). Similar studies in Canada have also found significant trends (Vanos and Cakmak 2014). These studies both found increasing warm, moist air masses; decreasing dry, cold air masses; and a declining frequency of transition days (Hondula and Davis 2010, Vanos and Cakmak 2014).

For the Southeast region, air mass frequency trends are less clear. Similarly, meteorological records show a great deal of precipitation and temperature variability, but no long-term trends are evident other than increased variability (Ingram et al. 2013). Models of future southeastern United States climatology produce conflicting predictions (Ingram et al. 2013). Klos et al. (2009) predicted much drier conditions, whereas Ingram et al. (2013) expected an increase in mean annual precipitation in the northern tier of the Southeast.

This study found that the southern Appalachian region has indeed experienced a changing air mass climate in the 1965–2014 study period, and that it differs from the observed continental changes. The mean annual frequencies of some air mass types have increased while others have decreased. Few air mass types have no significant trend. Overall, three data stations in the southern Appalachian region, AVL, TRI, and TYS, have experienced similar changes, while one, CHA, has experienced unique changes. More air mass types had significant trends at the Chattanooga location than at any other station.

Based on the results of this study, it appears that the southern Appalachian region has trended toward a warmer, drier climate. Across most of the region (except at CHA), Dry Moderate days have significantly increased. A study on tourism climate in

Atlanta and Indianapolis found a positive correlation between visitor attendance to zoological parks on Dry Moderate days and a negative correlation in attendance to Moist Polar days (Perkins 2016). An increasingly dry, moderate climate could bring more visitors to the Great Smoky Mountains National Park and surrounding communities. This would likely pose an economic advantage to the local communities, but an ecological disadvantage. GSMNP is already the most visited national park in the US and experiences high volumes of vehicle traffic and resource damage, such as erosion of roads and trails, due to overuse (US Department of the Interior 2008).

Vanos and Cakmak (2014) found, through their study in Canada, a significant negative correlation between Dry Moderate and Dry Polar days, where Dry Moderate days increased at the expense of Dry Polar days. Similarly, this study found that the annual frequency of Dry Moderate has increased, and the annual frequency of Dry Polar has decreased at all stations in the southern Appalachian region. The mean winter frequency of Dry Polar has significantly decreased at all stations except Asheville. A reduction in the frequency of Dry Polar may have positive implications for the region in terms of social and economic prosperity. However, the loss of colder air could significantly alter high-elevation habitats which depend on a cool climate, and invasive pests may more likely spread unabated without harsh winter conditions to stifle their growth.

Surprisingly, Dry Tropical has significantly increased at all stations. Dry Tropical had the strongest change in terms of absolute slope. Not only is this is disconcerting because drier conditions could be detrimental to the famed ecology of the region, but because Dry Tropical has been associated with heat-related mortality and damaging

storms (Sheridan 2002, Vanos and Cakmak 2014). On 30 June and 1 July 2012, a stagnant Dry Tropical air mass set record-high temperatures in southern Appalachia (Gaffin 2012). The Dry Tropical air mass, followed by a MT air mass, contributed to a powerful and historic derecho in the eastern U.S., which affected Great Smoky Mountains National Park on 5 July (Gaffin 2012). The derecho caused the blowdown of many trees, which resulted in significant injury of several park visitors, fatalities, and extended road and trail closures.

In this study, I expected to find an increase of Moist Tropical days at all stations, but this only occurred in Chattanooga, and the mean annual frequency of Moist Tropical days did not change at any other station. The mean seasonal frequency of Moist Tropical days in the summer has only increased at the Chattanooga and the Tri-Cities locations. This is likely attributable to the geographic location and characteristics of Chattanooga and the Tri-Cites, in that they are likely to receive warm, moist air from the Gulf of Mexico. I am surprised that Knoxville did not also show a significant seasonal increase. These results are particularly surprising for Asheville, which is located in southwestern North Carolina, one of the wettest locations in the Southeast (Ingram et al. 2013). Although the geography of Asheville is conducive to moist conditions, the frequency of Moist Tropical has not changed.

In the U.S. and Canada overall, transition days have decreased (Hondula and Davis 2010, Vanos and Cakmak 2013). In this study, the trend for transition days is either non-significant (at TRI and TYS) or significantly negative with a very slight rate of change (at AVL and CHA).

5.3 Stagnation

Arctic Amplification may be the driving factor behind a recent trend of persistent weather patterns and extreme weather in the mid-latitudes (Francis and Vavrus 2015). Evaluating the history of persistent air masses in the mid-latitudes is important in understanding the relationship between Arctic Amplification and changes in stagnation event frequency and duration. In addition to extreme weather, persistent air masses raise a concern of air quality. For example, persistent air masses have a positive correlation with elevated levels of ozone and particulate matter (Horton et al. 2012). This study evaluated the persistence, or stagnation, of potentially oppressive SSC air mass types Dry Polar in winter and Moist Tropical, MT+, and MT++ in summer.

The National Climatic Data Center identifies stagnation events as periods with light low-level winds, light upper-level winds, and no precipitation (Horton et al. 2012). Stagnation events are expected to increase in the eastern US over the next century with a 20% increase in winter and a 12% increase in summer (Horton et al. 2012). Furthermore, extreme weather events generated by persistent air masses are expected to increase (Francis and Vavrus 2015).

Although this study observed no major trends in stagnation events for the southern Appalachian region over the past half-century, the southern Appalachians, especially Great Smoky Mountains National Park, have experienced record extreme weather events in recent decades. For example, Mt. LeConte in Great Smoky Mountains National Park has registered both a record high and low temperature within the past decade. In the summer of 2012, Mt. LeConte recorded a high of 27.5°C (81.5°F) in a three-day period of unusually warm temperatures that produced

devastating storms at lower elevations. This was the first time in recorded history that Mt. LeConte had surpassed 26.67°C (80°F), and it did so for three consecutive days. Meanwhile, Knoxville recorded a new all-time high of 40.56°C (105°F) ("Knoxville Climate Page" 2015). In February 2015, Mt. LeConte recorded a new official low of –30.56°C (–23°F) (Matheny 2015). Many studies cite Arctic Amplification, and/or its effects, for causing increased extreme weather at the mid-latitudes (Francis and Vavrus 2012, Wang et al. 2013, Cohen et al. 2013, Tang et al. 2013, Cohen et al. 2014, Francis and Vavrus 2015).

CHAPTER SIX
CONCLUSIONS

Anthropogenic forcing is altering global climate. The greatest changes are seen in the polar areas, in a process referred to as Arctic Amplification (Francis and Vavrus 2015). Monitoring the frequency, trends, and stagnation of air masses is important to identifying the influence of Arctic Amplification on jet stream patterns, which influence weather and climate at the regional or local level. While investigating potential changes and trends in air mass frequency, trends, and stagnation, we consider the natural variability of climate to discern those trends that may be attributable to a global change in climate from those that are part of the oscillating climate pattern. Knight et al. (2008) acknowledged that the observed increase of warm, humid air masses and decrease of cold, dry air masses in winter over the continental U.S. in the past half century may be somewhat attributable to large scale climate variabilities such as the El Niño–Southern Oscillation, the North Atlantic Oscillation, the Arctic Oscillation, and the Pacific/North American teleconnection pattern. However, these observed changes meet the anticipated outcome of anthropocentric forcing, and so climate change is thought to be the main driver behind such changes (Knight et al. 2008).

This study focused on the southern Appalachian region, which is dominated by Dry Moderate air mass days. Moist Tropical is also common, especially in the summer. Dry Polar is fairly common in the winter. From 1965 to 2014, the frequency of Moist Tropical days has remained mostly static through the region, whereas Dry Polar days has significantly decreased, replaced by Dry Moderate and Dry Tropical. Dry Tropical air can be indirectly harmful as it is associated with poor air quality, and, according to these results, has significantly increased through the region over the past half-century.

Stagnation events of potentially oppressive air mass types have remained static, with no major change in frequency, or duration, as hypothesized. In some cases, the frequency of stagnation events has non-significantly decreased, particularly for the Dry Polar air mass in winter. Although this study found that many of the climate change trends for the southern Appalachian region are statistically significant, the changes are not very drastic.

Studies like this one are important for understanding the effects of climate change on the region. Little is known about how climate change may be affecting Great Smoky Mountains National Park, but the park is currently conducting phenology studies to help detect climate change and its impacts on the flora and fauna of the park. Future research should compare the data from these studies to air mass patterns in the region. Understanding how changes in phenology relate to air mass climatology changes can help both interpret past changes and predict future changes. For example, a seasonal evaluation of air mass trends in the spring would be helpful for understanding the potential impacts of changing air mass frequency, trends, and stagnation on plants during the growth season. Not only could climate change alter the ecological landscape of the southern Appalachians, but it could influence the human visitor landscape as well. Trends toward warming, stagnant air, and extreme weather events all have a great impact on the health, safety, and enjoyment of visitors and residents in the southern Appalachian region. Future research should explore the history of poor air quality days and extreme weather events in terms of air mass climatology.

Additionally, future research should explore the applicability of using SSC typing for the higher elevations of the southern Appalachians, especially in Great Smoky

Mountains National Park. For example, do changes in low-elevation (660 m) air mass data correspond to meteorological observations at higher elevations (1265 m), since air mass data are not available at these locations? This type of assessment could be executed with data (temperature, dew point, wind, and pressure; similar to the SSC) from mid- to high-elevation meteorological stations that are maintained by the National Park Service, such as the Cove Mountain and Clingmans Dome stations (Figure 3.1). The weather in the high elevations could be characterized on days when the same air mass type was present at all low elevation data stations, so that it could be inferred that there is no front on the region and the entire region is under the same air mass. Then it could be determined if the higher elevations experience similar patterns in daily air masses as lower elevations. This is important because higher elevations may be more affected by stagnant air mass events.

This study benefits science by expanding the literature on climate and climate change impacts in the Southeast, providing a discussion on the applicability of a popular air mass-typing system to mountainous environments, and formulating the first air mass study specifically concerning the southern Appalachian region.

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VITA

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