Long-term Changes in Synoptic-Scale Air Mass Persistence Across the United States

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ABSTRACT

From a climate dynamics perspective, air mass persistence reflects variability in the dynamic nature of the atmosphere. In this study, a historical analysis of synoptic air mass persistence across the continental United States is presented to portray spatial and temporal variability and trends in air mass residence times. Historical daily air mass calendars for 140 locations across the United States for the 60-year period 1955 through 2015 were extracted from the Spatial Synoptic Classification database. The data were stratified by season, and a historical climatology of seasonal air mass occurrence was created for each location. The historical daily air mass data were then translated into a record of residence time, or the length of consecutive days that a synoptic air mass type was in place at a location. Each historical record of seasonal air mass residence times, or persistence, was then analyzed for spatial variability across the United States and for temporal variability and trends. Results reveal a statistically significant increase in air mass persistence for many areas of the country during three seasons, but most commonly across the southern United States during the summer season (June-August). However, this pattern was reversed for the winter season (December-February), the analyses revealed a general pattern of decreasing cool-season air mass persistence across the continental United States. The seasonally-dependent change in air mass persistence across the United States may be indicative of changed or changing mid-latitude atmospheric dynamics in the form of a previously suggested northward migration of the polar jet stream.

GENERAL ABSTRACT

Research involving the persistence of synoptic scale air masses has focused almost exclusively on a relationship with human health, specifically the detriments of high concentrations of atmospheric pollution, dust, and pollen, and prolonged heat and humidity. This study examines historical air mass persistence for 140 locations across the continental United States over a 60-year period (1955 – 2015) using data extracted from the Spatial Synoptic Classification database. The data were divided into season and then analyzed to produce a record of persistence, or length of consecutive days that a synoptic air mass type was in place at a location. Results reveal an increase in air mass persistence across the southern United States during the summer season (June-August). However, this pattern was reversed for the winter season (December-February). The analysis revealed a general pattern of decreasing cool-season air mass persistence across the continental United States. The seasonally-dependent change in air mass persistence across the United States - an increase in spring, summer, and fall, and a decrease in winter – may be indicative of changed or changing mid-latitude atmospheric dynamics in the form of a previously suggested northward migration of the polar jet stream.

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1 Introduction

Over the past few decades, the idea of global warming has evolved into a broader discussion regarding global climate change. A consequence of warming globally, climate change engages the notion that not only are changes in variables other than temperature likely, but broadly, the dynamics of the global climate system have likely changed, including the possibility that the large-scale circulation of the atmosphere has changed. Long-term changes in climate characteristics such as precipitation, ocean salinity, wind patterns, and extreme weather patterns have been observed at continental, regional and ocean basin scales in recent decades (e.g., IPCC 2014).

One way that changing climate dynamics may be realized is through changes in surface-based expression of the dynamics of the atmosphere, which is to say the air masses that ultimately owe their existence within the middle latitudes to the large-scale dynamics of the atmosphere. Air masses are large bodies of air that have homogeneous temperature and moisture characteristics, and cover large areas of a continent at a time (Ahrens 2009). The concept of an air mass began with the renowned Norwegian school of meteorology in the early 1900s (Ahrens 2009). By the 1940s upper-air balloon launches that returned temperature, humidity, and pressure data were conducted, providing a three-dimensional view of the atmosphere (Ahrens 2009) that led to the theory linking the pattern of upper-tropospheric flow to air masses at the surface.

The characteristics of air masses are derived from their source or origin regions. Source regions tend to be topographically flat and have a uniform land cover (i.e., central Canada, Siberia, large deserts, and the northern and southern oceans) (Ahrens 2009). To develop the characteristics of a source region, an air mass must remain over that region for a prolonged period. The air mass will migrate from the source region when upper-atmospheric dynamics change to allow the air mass to emerge from the source region above which it has evolved. Air masses typically migrate into the middle latitudes from their high and low latitude source regions (Ahrens 2009).

Historically, air temperature, humidity, pressure, and source region have been used to classify air masses, with classification schemes relying on identification of the source region through manual analysis (Zander 2013). During the past 20 years, multiple classification schemes have been introduced that follow the methodology of resolving the source region of the air mass to identify the air mass type at a specific location outside of the source region (Zander 2013). Today, deriving the air mass type based on the source region is generally viewed as outdated since the methodology does not account for air mass modification as the air mass migrates over surfaces that can be very different from those of the source region. Upon modifying, the air mass can develop characteristics than are substantially different from those of the source region, in some cases altering the classification of the air mass.

Over the past 30 years, air mass classification methodologies have evolved such that automated classification systems are present today. The Spatial Synoptic Classification (SSC) developed by Kalkstein (1996) and updated by Sheridan (2002) is one automated classification system that accounts for air mass modification once it has left the source region. The SSC algorithm analyzes 6-hourly meteorological data from numerous weather stations across the mid-latitudes to identify areas with similar temperature and moisture characteristics for the purpose of defining the air mass over a region (Sheridan 2002). The middle latitudes broadly represent the global region in which air masses of high and low latitude origin interact. As a function of the wave-like propagation of the upper-atmospheric polar jet stream, high-latitude air masses migrate southward and low-latitude air masses migrate northward, which feeds-back to polar jet stream dynamics. Jet streams are rather thin ribbons of relatively fast-moving air in the upper atmosphere that are generated by large latitudinal temperature gradients. As the gradient in temperature from the warmth of the low-latitudes to the cold of the high latitudes is inherently most pronounced across the middle-latitudes, polar jet-streams often propagate through the middle latitudes. The dynamics of jet streams, which is to say their position as well as the degree to which they are zonal (oriented west-east) or meridional (oriented north-south), can be reflected in the characteristics of the surface-based air masses which they segregate.

Much of the recent applied research involving air masses has related their character and frequency to human health problems, particularly oppressive heat and dangerously high pollution. Far fewer studies have used air mass classifications as a mechanism to demonstrate changes in the atmosphere. A few studies have specifically used the SSC to examine changes in air mass frequency (e.g. Senkbeil et al. 2017), but few studies have focused on changes in air mass persistence, which could reflect the dynamic nature of the large-scale atmosphere. The lone study that focused on changes in air mass persistence (Vanos 2015) analyzed one type of air mass in one region for a specific season. In an attempt to provide another dimension to what is known about the recent evolution of Earth’s climate system, this thesis focuses on the temporal characteristics of air masses across the middle-latitude portion of North America, or specifically the continental United States.

The continental United States is appropriate for the study of changing air mass characteristics, as it is under the influence of arguably the most diverse array of air masses as any landmass on Earth. Central North America is bordered by source regions that include the high latitude landmass of northern North America, the northern extents of the Pacific and Atlantic Oceans, the warm continental land mass of southern North America and Central America, and the warm waters of the Gulf of Mexico, western Atlantic Ocean, and east-central Pacific Ocean (Figure 1).

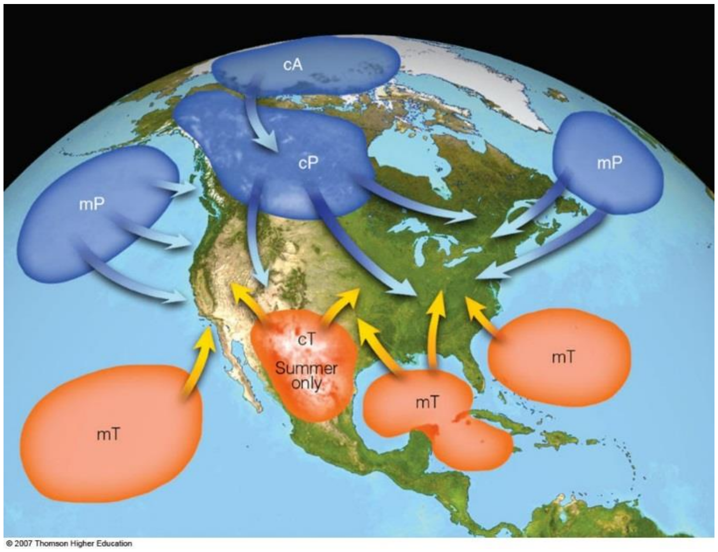


Figure 1. The continental United States and the source regions of the air masses that typically migrate into the region. The air masses are referenced based on moisture content moist (maritime, “m”), dry (continental, “c”) and the latitude of origin (tropical “T”, polar “P”, and arctic “A”) (Ahrens 2009)

The variety of air masses experienced over the continental United States through the year makes this particular region appealing for long-term temporal analysis of air mass persistence. The idea is that air mass persistence is a reflection of variability in the position, shape, and propagation of the middle-latitude, middle-atmospheric flow. While air mass analysis is key to accurately forecasting weather conditions, understanding longer-term variability in air mass frequency and persistence is a potentially informative means to understanding how the atmosphere is responding to climate change.

The research questions guiding this work are:

(1) What are the climatological characteristics of seasonal air mass persistence for the past 60 years across the continental United States?

(2) What changes, if any, have occurred in the residence time, or persistence, of air masses?

(3) What might the results suggest about the idea of changed or changing mid-latitude atmospheric dynamics in conjunction with the global warming of the past few decades?

The hypotheses are that air mass persistence has exhibited significant temporal variation during the past 60 years across the United States, and that a change toward air mass stagnation has occurred, most likely across the southern tier of the country. The idea that air mass stagnation has evolved across the southern portion of the United States is based on the notion that global jet streams have shifted poleward in conjunction with a warmed planet (Archer and Caldeira 2008).

2 Literature Review

2.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) recently concluded that there have been changes in climate characteristics such as precipitation, ocean salinity, wind patterns, and extreme weather patterns at the continental, regional and ocean basin scales in recent decades (IPCC 2014). One way to reveal changes in climate is to investigate for changes in synoptic scale patterns. One measure of synoptic scale changes is the jet stream. Disturbances in the jet stream influence storm tracks, and the changes in location of the jet stream can lead to variations in these disturbances (Archer and Caldeira 2008). While the field of synoptic climatology has developed greatly over the past 30 years, much of the applied aspect of the science has focused on mitigating problems related to human health, such as air pollution and heat stress. This study aims to contribute to the sciences of synoptic climatology and climate change by examining temporal patterns of air mass persistence across the continental United States over the past 60 years. There is some recent precedent for the use of synoptic climatology in the examination of changes in climate. Two such studies involving synoptic climatological approaches have focused on the changing frequency of weather front passage (Hondula 2011) and the impact of changing air mass frequencies on human health (Vanos 2015). Both of these studies found an increase in warmer air masses and warm front passages across the United States. Additionally, Vanos et. al found an increase in the number of heat waves, defined as three or more consecutive days of a warm humid air mass, in the Midwestern United States. These research efforts illustrate the use of synoptic climatological analysis in assessments of climate change, but each is relatively limited in scope. Climate change research is broad and deep, and therefore the greater focus of this literature review is on work involving synoptic climatological methodologies and approaches to portraying and understanding climate variability and change.

2.2 Air Mass Concepts and Synoptic Classification

The study of air masses, large bodies of air that have homogeneous temperature and moisture characteristics, dates back to the early 1900s (Ahrens 2009). However, the idea of air mass classifications was first introduced in the 1950s (e.g., Belasco 1952) to relate thermodynamic characteristics of atmospheric circulation to surface environmental processes (Yarnal 1993). Early research was focused primarily on distinguishing between homogeneous and inhomogeneous pressure patterns. Since the earliest air mass classifications were based on thermal, moisture, and pressure characteristics, the classifications had numerous inaccuracies, which made mapping the evolution of these air masses a problem (Bower 2007). However, the evolution of air mass research led to the classification of air masses based on thermal and moisture characteristics alone (Bower 2007), which improved accuracy.

Early air mass classifications were tailored to satisfy a researcher's specific need, thus making the schemes difficult to replicate or apply to future studies (Yarnal 1993, El-Kadi and Smithson 1992). Specifically, there is an issue with the early accepted method of weather type classification (Bergeron 1930), which used source regions. Since air masses evolve and modify as they advect away from their source region, an air mass may have different characteristics from when originally formed (Zander, 2013).

In an effort to create a "one-size fits all" classification scheme, many hybrid automated classification schemes were developed (Sheridan 2002). Hybrid classification schemes include both manual and automated classification processes (Sheridan 2002).

Many of these schemes took daily weather maps and observations for numerous stations and used a clustering technique to examine homogenous conditions and categorize them (Davis 1990). Davis (1990) created an automated scheme that produced 90 cluster categorizations that described all the major synoptic situations that occurred during 1984 for the contiguous United States (CONUS). From the analysis, some clusters were easily identified as maritime or continental polar air masses, frontal passages, or continental highs (Davis 1990). The clusters produced by Davis (1990) represented the seasonality and regionalism that could be derived from surface maps and observations over a short period.

At the time of Davis' work, the temporal synoptic index (TSI) was developed by Kalkstein et al. (1986) to create an air mass climatology using weather station data. The TSI is an automated hybrid classification scheme that used observations made four times daily at stations across the United States to determine the air mass classification for a station during a particular day. The suite of observations consisted of seven variables: air temperature (Celsius), dew point temperature (Celsius), visibility (km), total cloud cover (tenths of sky cover), sea level pressure (mb), wind speed (knots), and wind direction (azimuth). For each station, the observations were subject to a principal components analysis to reduce redundancy, and daily component scores were clustered into groups of days with similar meteorological characteristics (Kalkstein 1986). The TSI has been used to examine air mass frequencies in the past; however, as Kalkstein (1996) noted, the "TSI is virtually impossible to develop beyond single point analysis, as the statistical procedures are not sensitive to similar categorizations developed at adjacent locations." While the TSI is helpful when examining a single location, it is not designed for inter-site comparison (Kalkstein 1996). Without the ability to relate two adjacent sites, it is difficult to perform an effective analysis of changes in air mass frequencies. However, the studies that used the TSI to examine long term change (e.g., Kalkstein 1990) at individual locations discovered a positive trend in the frequency of the warmest TSI clusters. At the time, this finding was unprecedented, as no previous studies uncovered statistically significant changes in air mass characteristics. Due to the limited application of the TSI, there was a need for a classification scheme that could be applied more broadly.

2.3 Spatial Synoptic Classification (SSC)

The Spatial Synoptic Classification (SSC), introduced by Kalkstein et al. (1996), was the first comprehensive classification of air mass types for scientific analysis. The SSC combined numerous previously disparate variables to classify weather types into six different air mass types: Dry Polar (DP), Dry Moderate (DM), Dry Tropical (DT), Moist Polar (MP), Moist Moderate (MM), and Moist Tropical (MT) (Sheridan 2002) (Table 2.1).

Table 2.1 The air mass classification types of the SSC (Sheridan 2002).

Air Mass Type (Abbreviation)	**Air Mass Weather Conditions**
Dry Polar (DP)	Cold, dry air, associated with artic high pressure systems
Dry Moderate (DM)	Cool, dry air, warmer modification of DP
Dry Tropical (DT)	Warm, dry air, usually has southerly wind flow
Moist Polar (MP)	Cold, humid air, associated with Aleutian and Icelandic low pressure systems

Moist Moderate (MM)	Cool, humid air, warmer modification of MP
Moist Tropical (MT)	Warm, moist/humid air, usually has southerly wind flow, associated with heat waves

Sheridan (2002) redeveloped the Kalkstein et al. (1996) original classification scheme by redesigning selection criteria for each season so that the classifications may be used year-round instead of only for the summer and winter, as originally designed. The Spatial Synoptic Classification 2 (SSC2) also includes a seventh classification category in addition to the original six developed by Kalkstein et al. (1996), the Transitional air mass (Sheridan 2002). The transitional air mass is applied to days where “one weather type yields to another based on large shifts in pressure, dew point, and wind over the course of the day” (Sheridan 2002). Additionally, the SSC2 incorporates an increased number of stations in the United States and Canada with a mean station record-length of 44.6 years (Sheridan 2002). Until the work of Kalkstein (1996) and Sheridan (2002), there was a lack of information on air mass characteristics for any given location over a long time period (Leathers 2004). Since the SSC2 is grounded in the climatological theory of air masses, it compensates for the modification of air masses over different geographic regions and it is applicable both spatially and temporally. The SSC2 has been used as the basis for a similar classification scheme for Western Europe (Bower 2007). With an extensive collection of daily air mass records, the SSC2 can be applied to diverse fields and research questions (Zander 2013).

In creating the SSC2 from the basis of the SSC, Sheridan (2002) allowed for application of the classification scheme year-round, instead of just a six-month period during the year, as was the case with the original SSC. The first iteration of the SSC

(Kalkstein 1996) involved manually defined seed days that were actual days in a station's record that contained the typical meteorological characteristics of a particular weather type (air mass type) at that station. A computer algorithm selected these seed days, based on predefined seed day criteria, from a station's record during a particular time of year. Each day was classified based on maximum and minimum air temperature, dew point temperature, mean daily cloud cover, dew point depression, and diurnal dew point range. After seed day selection was complete, weather maps for those seed days were analyzed to ensure that the selected day met the criteria for the chosen weather type. However, the seed days were only chosen for winter (December, January, February) and summer (June, July, August), thus the limited application of the SSC to just those six months.

To create a classification scheme that was applicable year-round, Sheridan (2002) used "sliding seed days" instead of the previously identified seed days. "Sliding seed days" were created in four two-week windows throughout the year. Additionally, theoretical seed days were produced for each weather type. The four two-week periods shifted by location to correspond to the hottest and coldest two weeks as well as to the midway points between the two. This method accounts for the gradual change in climate with season, without having to analyze additional weather maps to help with identification. A period of two weeks was chosen because it represented "a reasonable maximum period during which seed day criteria would not change considerably during transitional seasons (i.e., spring and fall)" (Sheridan 2002). Seed days for the transitional air mass type were selected based on days that had the same weather type present over two stations using a modified criterion that only considered the parameters of diurnal dew point range, mean sea level pressure, and diurnal wind shift (largest vector between two time periods). By assigning seed days based on two stations instead of a single station, the seed days can account for the local meteorological differences between the two stations (Sheridan 2002).

Classification of weather types for each station is similar to the SSC and excludes “extreme days” or days with the coldest Dry Polar air mass and the most humid Moist Tropical air mass. The SSC2 also updated the parameters that were examined to determine classification. The SSC2 uses station observations four times a day at local hours 04, 10, 16, and 22, instead of taking single values from each day. For each of the four daily times the following data are incorporated: air temperature, dew point depression, mean cloud cover (averaged over the four time periods), mean sea level pressure (averaged over the four time periods), diurnal temperature range, and diurnal dew point range. These values were then evaluated using discriminant analysis to assign a weather type classification for that day for a particular station.

The SSC2 uses a method of equally weighted sum of squared z-scores to designate weather type classification. The mean variables from each of the parameters are evaluated for a particular day of the year, then compared to the actual day’s data. This calculation provides an h_k *score*. The h_k *score*, also known as an “error score”, provides the discrepancy between the typical weather type (one of the six specified types) and that particular day. Each day is then assigned the weather type with the lowest h_k *score*. Analysis of transitional days occurs after a day is given an initial air mass designation. In order to designate a day as a transitional day, a transitional z-score is computed similarly to the method described above, but it is based on the three parameters relevant to transitional weather types (diurnal dew point, mean sea level pressure, and diurnal wind shift) and assigned an h_k *score*. If the h_k *score* for the transitional type is lower than that of the day's initial designation, the day is reclassified as a transitional day. If the h_k for the transitional day is higher than that of the day's initial designation, the day keeps the initial air mass designation. This procedure of classifying weather types (air masses) is run daily for 327 stations across the United States, including Hawaii and Alaska, and Canada. As the SSC2 has fully replaced the original SSC, hereafter it will be simply referenced as SSC.

2.4 Air Mass Climatology

Over the past decade, atmospheric scientists have significantly increased the focus on climate change, with some recent research focusing on the role air masses play in these changes. Some applications of air masses in recent research include air pollution variability (Hondula et al. 2009), air mass climatology (Zander, 2013), the relation of snow cover to air mass frequencies (Leathers et al. 2004), and public health (Knight et al. 2008).

In searching for a temporal threshold for a noticeable change in the global atmosphere, Livezey et al. (2007) found that 1975 appears to be the point in time when global climate change became obvious in several meteorological variables. Zander (2013) noticed this same increase in warm and moist air masses post-1975 compared to data pre-1975. In recent years there has been a significant increase in warm, humid air masses over the United States at the expense of cold, dry air masses (Rebecca Zander, 2013; Vanos and Cakmak 2014; Vanos, 2015). This increase in warm, moist air masses has led to a focus of research on public health and the relationship between these warm, moist air masses and heat-related fatalities.

Knight et al. (2008) used the SSC database to examine the change in air mass frequency in the continental United States from 1948-2005. They found what previous researchers had already discovered, that there has been an increase in warm, moist air masses at the expense of dry, polar air masses. Zander (2013) used the SSC to examine the beginning of meteorological spring in the Northeast. By examining the frequency and timing of air masses in the Northeast United States, Zander was able to determine that there has been a shift in the onset of meteorological spring such that it occurs earlier in the year than in the early period of the study (pre-1975).

Some researchers have studied the role that air masses play in the transportation of pollutants from one region to another. Hondula (2009) examined the relationship between the classification of an air mass based on the SSC and the classification of the same air mass based on the source region of the air mass using back trajectories. Hondula found that the SSC alone cannot be used to determine the source region of certain pollutants, but in combination with back-trajectories can be useful to track the path of pollutants from their source region to where they are observed.

The idea that air mass stagnation causes pollution accumulation is not a new concept. Many studies have examined the relationship between air masses and the pollutants that are found in the atmosphere. Comrie (1994) created a climatology of rural ozone levels at three forest sites in Pennsylvania citing that “synoptic climatological approaches have enjoyed considerable success in relating the atmospheric circulation to environmental variables” (1994). Using air mass trajectories, Comrie found that pollutants in rural areas of Pennsylvania are most commonly transported by air masses from the air mass source regions compared to pollutants found in urban regions. Urban pollution, Comrie found, results more commonly from air stagnation over a region.

Although some research has focused on temporal patterns of atmospheric pollution related to air mass movement and general air mass climatology, those studies only addressed the temporal aspect of the chemicals rather than exploring the duration of an air mass at a single location. For example, Barrie and Hoff (1984) examined the residence time of sulfur dioxide in the atmosphere as it related to air masses in the Arctic atmosphere. Per the study, the residence time of sulfur dioxide was 12 days longer during mid-winter than the longest time span during late-fall (20 days). For sulphur dioxide to be removed from the atmosphere, the arctic air mass would have to change, thus allowing the atmosphere to mix and remove the sulfur dioxide. The increase in residence time of sulfur dioxide relates to air mass residence time. Specifically, the increased residence time of sulfur dioxide in the winter could indicate that air masses in the Arctic atmosphere were not transitioning as often during the study period of Barrie and Hoff (1984). If the air masses did not transition as often during winter, one hypothesis is that the atmosphere and air masses may have become more stagnant during the winter months.

2.5 Air Mass Persistence/Stagnation

While some research has focused on the relationships of air masses to other environmental factors (e.g., air quality, public health), others have focused on examining the long-term climatology of air masses. While there is some evidence of a focus on air mass frequency in the literature (e.g., Knight 2008, Hondula 2009, Vanos 2015), the persistence/stagnation of air masses over an extended period for the continental United States does not appear within the scientific literature.

Two previous studies that are used as a basis for the current research are Vanos (2015) and Hondula (2011). Vanos focused on the relationship between changing air mass frequency and the impact of heat waves on society. Vanos' research is part of a limited amount of research that evaluates long-term temporal trends within synoptic weather patterns. The goal of Vanos' research was to investigate 60-year (1948-2010) trends in the frequency and characteristics of dangerously hot summer days, as well as cool and dry summer days across five cities in the Midwestern United States. The study aimed to determine if any trends in frequency are prevalent in those weather types (air masses) that have historically been associated with negative health impacts (Vanos 2015). Vanos defined a "heat wave" as any period in which there are three or more consecutive days of the dangerous weather types Moist Tropical and Dry Tropical within the SSC database. The results revealed a mean frequency increase of greater than one day per decade for the five cities. The three largest cities, Cincinnati, Detroit, and St. Louis, experienced similar increasing trends and statistical significance for the extreme Moist Tropical air mass. The extreme Moist Tropical air mass (MT+) is a day classified as MT where "both the morning and afternoon apparent temperatures are above the seed day means and thus captures the most 'oppressive' subset of MT days" (Sheridan 2002). An increase in the frequency of three or more consecutive days of the Moist Tropical and Dry Tropical weather types was evident in four of the five cities. This increase provides a precedent for the current study to examine air mass persistence.

Hondula (2011) used the SSC to create a climatology of frontal passages across the continental United States. Frontal passages are symbolized by a transition air mass type, as the station is transitioning from one air mass to another, and thus the day cannot be defined as of one air mass. Hondula separated the traditional transition air mass type into four subtypes based on intra-day sea level pressure change and dew point change. The four subtypes represented the relationship between the dew point and sea level pressure: 1) decreasing dew point, increasing sea level pressure, 2) increasing dew point, increasing sea level pressure, 3) decreasing dew point, decreasing sea level pressure, and 4) increasing dew point, decreasing sea level pressure. Subtype 1 is consistent with cold front passages, subtype 2 is consistent with moist high pressure centers or anticyclones, subtype 3 is consistent with a dry low, and subtype 4 is consistent with warm frontal passages. Similar to Vanos (2015), Hondula (2011) found that there has been a significant decrease in Dry Polar days and an increase in the Moist Moderate and Moist Tropical air masses indicated by the change in distribution of frontal passages. This study indicates that increased ridging in the northwest and Rocky Mountains over the study period of 1951-2007 has led to fewer transition days. In addition, Hondula also found an increase in cold front passage in the Northeast United States. On a synoptic scale this study illustrated the relationship between these frontal passages, or transition days, to a shift in storm tracks and position of the polar jet stream. Based on the outcome of this study it was observed that there has been a shift of storm tracks northward, which indicates a contracting polar vortex, or polar jet stream. The work of both Vanos (2015) and Hondula (2011) provide precedent and a foundation for examining not only the temporal aspect of air masses, but the broader implications of temporal changes on synoptic scale circulation across the continental United States.

2.6 Summary

Recent climate change research has begun to examine the relationship between climate change and atmospheric circulation. Examples include the relationship between circulation and changes in extreme precipitation in Northern Xinjiang, China (Huang et. al 2017), changes in the central Asian Vortex (Yang and Zhang 2017), or changes in the monsoon season in the Karakoram mountain range in south Asia (Janes and Bush 2012). The studies, however, are focused primarily in the western Pacific Ocean and Asian continental regions.

While global climate change may reveal itself in changed atmospheric circulation, the surface-based reflections of circulation, air masses, have been of little focus in this regard. Many researchers have chosen to focus on how air masses affect localized processes at the surface, largely for the purpose of mitigating human problems. Public health and air quality have long been the focus of air mass studies. Air mass persistence may be a variable that aids in understanding the changes that the global atmosphere has undergone in past decades, and the potential implications of these changes for the future. Until now, no published study has included comprehensive examination of the persistence of air mass types. By utilizing the SSC, this study aims to quantify the mean persistence of different air masses over the continental United States while engaging three research questions: (1) What are the climatological characteristics of seasonal air mass persistence for the past 60 years across the continental United States? (2) What changes, if any, have occurred in the residence time, or persistence, of air masses? (3)

What might the results suggest about the idea of changed or changing mid-latitude atmospheric dynamics in conjunction with the global warming of the past few decades?

3 Research Methods

3.1 Study Area

The study area for this research is the contiguous United States (CONUS) (Figure 3.1), and this domain was selected based on several factors. Geographically, the location of the CONUS in the middle latitudes adjacent to large land masses and bodies of water makes it susceptible to invasion by nearly all air mass types in conjunction with active synoptic atmospheric dynamics. Additionally, the quality, spatial coverage, and detailed data available from the SSC provide a strong foundation for statistical pattern analysis. Since air masses are spatially expansive, a local scale analysis is inadequate due to the limited density of stations for which air mass data are available in some areas of the United States. The large CONUS study area also allows for the inclusion of many weather stations across the United States, thus providing a statistically relevant number of data points for robust analysis. By increasing the number of stations included in the study and therefore the sample size, a more comprehensive statistical analysis can be performed. This approach also aligns with numerous previous studies that also used the CONUS as the study area due to the large spatial domain and the numerous data sources available for analysis.

Figure 3.1. Location of SSC stations (dots) included in the study.

3.2 Study Period

The study period for this research is the 60-year period from December 1955-November 2015. This timeframe was chosen primarily to encompass two 30-year periods, which represents the commonly defined length of a climatological period. Further, a sample size of 30 is often considered to be the minimum necessary to generate robust statistical results when assuming a normal distribution. While only the past 30 years (December 1985 - November 2015) could have been engaged, the goal of this study is to examine temporal shifts in air mass persistence, and therefore the prior 30-year period (December 1955- November 1985) was included to allow for study of air mass changes through time using a difference of means test (1955-1985 versus 1985-2010) in addition to linear trend analysis. Due to the length of air mass records for the SSC database, a time period longer than the study period of 60 years was not possible. While the earliest air mass record in the SSC database for a station in the CONUS is 1930 at Louisville, Kentucky, the number of stations with a record length greater than 60 years is small.

3.3 Data Source

The data source for this research is the Spatial Synoptic Classification 2 database, referenced hereafter as SSC. For this research, daily air mass classification data were downloaded from the SSC database, and both missing data days and transition days were excluded since the focus is only on the persistence of air masses. The data for this study were extracted using the SSC data portal (http://sheridan.geog.kent.edu/ssc.html). The 327 stations within the continental United States were then filtered to only include stations that contained data during the period 1955-2015. The final filter was elimination of stations that did not have continuous data for the period 1955-2015. In this context, data continuity was defined as instances where no more than 10% of the data (nine days) were missing from a single season consisting of approximately 90 days (described below). If 10% of the data from a single season was missing then that season for the particular station and year was removed from the analysis. From the initial data set of 327 total stations, the final data set contains 140 stations, however, some seasons for some years contain fewer stations (e.g. 2015 contained the least number of stations with 134 included in the analysis) due to lack of complete data for a season at a particular station.

3.4 Data Stratification and Air Mass Climatology

The daily SSC air mass type data were stratified into meteorological seasons: winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). Due to the overlapping of years for the winter seasons, the data from the previous December was included in the winter for the following year. For example, December 2014 was included in the 2015 winter season. After all station data were checked and seasons missing 10% or more of the data were eliminated, a seasonal air mass climatology for the CONUS was conducted to ensure the data were consistent with previous studies (i.e., Sheridan 2002). This was done by creating a climatological map (i.e., mean air mass frequency) using the SSC data for each station for the past 60 years and visually comparing it with the climatology produced by Sheridan (2002). Each station was geocoded into ArcMap using the North American Datum (NAD) 1983 Contiguous USA Albers coordinate system. By geocoding the locations using the latitudes and longitudes of the stations with their independent data, an inverse distance weighted (IDW) methodology was used to visualize spatial homogeneity and spatial climatology (Lu and Wong 2008).

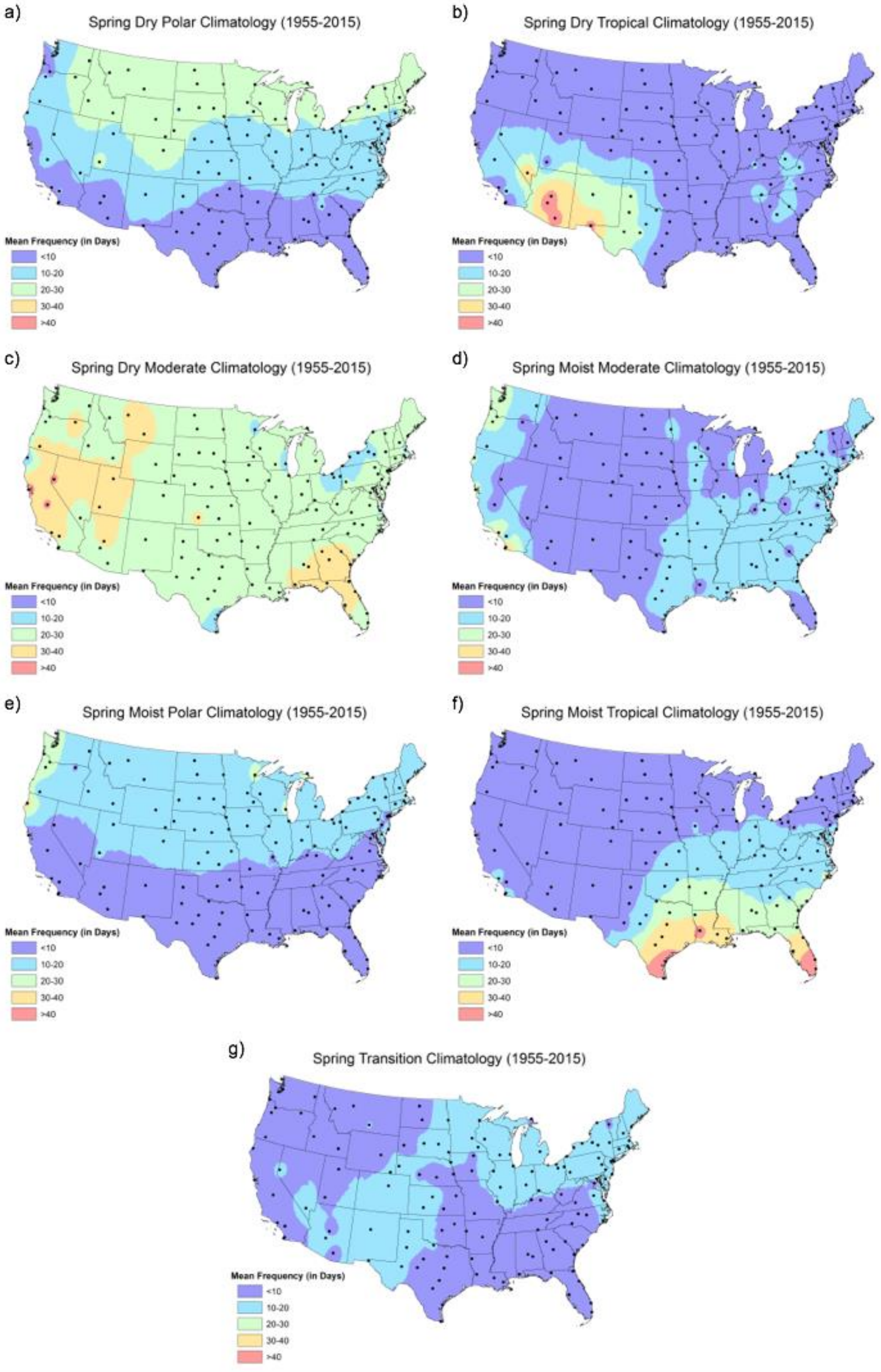


Figure 3.2. Spring season mean frequency (days) of each of the 7 air mass types: a) Dry Polar (DP) b) Dry Tropical (DT) c) Dry Moderate (DM) d) Moist Moderate (MM) e) Moist Polar (MP) f) Moist Tropical (MT) g) Transitional (TR).

Mean air mass frequency represents the average number of days on which an air mass is present at a location during a given season. During spring, the Dry Tropical (DT) air mass occurs most frequently in the southwest United States, with much of Arizona and New Mexico experiencing 20 or more days of the air mass (Figure 3.2b). The most frequent air mass across the CONUS during spring is the Dry Moderate (DM) air mass type, with every station experiencing at least 10 days of the air mass type (Figure 3.2c). The southeastern United States is dominated by the Moist Tropical (MT) air mass, with stations along the Gulf of Mexico coastline typically experiencing 20 or more days of the air mass during spring, while southern Florida and southeastern Texas experience 40 or more days of MT air (Figure 3.2f).

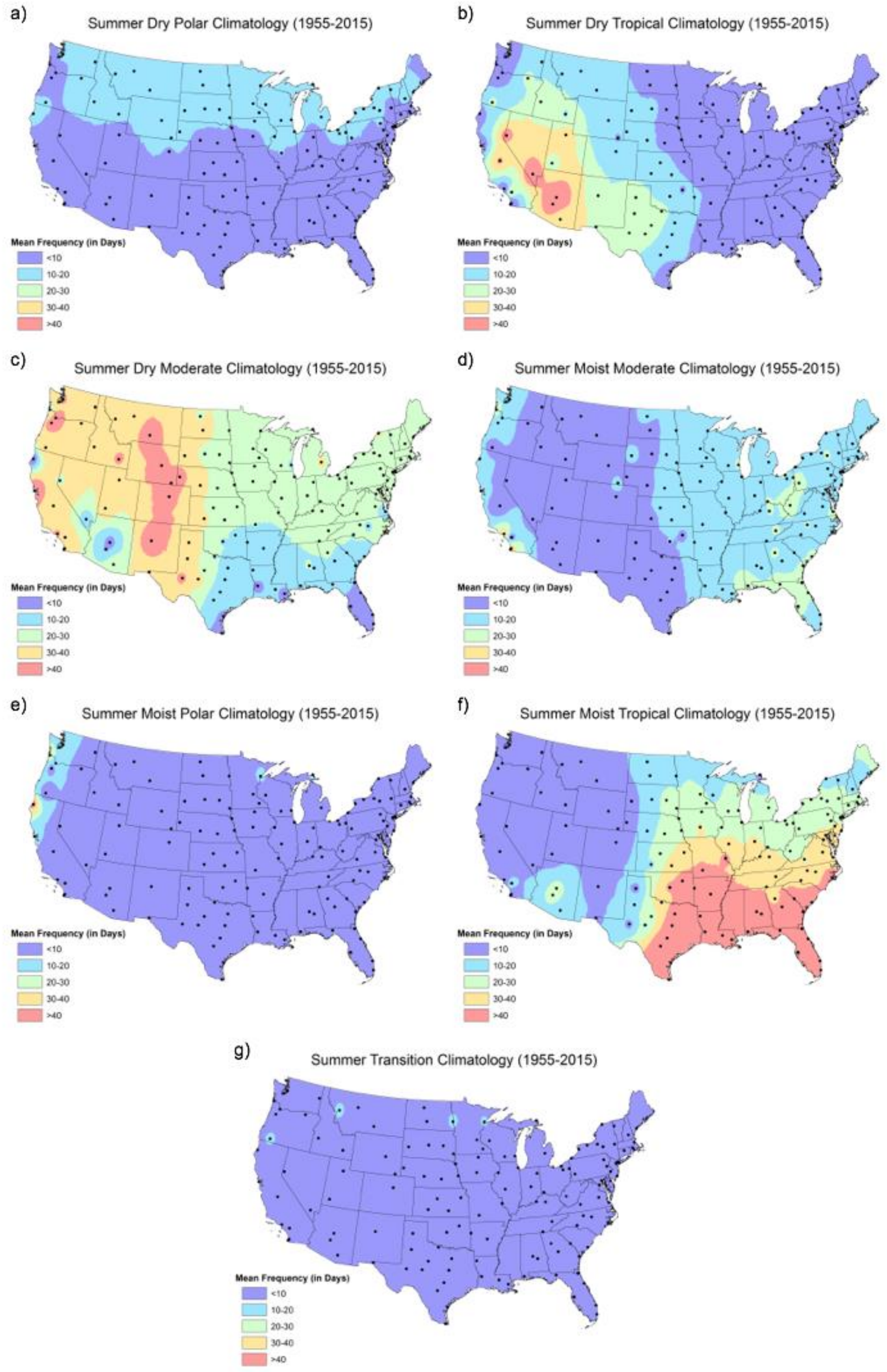


Figure 3.3. Same as Figure 3.2 but for the summer season.

The pattern of dominance by MT air mass continues through summer, with all of Florida, Mississippi, Arkansas, and Louisiana experiencing 40 or more days of the air mass type (Figure 3.3f). The DM air mass type occurs most frequently along the Rocky

Mountain range during summer, with this region typically experiencing 40 or more days. The DM air mass type typically occurs on 10 or more days during summer across all of the CONUS except for south Florida and for four stations along the Gulf of Mexico coast (Figure 3.3c). Again, the DT air mass has a high frequency in the southwestern United States, typically occurring on 30 or more days during summer (Figure 3.3b). Through fall, the DT air mass remains the most frequent (more than 30 days) air mass type in the southwestern United States (Figure 3.4b). The DP air mass becomes frequent in the northern Great Plains region and across Montana and Wyoming during the fall season, which is consistent with colder and drier air masses moving south from Canada as the polar jet stream expands southward (Figure 3.4a). The DM air mass is the only air mass that occurs on more than 10 days on average during fall across the entire continental United States (Figure 3.4c).

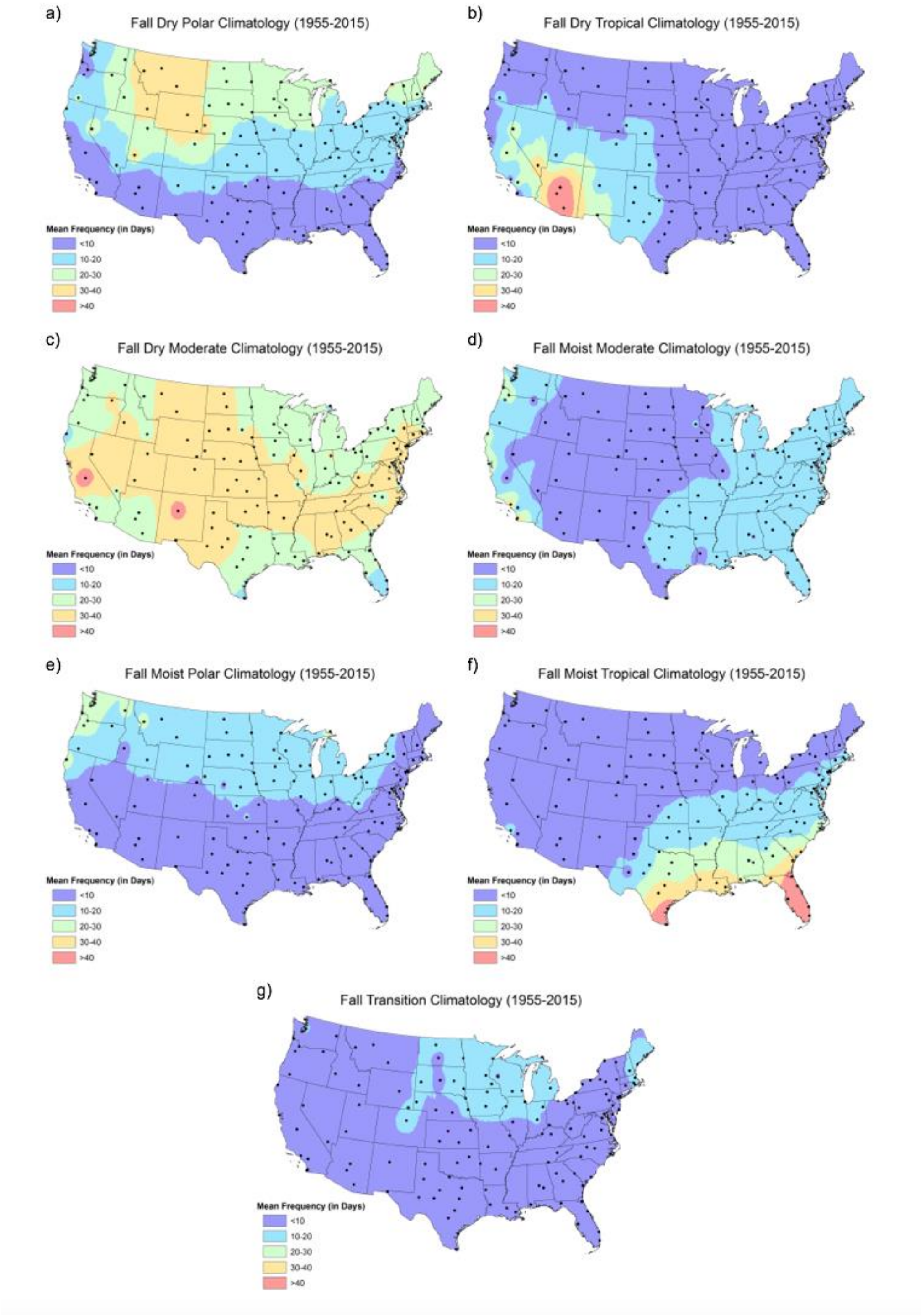


Figure 3.4. Same as Figure 3.2 but for the fall season.

In southeast Texas and across Florida, except for the panhandle area, the MT air mass remains the most frequent, occurring on more than 40 days during fall (Figure 3.4f).

During winter, the frequency of MT air decreases to less than 10 days across most of the CONUS, except across southern Florida, where the air mass continues to occur on more than 40 days during the season (Figure 3.5f). The drier air masses become more frequent during winter, with the DP air mass occurring on 10 or more days at each station (Figure 3.5a), and the DM air mass occurring on 20 or more days across the CONUS, with the exception of the Midwest/Great Lakes region, New England, and the Pacific Northwest (Figure 3.5c). Through each season, the transitional air mass type occurs on less than 20 days across the CONUS (Figure 3.2g, 3.3g, 3.4g, 3.5g).

The air mass climatology created for this study replicates the patterns depicted within the maps created by Sheridan (2002) when comparing them visually. While not revealing anything new, reinforcing the climatology generated by the creator of the SSC provides quality assurance of the handling of the raw SSC data within this study.

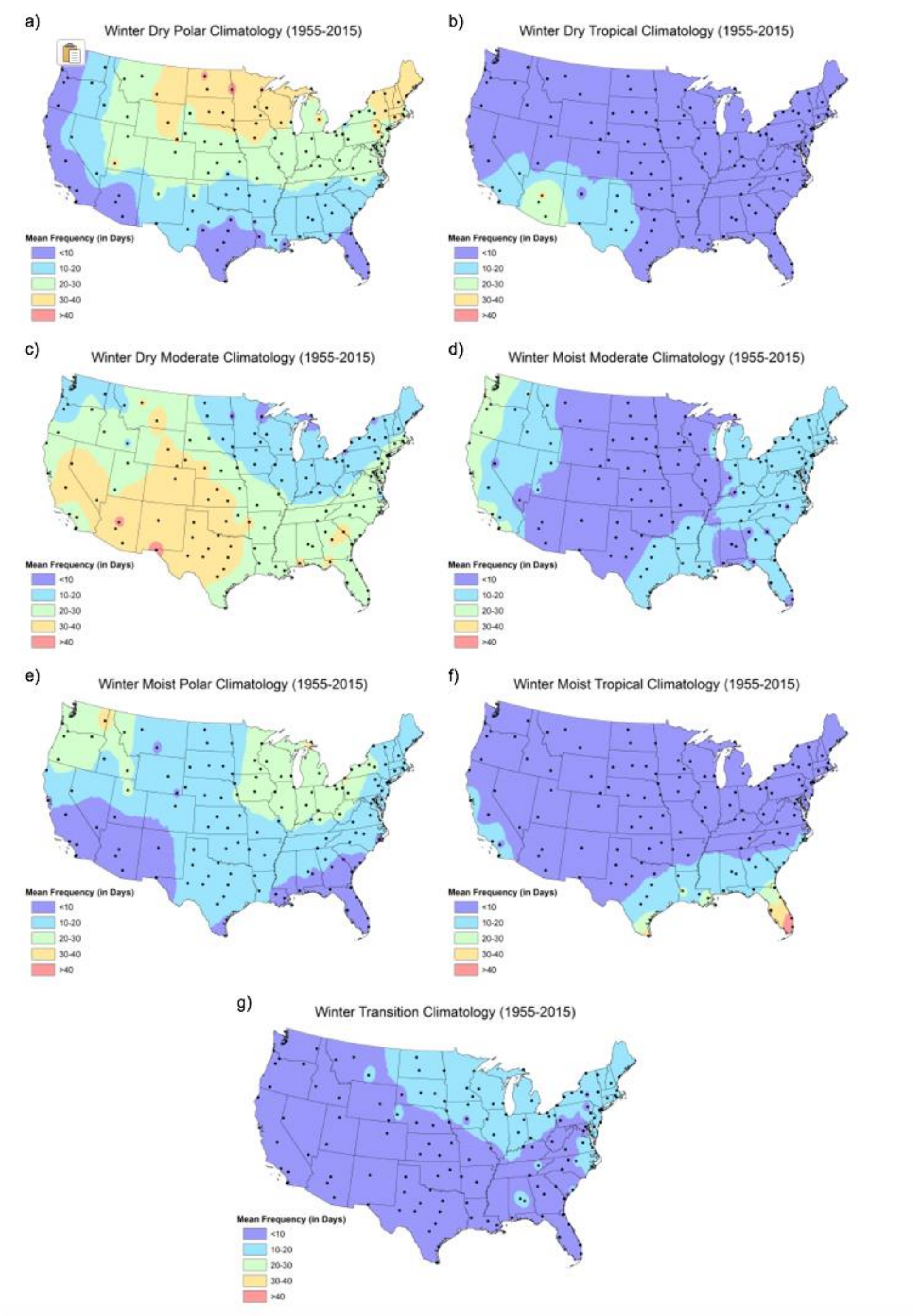


Figure 3.5. Same as Figure 3.2 but for the winter season.

3.5 Air Mass Persistence Calculation and Analysis

To establish air mass persistence at each station by season for each year of the period of record, the historical "calendar" of SSC data was passed through a computer algorithm that calculated the mean air mass persistence (i.e., number of successive days of a given air mass type) (regardless of type), the maximum air mass persistence (regardless of type), and the type of air mass associated with the mean maximum persistence. This yielded a time series (1955-2015) of air mass persistence for each season at each SSC location. A simple linear regression was run on the mean air mass persistence using the year as the predictor (exploratory variable) and the mean persistence as the response (dependent variable). Further, a historical mean air mass persistence was calculated per season for each station, as was a historical mean maximum persistence.

The full data set was also separated into two halves: an early period of 30 years (December 1955- November 1985) and a late period of 30 years (December 1985- November 2015). The yearly mean and maximum air mass persistence values for each season at each station from the early and late periods were then subjected to a two-sample t-test to determine if air mass persistence was significantly different between the early and late periods.

Air mass persistence changes between the early and late period were mapped to illustrate spatial patterns. An inverse distance weighted (IDW) interpolation pattern was applied to the data to examine the spatial patterns. IDW determines the interpolation values using a linearly weighed combination of the given data points and assumes that the correlation between points decreases with distance. "A power or exponential function modifying the distance weight is often used to model spatial interaction between places" (Lu and Wong 2008). For this study, a power of two was used to interpolate values of air mass persistence at SSC stations to a grid across the CONUS. While some consider a power greater than 3 to be unreasonable (Bekele et al. 2003), others have used powers up to 5, to model spatial autocorrelation and patterns in nominal data (Ping et al. 2004). Given the spatial extent of synoptic-scale air masses, relative spatial homogeneity is assumed, and thus the lower power used in the IDW interpolation. The IDW was applied to a spatial resolution of 3.15 degrees latitude by 3.25 degrees longitude in size, to yield 140 grid cells across the CONUS.

Different interpolation methods were employed, before IDW was determined to be the most effective method. Other methods attempted included kriging, the accuracy of which Setianto and Triandini (2013) found to be similar to IDW. IDW was chosen instead of kriging because of its simplistic approach, and because of its past usage in examining spatial climate data. Daly (2006) identified IDW as a simpler, faster method to interpolate deviation from mean climatology to a grid, setting a precedent for the use of IDW in the spatial examination of climate data.

3.6 Statistical Validation

To determine the statistical significance of the results of the linear trend analyses and the two-sample t-tests, the p-value, or probability of obtaining a result equal to or more extreme than what was observed, was calculated for each station and season. The p-value was then referenced to a predetermined alpha value of 0.05, which serves as the probability threshold of a value being falsely identified as significant. Each tested variable with a p-value less than 0.05 was identified as showing a statistically significant change in air mass persistence either linearly through time (trend analysis) or between the early and late periods (two-sample t-test). A two-sample t-test was deemed an appropriate method for analyzing the data after validating the normality assumption. Normality was determined using the Kolmogorov-Smirnov test (Chakravarti et al. 1967) and the Anderson-Darling test (Stephen 1974). The results of each test concluded that the data used followed the theoretical normal distribution.

4 Results

4.1 Spatial Climatology of Air Mass Persistence

4.1.1 Mean Air Mass Persistence

For all seasons and all 60 years of the study period (1955-2015), the mean persistence of any air mass across the United States is 1.95 days with a standard deviation of 0.53 days. Stratifying by season reveals that summer is characterized by both the greatest mean persistence and greatest mean maximum persistence, followed in descending order by fall, winter, and spring (Table 4.1).

Table 4.1. Study period mean values for historical mean and mean maximum seasonal air mass persistence for the CONUS as a whole.

Season	Mean Persistence (days)	Standard Deviation (days)	Mean Maximum Persistence (days)	Standard Deviation (days)
Spring	1.78	0.36	7.00	3.25
Summer	2.17	0.78	9.34	5.26
Fall	1.99	0.65	8.50	4.96
Winter	1.87	0.34	7.57	3.26

The southwest United States and southern Florida are concentrated areas of higher mean air mass persistence during the spring season (Figure 4.1a), while a less homogeneous spatial pattern of mean persistence is evident during summer (Figure 4.1b) and fall (Figure 4.1c). The winter (Figure 4.1d) seasons exhibit greater homogeneity in air mass persistence across the United States, with the northwest portion of the country characterized by the least air mass persistence.

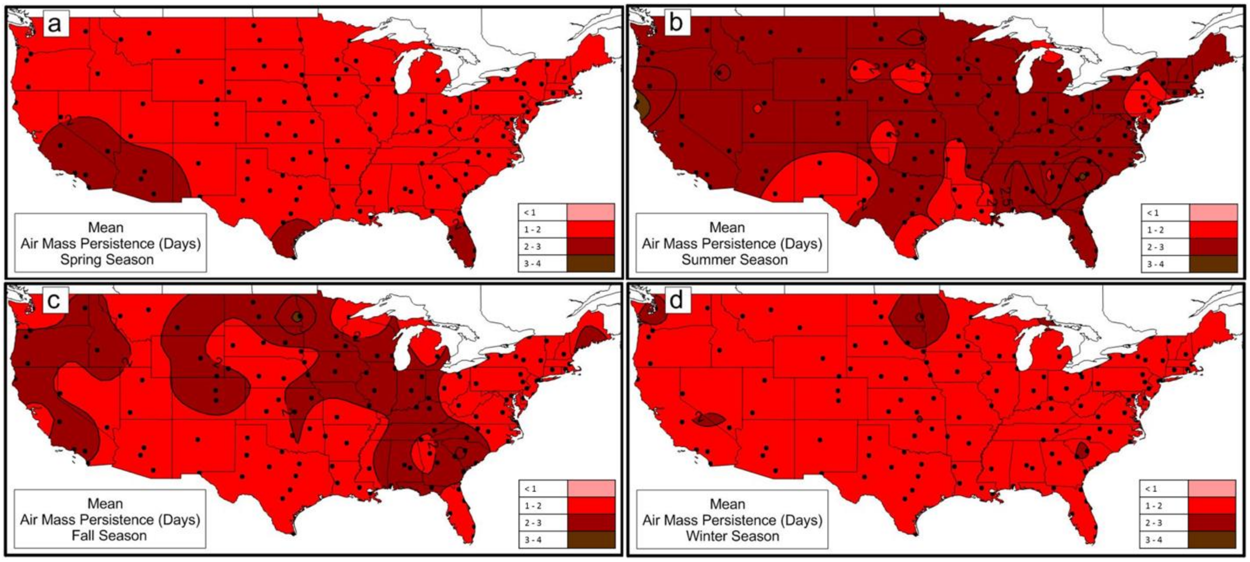


Figure 4.1: Historical mean air mass persistence for the period 1955-2015 across the United States during a) spring, b) summer, c) fall, and d) winter.

4.1.2 Mean Maximum Persistence

The mean maximum persistence of any air mass is 8.10 days with a standard deviation of 4.18 days for the total study period across CONUS. Mean maximum air mass persistence tends to be more spatially homogeneous than does mean air mass persistence throughout all four seasons (Figure 4.2a-d). There is a concentration of high mean maximum persistence in the southwest United States and southern Florida during the spring season, with lower mean maximum persistence in the Midwest and Northeast regions (Figure 4.2a). The Gulf Coast and the Southwest regions experience maximum persistence during the summer (Figure 4.2b). This pattern of higher maximum persistence in the southern part of the United States is consistent with the general concept of a more northerly-located polar jet stream during summer.

The pattern of maximum air mass persistence for the fall season is similar to that for the spring season, with the greatest mean maximum persistence in the southwest and southern Florida (Figure 4.2c). However, a southward migration of lesser persistence into the southern Great Plains is evident, while an increase in mean maximum persistence occurs in the Northwest and north-central Great Plains. This migration of lesser maximum persistence into the southern plains is expected as the polar jet stream tends to expand and migrate southward during the fall season, bringing more frequent air mass changes to the south and fewer to the north.

The winter mean maximum persistence has a different spatial pattern than the other three seasons (Figure 4.2d). However, high mean maximum persistence is still focused in the southwestern United States and southern Florida. Additionally, persistence increases northward along the west coast and along the Canadian border, with slightly lower mean maximum persistence just east of the Rocky Mountains. A unique aspect of winter is the low mean maximum persistence in the mid-Atlantic and Southeastern United States. The winter pattern is consistent with the spatial pattern of the transition air mass climatology for the winter produced by Sheridan (2002).

The presence of higher mean maximum persistence in the southwest CONUS and Florida may be a result of the typical location of the polar jet stream throughout the year. The polar jet stream retreats northward during the summer into the northern half of the United States and Canada, while it expands farther south during the winter. However, the polar jet stream infrequently migrates far enough south to introduce a new air mass in the Southwest and Florida. Similarly, the subtropical jet stream that is typically to the south of the southwestern CONUS and Florida, does not regularly migrate northward enough to significantly alter air mass type in the Southwestern CONUS and Florida.

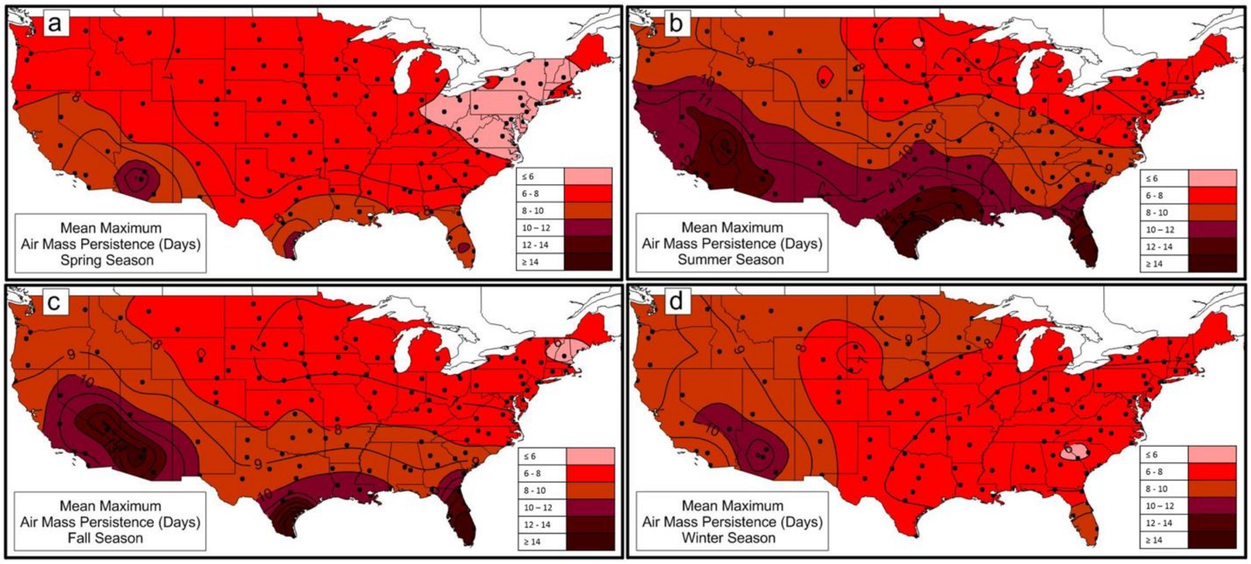


Figure 4.2: Historical mean maximum air mass persistence for the period 1955-2015 across the United States for a) spring, b) summer, c) fall, and d) winter.

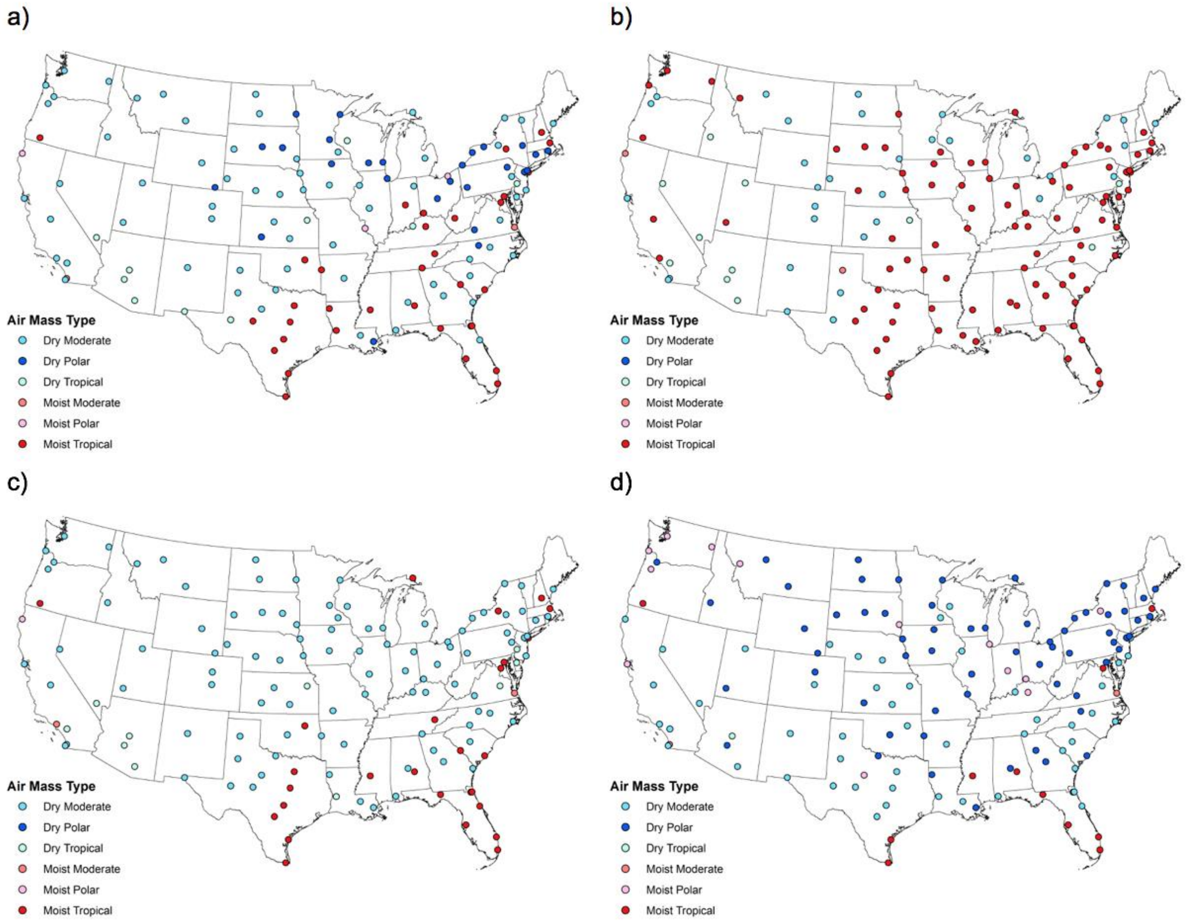


Figure 4.3. Mean maximum air mass type for the period 1955-2015 across the United States for a) spring, b) summer, c) fall, and d) winter.

The spatial pattern of the mean maximum air mass type for each season (Figure 4.3a-d) follows a pattern similar to what is evident for values of maximum mean persistence. For example, the Moist Tropical air mass is dominant across much of Texas and Florida during spring (Figure 4.3a), while the Dry Polar air mass type is dominant across the western United States. During the summer season the Moist Tropical air mass type is dominant across the eastern United States, most likely reflecting southerly return flow around the western periphery of the Bermuda high pressure center over the western Atlantic Ocean (Figure 4.3b).

The fall season is characterized by Moist Tropical air in southern Texas and southern Florida and drier, cooler air in the western United States (Figure 4.3c). By winter, there is a dominance of Dry Polar and Dry Moderate air across the United States (Figure 4.3d). Southeastern Texas and south Florida continue with Moist Tropical air through winter, however, east of the Appalachian Mountains and across much of the central Great Plains the Dry Polar air mass type is predominant. In the Pacific Northwest the Moist Polar air mass type is typical, which is consistent with the cool, wet winter season that is characteristic of the region.

4.1.3 Prominent Locations of Air Mass Persistence

While mean air mass persistence across the United States varies considerably, a few locations are prominent for the greatest mean persistence. West Palm Beach, Florida has the greatest mean and mean maximum persistence for spring with 2.77 days and 14.13 days respectively (Table 4.2 and 4.3). For the summer season, nearby Miami, Florida has the highest mean persistence and mean maximum persistence with values of 4.78 days and 23.52 days respectively. For the fall season, the data reveal that two Florida locations have the greatest mean persistence and greatest maximum persistence - Daytona Beach and West Palm Beach, respectively. Daytona Beach, Florida has a mean persistence of 2.96 days while West Palm Beach, Florida has a mean maximum persistence of 20.42 days. The winter season shows a shift westward out of Florida for the highest mean persistence and mean maximum persistence. Seattle-Tacoma, Washington has the highest mean of 2.08 days, and Boise, Idaho has a mean maximum persistence of 9.47 days. The winter season is characterized by notably lesser values of mean air mass persistence than the other three seasons.

Table 4.2. Locations with the greatest historical mean air mass persistence by season. Included is the deviation of the persistence from the mean value for the United States as a whole.

Season	Station	Mean Persistence (days)	Deviation from CONUS Mean (days)
Spring	West Palm Beach, Florida	2.77	+0.99
Summer	Miami, Florida	4.78	+2.61
Fall	Daytona Beach, Florida	2.96	+0.97
Winter	Seattle-Tacoma, Washington	2.08	+0.21

Table 4.3. Locations with the greatest historical mean maximum air mass persistence by season. Included is the deviation of the maximum persistence from the mean value for the United States as a whole.

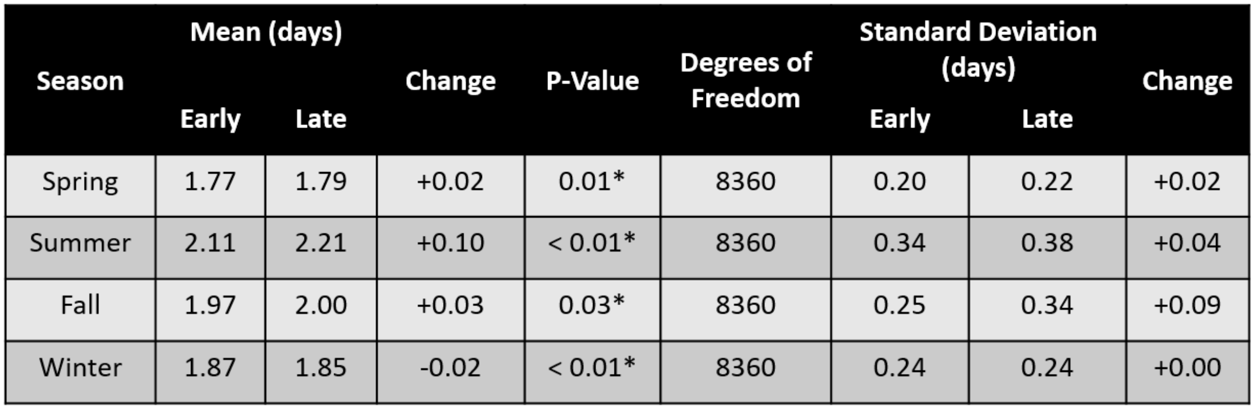
Season	Station	Mean Maximum Persistence (days)	Deviation from CONUS Mean Maximum (days)
Spring	West Palm Beach, Florida	14.13	+7.13
Summer	Miami, Florida	23.52	+14.18
Fall	West Palm Beach, Florida	20.42	+11.92
Winter	Boise, Idaho	9.47	+1.90

4.2 Temporal Climatology of Air Mass Persistence

As a 30-year period is generally considered to be the minimum time necessary to characterize the climate of a location, the characteristics of air mass persistence for each of the two halves of the 60-year study period ("early period" (1955-1985) and "late period" (1986-2015)) can be used to illustrate any change that occurred. Across the CONUS as a whole, the summer season is characterized by the largest change in mean air mass persistence – increasing by 0.10 days from the first to second half of the study period (Table 4.4). The positive change in mean persistence indicates that air masses across the CONUS became more stagnant over the period of record. This is especially the case when quantifying the change in mean maximum persistence, which increased by

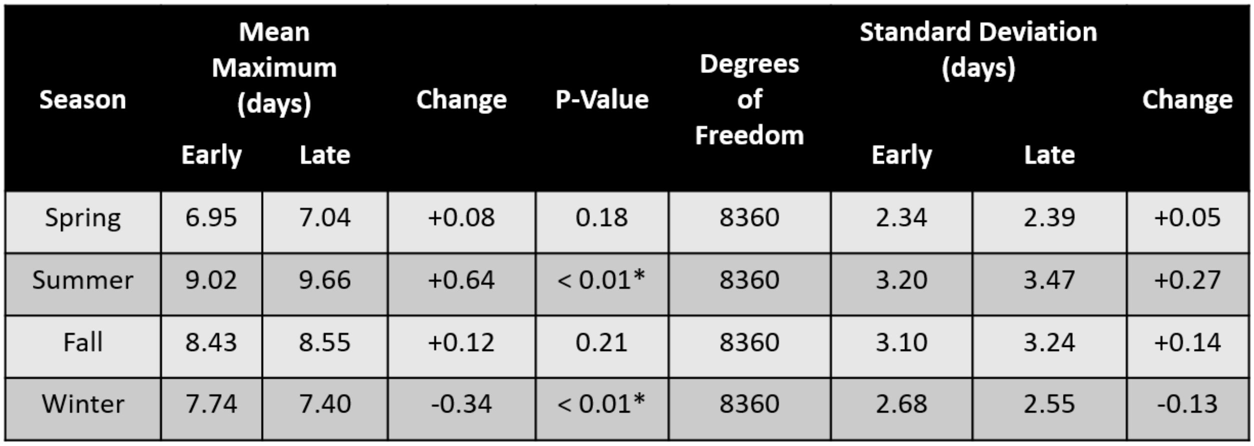
0.64 days during summer (Table 4.5), or double that of the next largest change. Winter is the only season characterized by a decrease in air mass persistence, as mean persistence decreased by 0.02 days (Table 4.4) and mean maximum persistence decreased by 0.34 days (Table 4.5).

Table 4.4. Thirty-year mean and standard deviation values for mean historical seasonal air mass persistence (days) for the United States for the periods 1955-1985 (early) and 1986-2015 (late). Included are the change in the mean and standard deviation between the two periods. The result (p-value) of the two-sample t-test of the difference in mean air mass persistence during the early and late periods for each season is indicated. Values marked with an asterisk (*) are considered significant, meaning the change in persistence between the early and late periods for that season was statistically significant.



Season	Mean (days)		Change	P-Value	Degrees of Freedom	Standard Deviation (days)		Change
	Early	Late				Early	Late	
Spring	1.77	1.79	+0.02	0.01*	8360	0.20	0.22	+0.02
Summer	2.11	2.21	+0.10	< 0.01*	8360	0.34	0.38	+0.04
Fall	1.97	2.00	+0.03	0.03*	8360	0.25	0.34	+0.09
Winter	1.87	1.85	-0.02	< 0.01*	8360	0.24	0.24	+0.00

Table 4.5. Same as Table 4.4 but for historical maximum air mass persistence.



Season	Mean Maximum (days)		Change	P-Value	Degrees of Freedom	Standard Deviation (days)		Change
	Early	Late				Early	Late	
Spring	6.95	7.04	+0.08	0.18	8360	2.34	2.39	+0.05
Summer	9.02	9.66	+0.64	< 0.01*	8360	3.20	3.47	+0.27
Fall	8.43	8.55	+0.12	0.21	8360	3.10	3.24	+0.14
Winter	7.74	7.40	-0.34	< 0.01*	8360	2.68	2.55	-0.13

A two-sample t-test was performed on the seasonal mean air mass persistence and seasonal mean maximum air mass persistence for the early and late periods (Table 4.4 and Table 4.5). The change in mean persistence was statistically significant (<0.05) for each season, with the change being most significant for the summer season (i.e., the lowest p-value). The only seasons that had a significant change in mean maximum persistence were the summer and the winter, which are the seasons when the atmosphere is generally less transitional in nature, allowing air masses to remain over a location longer than during the spring and fall seasons.

Not surprisingly, summer had the most stations with a significant change in air mass persistence between the early and late periods. The difference in mean summer air mass persistence was found to be significant (p-value <0.05) at 35 of the 140 stations (25%), while the difference in mean maximum air mass persistence was found to be statistically significant at 20 of the 140 stations (14%) (Table 4.6).

Table 4.6. The number of stations characterized by a statistically significant change in historical seasonal air mass persistence and maximum air mass persistence between the early (1955-1985) and late (1986-2015) periods.

Season	Mean Persistence #/140 (% significant)	Mean Maximum Persistence #/140 (% significant)
Spring	15 (10.71)	6 (4.29)
Summer	35 (25.00)	20 (14.29)
Fall	13 (9.29)	10 (7.14)
Winter	8 (5.71)	6 (4.29)

Table 4.7. The number of stations exhibiting an increase, decrease, or no change in historical seasonal air mass persistence and maximum air mass persistence between the early (1955-1985) and late (1986-2015) periods

Season	Increase in Mean Persistence #/140 (%)	Decrease in Mean Persistence #/140 (%)	No Change in Mean Persistence #/140 (%)	Increase in Mean Maximum Persistence #/140 (%)	Decrease in Mean Maximum Persistence #/140 (%)	No Change in Mean Maximum Persistence #/140 (%)
Spring	80 (~57)	57 (~41)	3 (~2)	66 (~47)	71 (~51)	3 (~2)
Summer	114 (~81)	25 (~18)	1 (< 1)	104 (~74)	34 (~25)	2 (< 1)
Fall	70 (~50)	68 (~49)	2 (< 1)	70 (~50)	67 (~48)	3 (~2)
Winter	38 (~27)	100 (~72)	2 (< 1)	35 (~25)	104 (~74)	1 (< 1)

The summer season had the most stations with an increase in air mass persistence (whether statistically significant or not), with 81% of the stations characterized by an increase in air mass persistence, and 74% of the stations experiencing an increase in maximum air mass persistence. A majority of the stations evidenced an increase in mean persistence through the spring, summer, and fall, however, 72% of the stations exhibited a decrease in air mass persistence during winter. Summer and fall were the only seasons that had a majority of stations characterized by an increase in maximum air mass persistence from the early to late periods. For spring and winter, 50% and 74% of stations, respectively, experienced a decrease in maximum air mass persistence (Table 4.7).

4.2.1 Spring Season

The spring season is characterized by the second largest percentage of stations that recorded a statistically significant change in air mass persistence. There seems to be a north-south stratification of the type of change in air mass persistence from the early period to the late period (Figure 4.4). The minimal change (-0.025 < 0 < 0.025) line transverses the CONUS, starting in northwest Washington and extending as far south as the Texas panhandle, and then back north into the mid-Atlantic states. To the north, spring air mass persistence decreased, while it increased to the south (Figure 4.4).

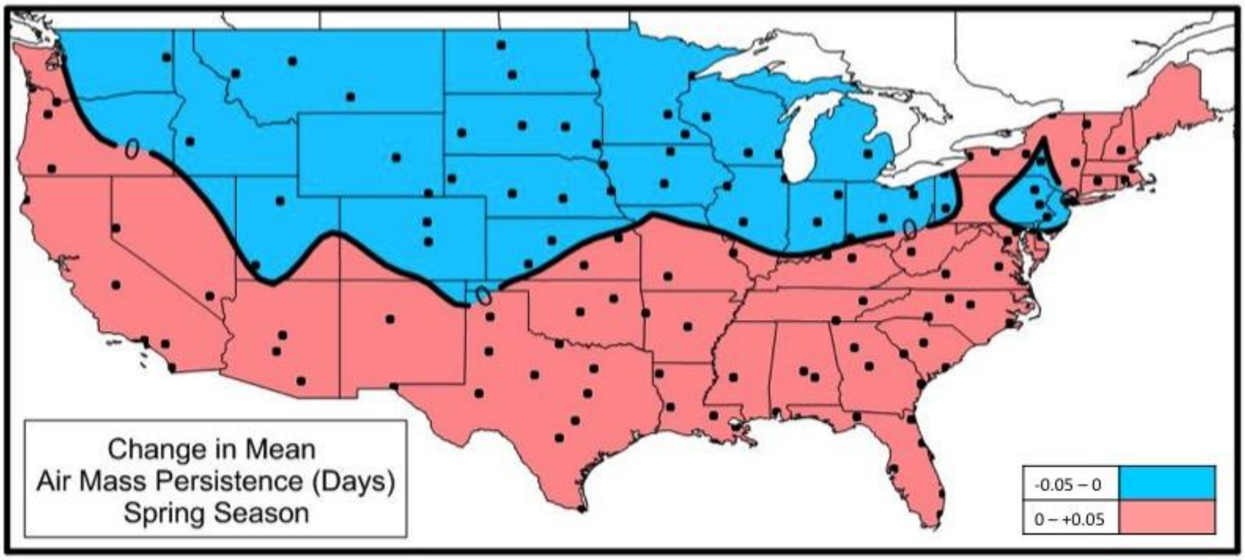


Figure 4.4. Change in mean spring air mass persistence between the early and late periods.

For example, West Palm Beach, Florida recorded the most statistically significant change (p-value <0.01) with an increase of 0.54 days in air mass persistence (Figure 4.5). Through the 60-year study period, spring air mass persistence at West Palm Beach is positively linearly correlated with time (r = +0.37, p-value = 0.01). Nine of the fifteen stations characterized by a statistically significant change in spring air mass persistence exhibited a decrease in the persistence of air masses.

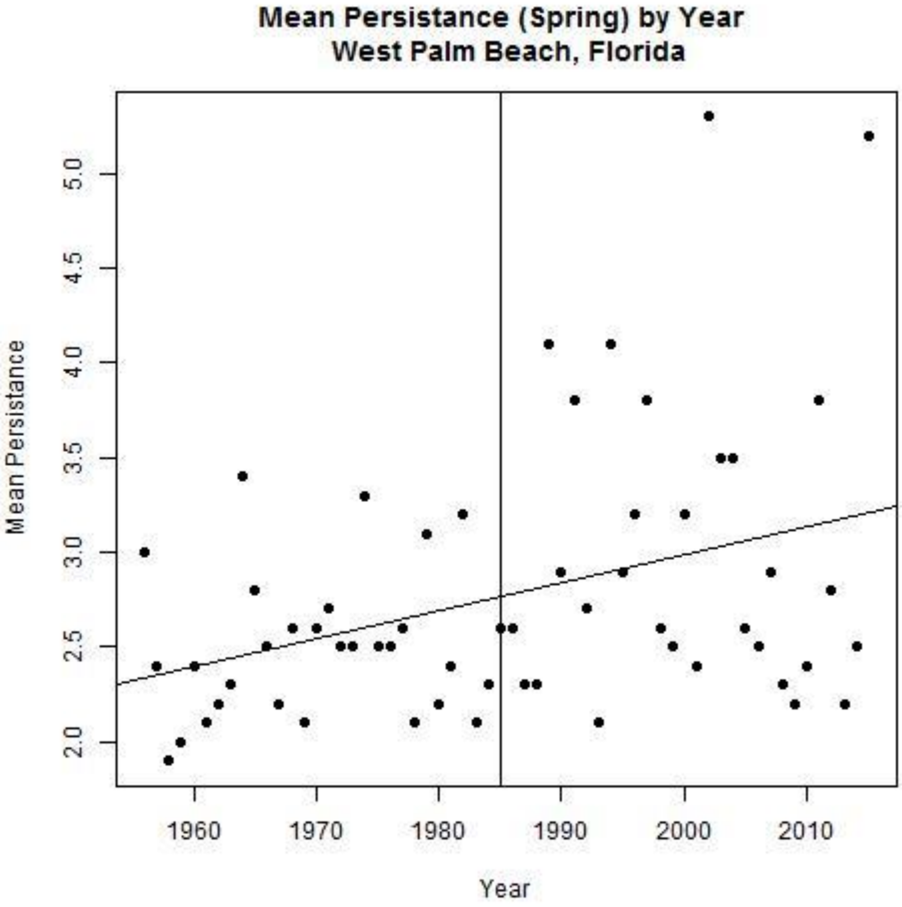


Figure 4.5. Mean spring air mass persistence through the period of record at West Palm Beach, Florida. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

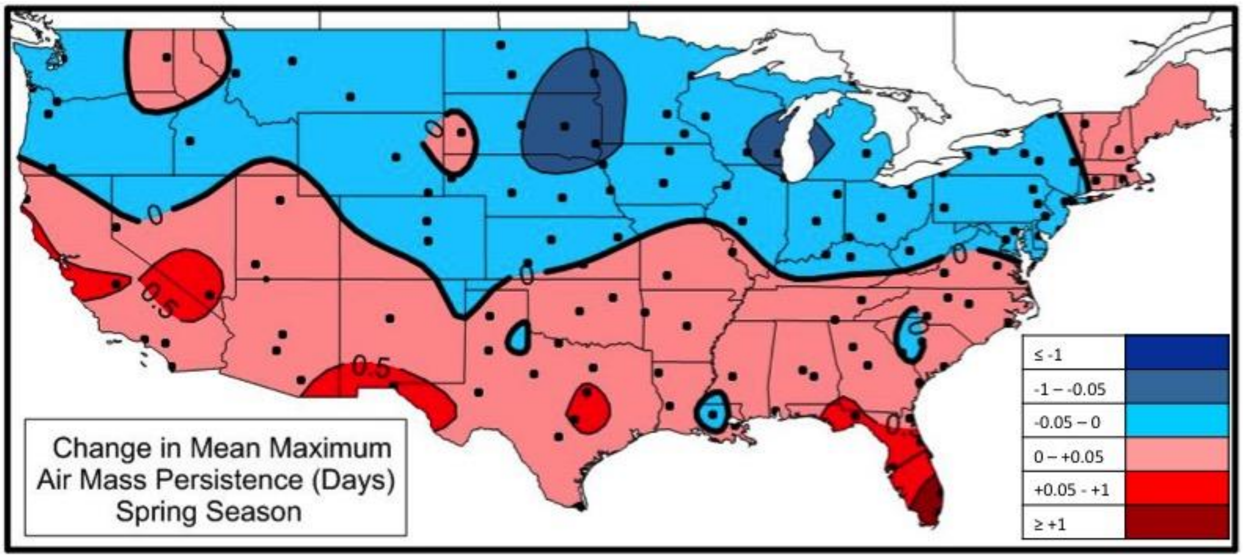


Figure 4.6. Change in maximum spring air mass persistence across the United States between the early and late periods.

The mean maximum air mass persistence has a similar pattern to mean air mass persistence during the spring season (Figure 4.6). Charleston, South Carolina experienced the most statistically significant change (p-value <0.01) in air mass persistence between the first and second halves of the historical record (Figure 4.7), while Miami, Florida is characterized by the largest change in maximum air mass persistence with an increase of 4.67 days between the early and late periods. Through the 60-year study period, maximum spring air mass persistence at Charleston is positively linearly correlated with time (r = +0.38, p-value = 0.30).

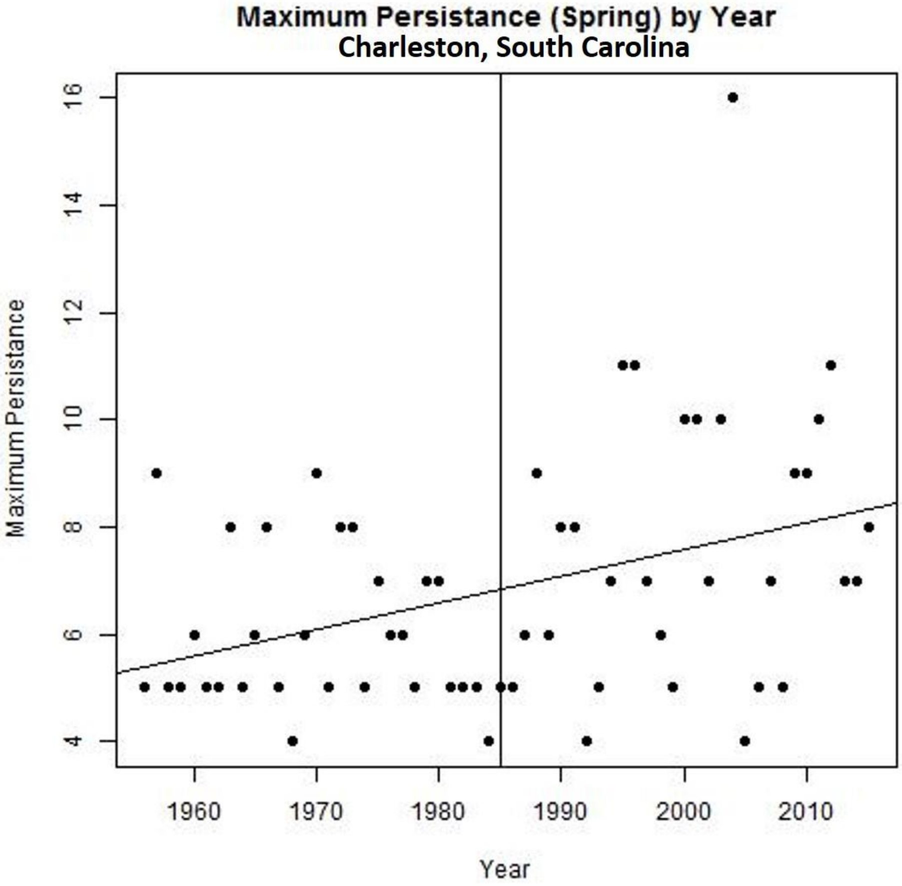


Figure 4.7. Mean Maximum spring air mass persistence through the period of record at Charleston, South Carolina. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

4.2.2 Summer Season

An increase in summer air mass persistence has dominated the continental United States over the past 60 years (Figure 4.8). Mean air mass persistence has increased across most of the United States, except for large portions of Montana and North Dakota and a smaller scale decrease in northeast Florida. These localized decreases in air mass persistence may be attributed to relatively minor changes in the air mass type over that region, such as changing from Moist Tropical (MT) to Moist Moderate (MM), which could be a reflection of air mass modification rather than true air mass change. Further, some changes in air mass type may be local in nature, such as influences of marine boundary layers at coastal locations or local wind regimes in areas of terrain, such as warming katabatic winds.

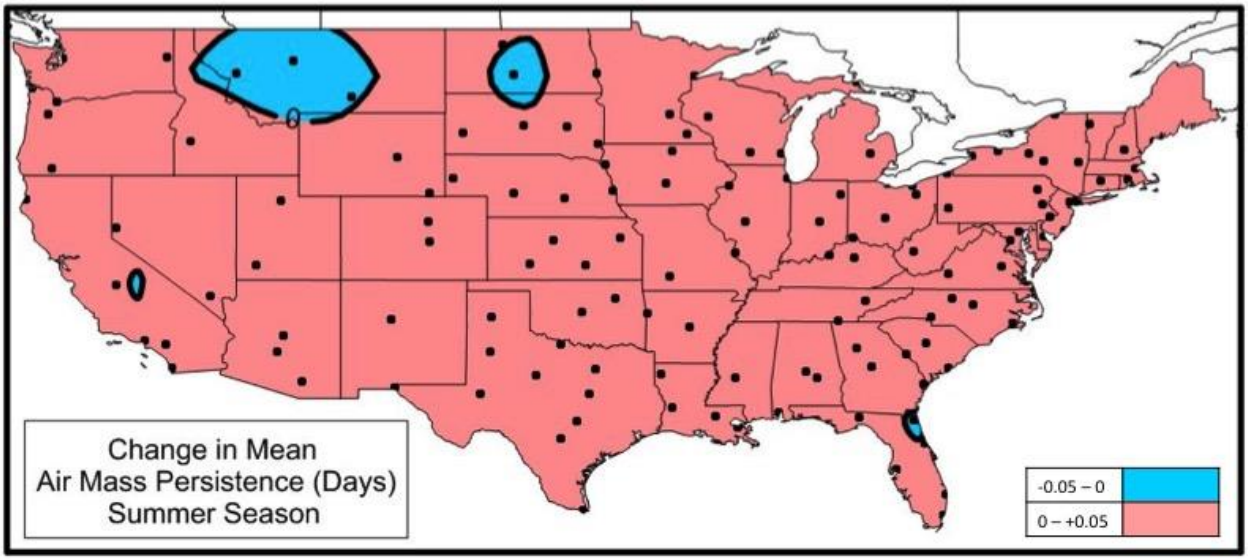


Figure 4.8. Change in mean summer air mass persistence across the United States between the early period and late periods.

Erie, Pennsylvania recorded the most statistically significant change between the early and late periods with a p-value <0.01 and a change of +0.21 days (Figure 4.9). Further, there is a positive linear correlation (r = +0.60, p-value = 0.943) between time (year) and mean air mass persistence for Erie. However, while the correlation between year and mean air mass persistence for Erie, Pennsylvania seems to be strong, there is insufficient evidence to conclude that the relationship is only cause-and-effect between the two variables and not influenced by other variables.

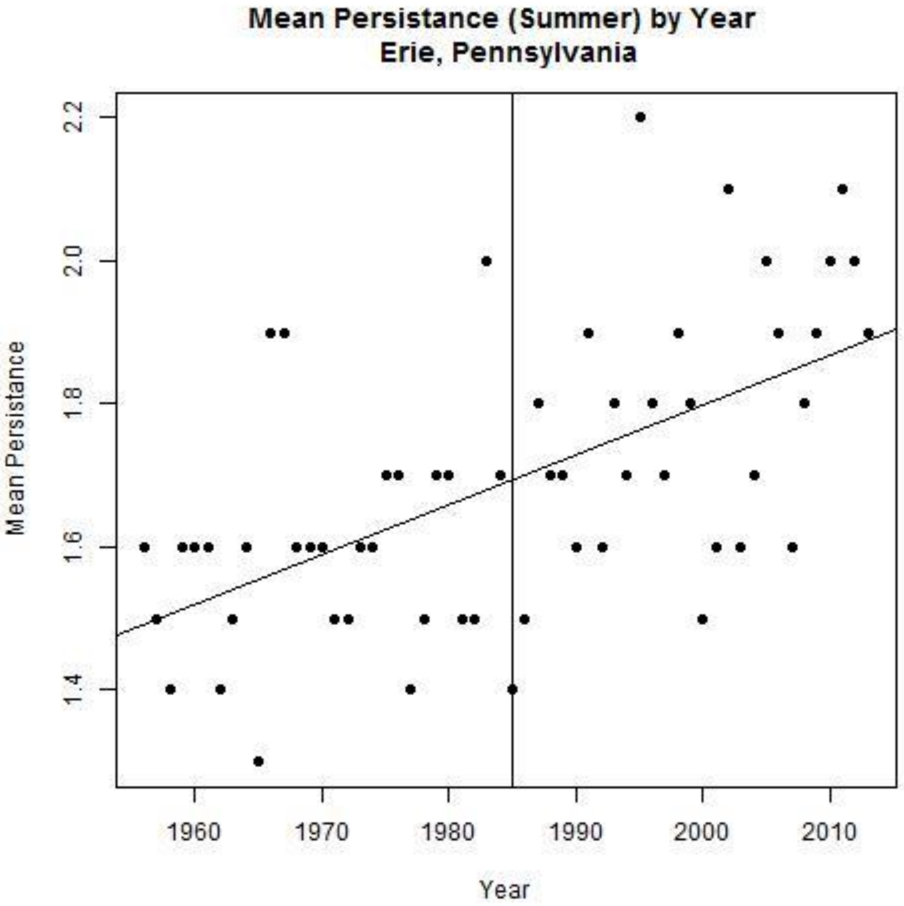


Figure 4.9. Mean summer air mass persistence through the period of record at Erie, Pennsylvania. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

The largest change in mean summer air mass persistence (+0.97 days) between the early and late periods occurred at West Palm Beach, Florida. Only two stations recorded a statistically significant decrease in summer air mass persistence: Denver, Colorado, and Tallahassee, Florida. The decreases in Denver and Tallahassee were small, local deviations, and due to the nature of the interpolation technique used, these decreases were masked by the increases at surrounding stations in Figure 4.8. The remaining 33 stations with a statistically significant change in summer air mass persistence where characterized by an increase in persistence from the first to second halves of the record.

Mean maximum summer air mass persistence generally increased across the United States, except for the area through the west-central plains (Figure 4.10). This decrease indicated a change toward more frequent air mass transitions on the leeward side of the Rocky Mountains. The potential influence of mountain ranges is also evident in the Cascade Mountains region in western Washington. Other influences that led to the decrease in air mass mean maximum persistence in some of the coastal locations may be influential marine boundary layers, such as in California (Figure 4.10). Overall there is a dominant pattern of increasing mean and mean maximum summer air mass persistence across the United States during the past 60 years.

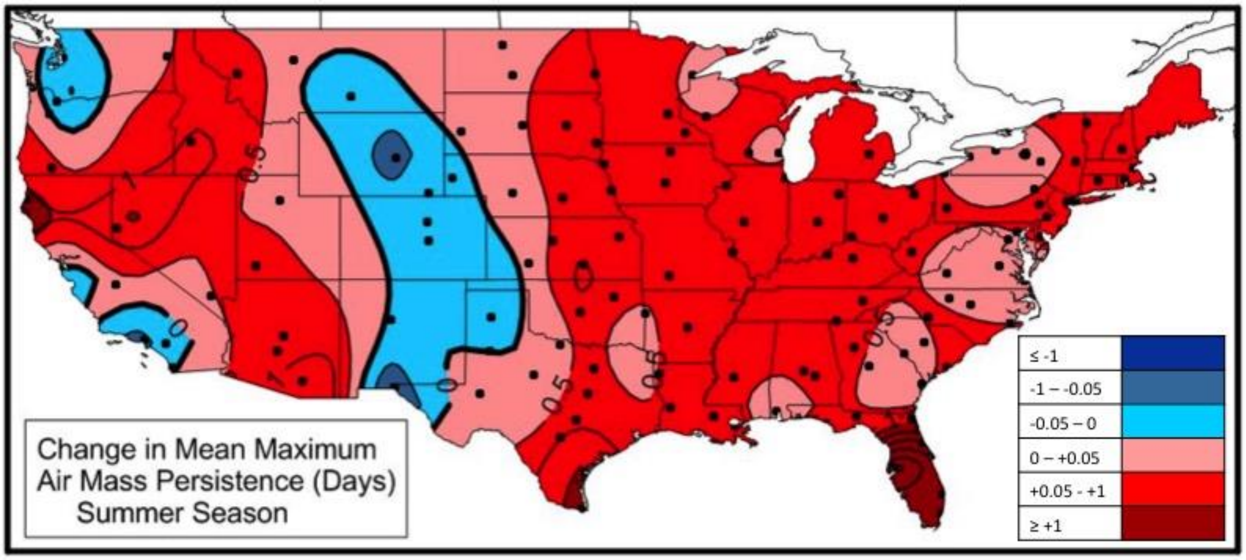


Figure 4.10. Change in mean maximum summer air mass persistence across the United States between the early and late periods.

Erie, Pennsylvania experienced the most statistically significant change in mean maximum summer air mass persistence with a p-value < 0.01 and an increase of 2.14 days (Figure 4.11). Similar to mean air mass persistence, there is a moderate positive linear correlation (r = +0.40, p-value = 0.02) between time (year) and mean maximum air mass persistence for Erie, Pennsylvania. The location with the largest non-statistically significant change in mean maximum summer air mass persistence from the first to second half of the record was Tampa, Florida, which experienced an increase of 4.33 days in mean maximum persistence from 11.33 days (early period) to 15.66 days (late period).

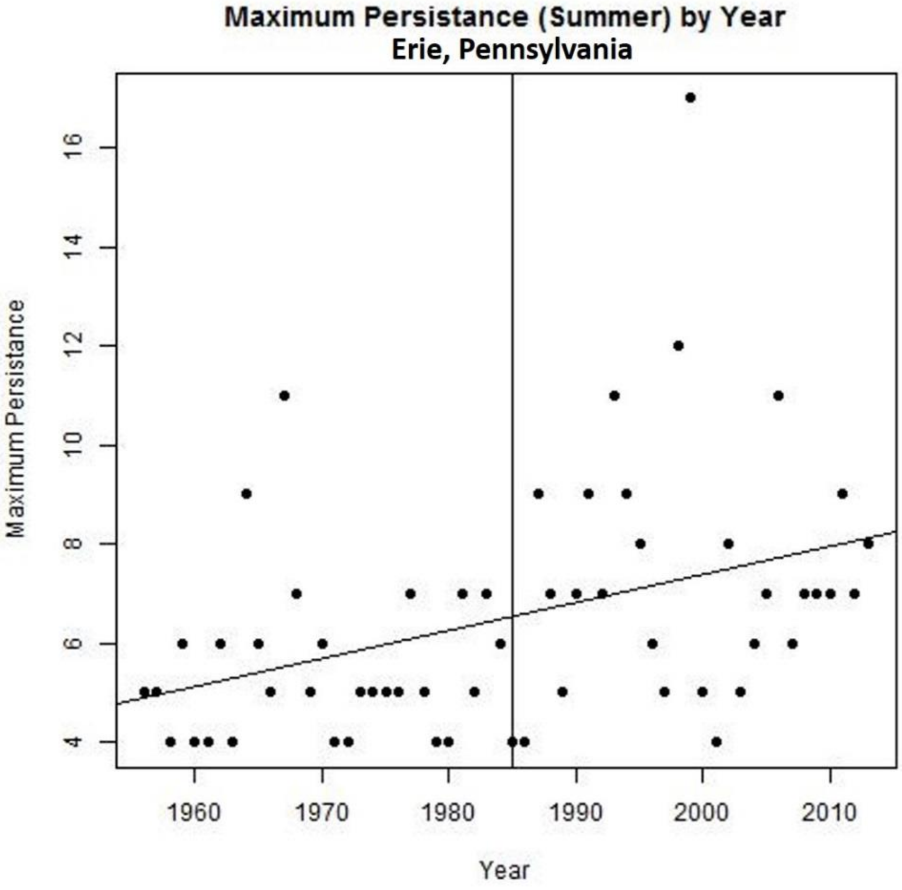


Figure 4.11. Mean maximum summer air mass persistence through the period of record at Erie, Pennsylvania. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

4.2.3 Fall Season

An increase in fall air mass persistence is clear in much of the central and eastern portions of the United States, while the western part of the United States has been dominated by a decrease in fall air mass persistence over the past 60 years (Figure 4.12). While relatively few stations experienced a statistically significant change in fall air mass persistence, the station with the most significant change was Denver, Colorado (p-value < 0.01) with a decrease of 0.15 days from the first half of the record to the second half (Figure 4.13).

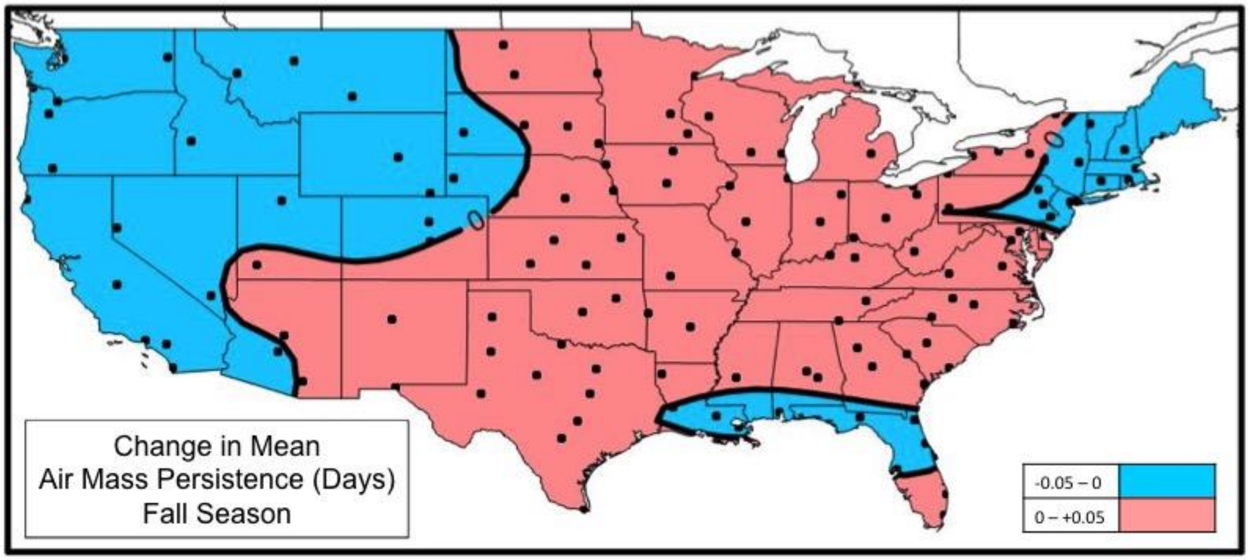


Figure 4.12. Change in mean fall air mass persistence across the United States between the early and late periods.

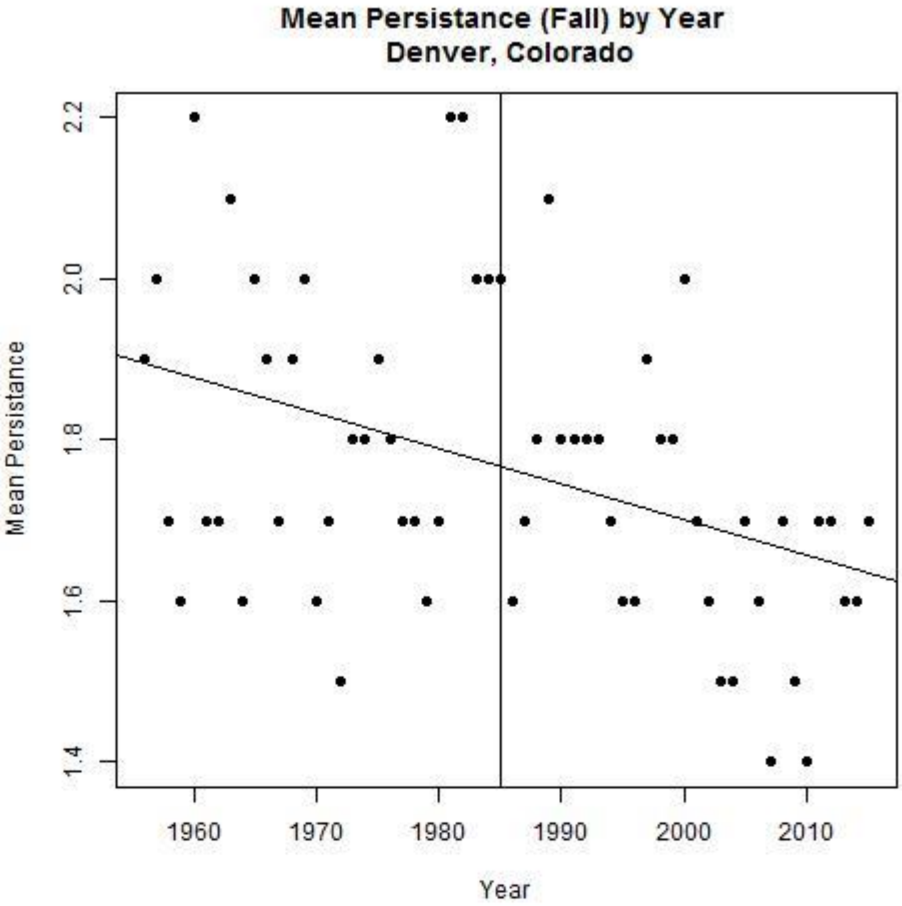


Figure 4.13. Mean fall season air mass persistence through the period of record for Denver, Colorado. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

Denver was one of four locations that recorded a statistically significant decrease in air mass persistence during fall, characterized by a moderately negative linear correlation between time (year) and mean air mass persistence (r = -0.40). In addition to Denver, Rapid City, South Dakota (-0.09 days) comprised the only statistically significant decrease in air mass persistence for the fall season from the first to second half of the historical record. The remaining nine stations with a statistically significant change in air mass persistence experienced an increase, with Miami, Florida experiencing the largest change of +0.75 days.

There is little spatial homogeneity in the change in mean maximum air mass persistence for the fall season across the United States (Figure 4.14). The west-central plains just to the east of the Rocky Mountains is an area of decreased air mass persistence, however, a noticeable increase in mean maximum persistence exists in the western United States, as well as across Florida and through the central Great Plains and Midwest. Most of the eastern United States experienced a decrease in mean maximum fall season air mass persistence between the early and late periods. Compared to the spring and summer seasons, the change in mean maximum air mass persistence during the fall has a more discontinuous spatial pattern.

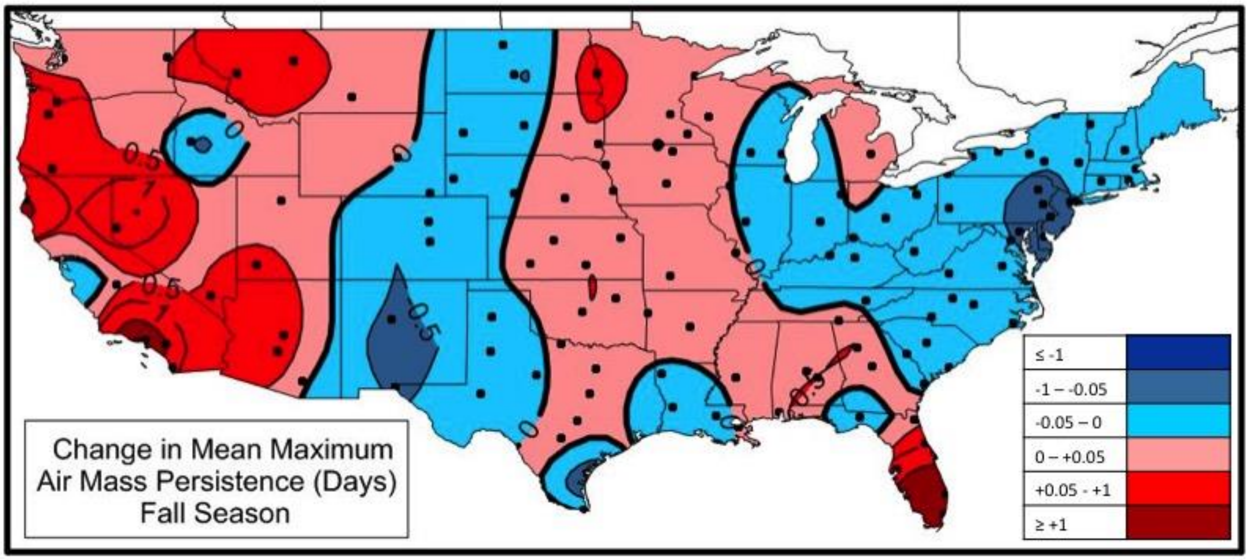


Figure 4.14. Change in mean maximum fall air mass persistence across the United States between the early and late periods.

The mean maximum air mass persistence for the fall season changed in a statistically significant way for relatively few stations. Missoula, Montana experienced the most statistically significant change in mean maximum fall air mass persistence with an increase of 1.53 days (p-value < 0.01) (Figure 4.15). There is minimal linear correlation between time (year) and mean maximum persistence (+0.16) for Missoula.

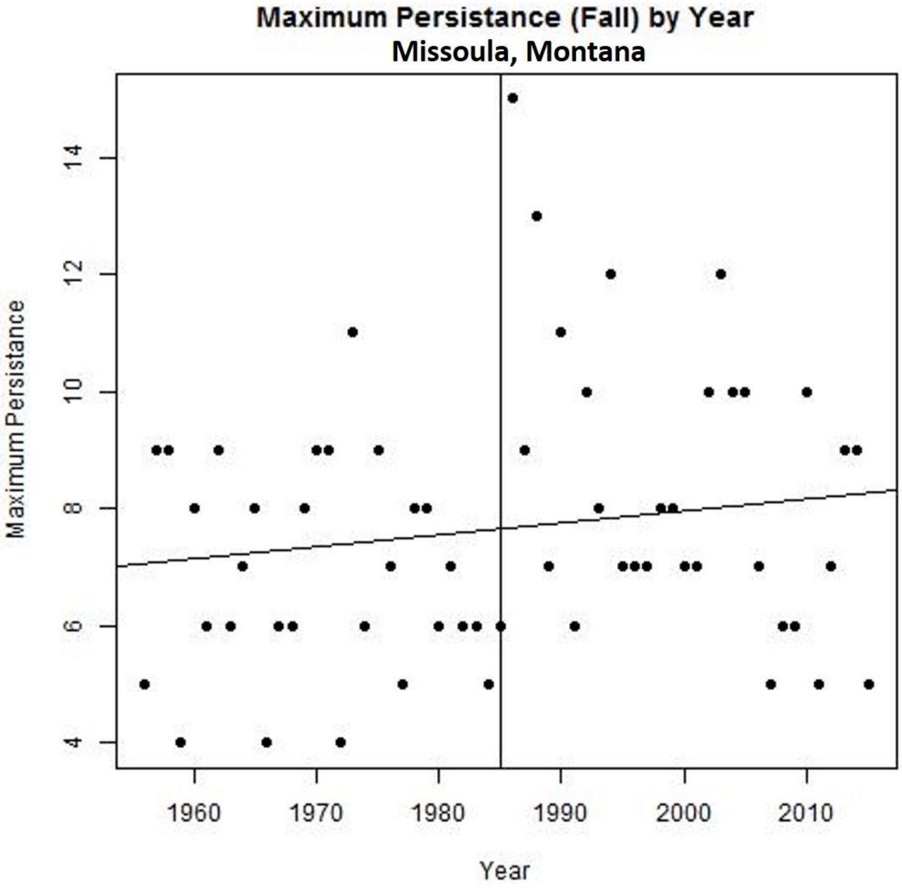


Figure 4.15. Mean fall season maximum air mass persistence through the period of record for Missoula, Montana. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

While not as statistically significant as the change at Missoula, West Palm Beach, Florida experienced the largest change in mean maximum air mass persistence with an increase of 4.43 days from the first half of the record to the second half. Of the ten stations with a statistically significant change in mean maximum air mass persistence across the two halves of the historical record, four experienced significant decreases: Newark, New Jersey (-1.2 days), Allentown, Pennsylvania (-1.1 days), San Francisco, California (-1.8 days), and Philadelphia, Pennsylvania (-1.1 days). The other six stations all experienced increases of greater than one day between the early and late period.

4.2.4 Winter Persistence

Of the four seasons, winter possessed the fewest stations experiencing a significant change in both mean air mass persistence and mean maximum air mass persistence. The predominant pattern for the winter season is one of decreasing mean air mass persistence between the two halves of the historical record (Figure 4.16).

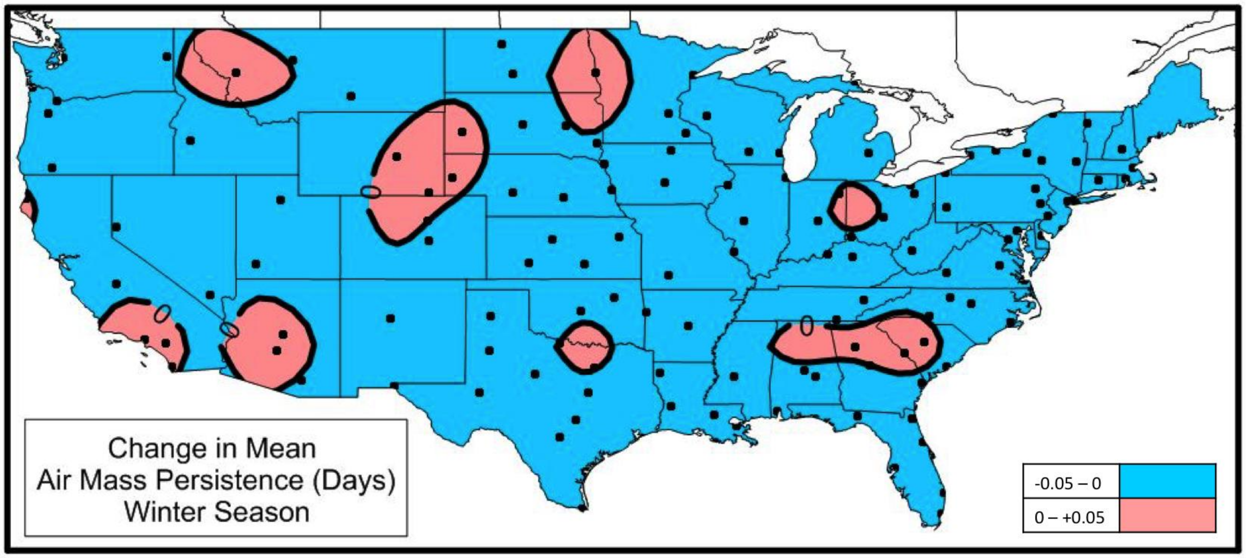


Figure 4.16. Change in mean winter air mass persistence across the United States between the early period and late period.

Erie, Pennsylvania, again, experienced the most statistically significant and largest change in mean air mass persistence between the two study periods with a decrease of 0.17 days (p-value < 0.01) (Figure 4.17). The correlation between time (year) and mean winter air mass persistence is moderately negative (r = -0.35, p-value < 0.01) for Erie.

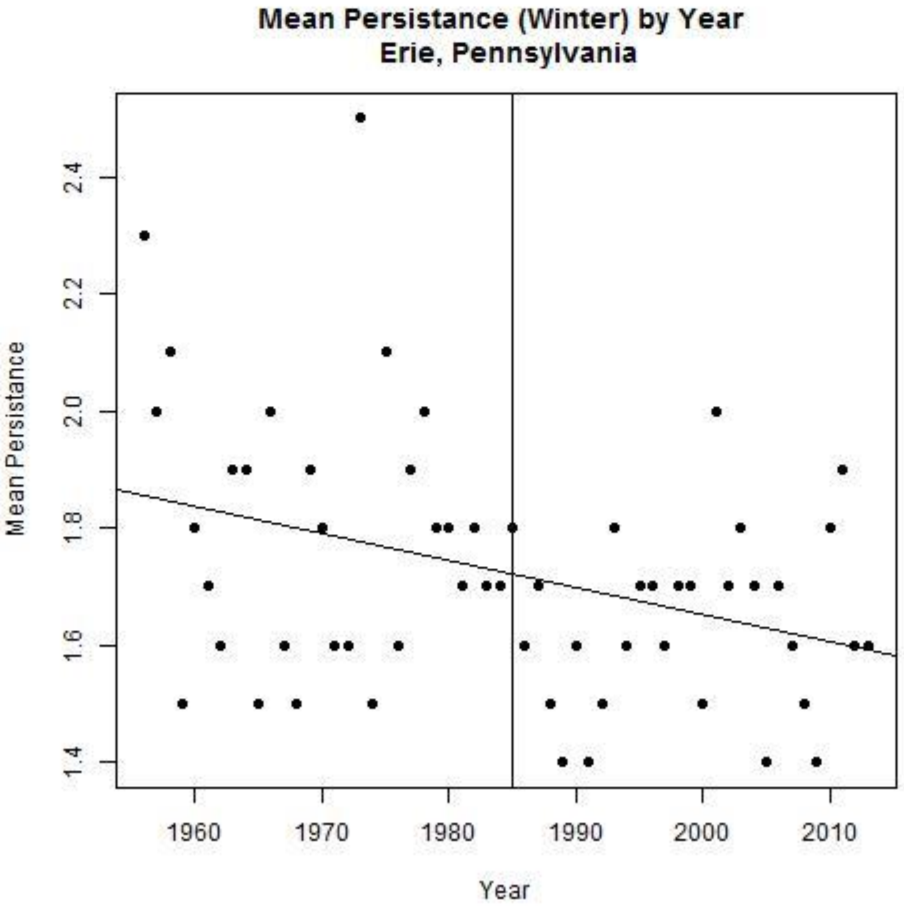


Figure 4.17. Mean winter season air mass persistence through the period of record for Erie Pennsylvania. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

Six of the eight stations with a statistically significant change in mean winter air mass persistence between the first and second halves of the historical record experienced a decrease. As was the case for mean air mass persistence, there is a predominant pattern of decreased maximum winter season air mass persistence across the United States (Figure 4.18). A few locations across the eastern half of the United States experienced an increase in mean maximum winter air mass persistence, but none of these increases was statistically significant.

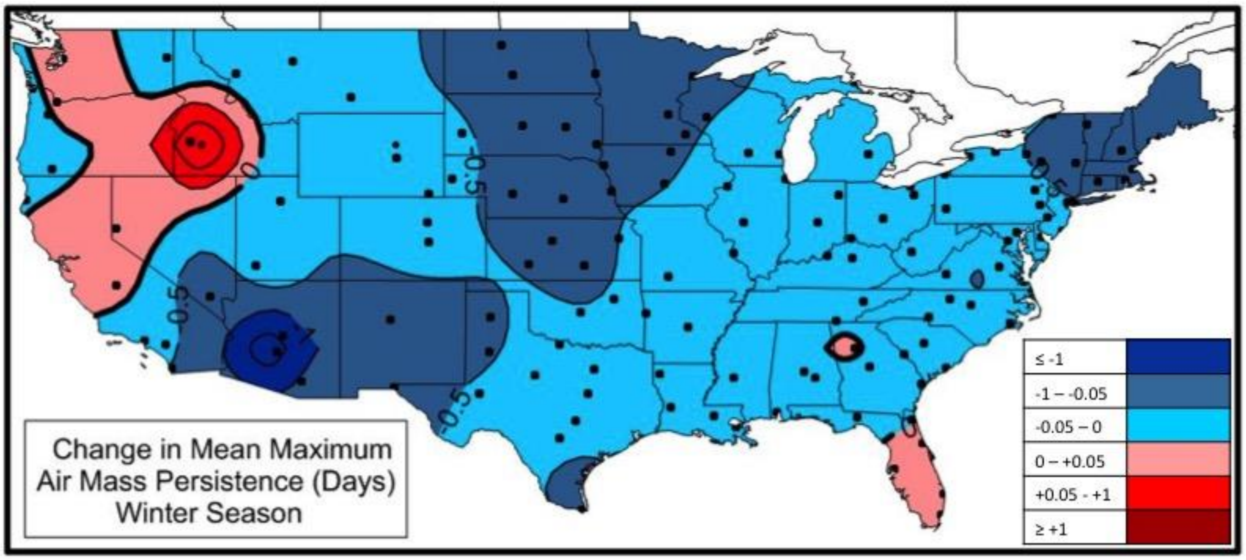


Figure 4.18. Change in mean maximum winter air mass persistence across the United States between the early period and late period.

Rapid City, South Dakota experienced the most statistically significant change, with a decrease of 1.83 days (p-value = 0.01) (Figure 4.19). Mean maximum winter air mass persistence at Rapid City is moderately negatively correlated with time (year) (r = -0.25, p-value < 0.01).

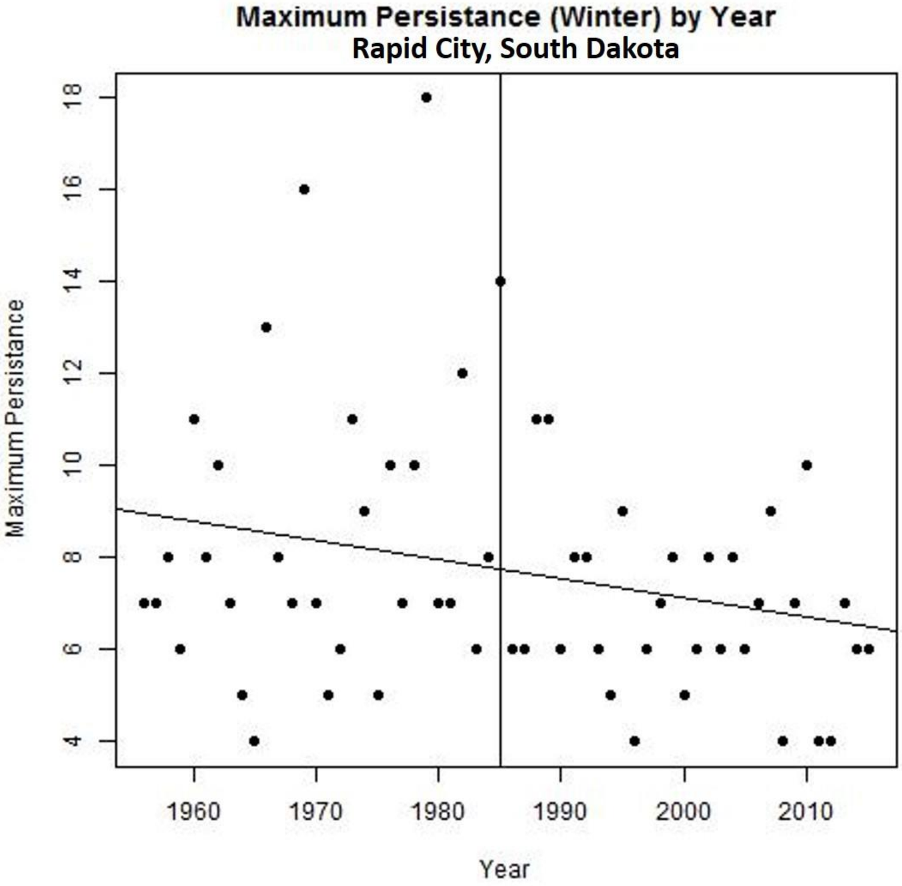


Figure 4.19. Mean maximum winter season air mass persistence through the period of record for Rapid City, South Dakota. The linear trend line is indicated, while the mid-point of the historical record is indicated by the vertical line.

The station with the largest change in winter season maximum air mass persistence between the first and second halves of the historical record was Erie, Pennsylvania, with a decrease of 1.95 days. The only station to record a significant increase in mean maximum air mass persistence during the winter season was Boise, Idaho with an increase of 1.94 days.

5 Discussion and Conclusions

Climate change engages the notion that changes in variables, for example air temperature, have occurred or will occur, but that also the broader dynamics of the global climate system have changed or will change. This includes the possibility of changes in the large-scale circulation of the atmosphere. One way that changing climate dynamics may materialize is through changes in surface-based expression of the dynamics of the atmosphere, such as air masses. Today, deriving air mass type based on the source region is generally viewed as outdated and inferior to newer methods that consider air mass modification as the air mass moves out of the source region. Upon modifying, the air mass can develop characteristics that are substantially different from those of the source region, in some cases altering the classification of the air mass. While the science of automated air mass identification has advanced greatly over the past decade, much of the recent applied research involving air masses has narrowly related their character and frequency to human health problems, particularly oppressive heat and dangerously high pollution. Far fewer studies have used air mass classifications as a mechanism to demonstrate changes in the atmosphere. Understanding longer-term variability in air mass frequency and persistence is a potentially informative means to understanding how the atmosphere is dynamically responding to global climate change.

The goals of this study were to (1) characterize the climatological characteristics of air mass persistence over the past 60 years across the continental United States, (2) to determine if air mass persistence across the continental United States appreciably changed over the course of the 60-year period, and (3) to hypothesize what these changes may indicate about changes in mid-latitude atmospheric dynamics in conjunction with global warming. At the outset of the study, the hypotheses were that air mass persistence exhibited significant temporal variation during the past 60 years, and that a change toward air mass stagnation occurred, most likely across the southern tier of the country in accord with theories of northward migrating polar jet stream dynamics. Recent research (e.g. Hondula 2011) has suggested that global jet streams have shifted poleward in conjunction with a warmed planet.

This study utilized daily air mass data from the Spatial Synoptic Classification (SSC) database for 140 stations across the continental United States. From these data, a mean and maximum air mass persistence was quantified for each of the 140 stations annually and by season. To analyze any trends throughout the study period a simple linear regression trend analysis was conducted using the full data record. The data were then divided into two halves (early and late period) and a two-sample t-test was used to determine any statistically significant (p-value < 0.05) changes in air mass persistence at all 140 stations.

The spatial variability of mean air mass persistence across the United States varies by season, presumably dictated by the general weather patterns typical for each season. A typically more dynamic atmosphere during the winter and spring seasons yields less air mass persistence, while a less dynamic atmospheric pattern during summer yields greater persistence across the United States. Greatest persistence during summer is expected, as the polar jet stream typically migrates to the northern part of the United States and across Canada, such that the synoptic forcing at the surface across the United States is not as strong as in other seasons. Results reveal that indeed summer has the highest mean air mass persistence (2.17 days) for the CONUS as a whole, while the winter season has the lowest (1.87 days). The fall season is characterized by a mean persistence between summer and winter with 1.99 days. Seasonality is most evident in the patterns of mean maximum air mass persistence for the United States as a whole, with the summer season exhibiting the greatest mean maximum air mass persistence (9.34 days), and the winter season characterized by the least (7.57 days). The mean maximum persistence reveals pronounced stagnation of air masses in the southwest United States and south Florida, presumably due to relatively little influence from the polar jet stream in those locations throughout the year.

Examining differences in air mass persistence between the early and late periods of the 60-year historical record may indirectly reveal differences in atmospheric dynamics at the synoptic scale. The results of this research reveal that the summer season experienced the largest and most spatially pervasive change in both mean and mean maximum air mass persistence between the early and late periods, with 25% of the stations studied experiencing a significant increase in air mass persistence. The summer season also had the highest percentage of stations (81.4%) experiencing an increase (regardless of statistical significance) in mean and mean maximum air mass persistence between the two periods.

Only during the winter season did the mean air mass persistence decrease for the majority of the stations analyzed, with 71.4% of the stations indicating a decrease in persistence from the first half to the second half of the historical record. In very general terms, this result suggests a potential increase in atmospheric dynamics across the United States, which may suggest more frequent north-south oscillation of the polar jet stream, which is often positioned within the United States in winter.

The spring season exhibits a north/south stratification of change in mean air mass persistence that is not present in the other three seasons. This north/south pattern is reminiscent of the polar jet stream position across the CONUS in winter and spring. The change in mean maximum air mass persistence exhibited a slight north/south pattern, but not as pronounced as for the change in mean air mass persistence. Mean maximum spring air mass persistence exhibited an increase in the southwest United States and the southeast United States, while values across the Midwest region predominantly decreased.

Mean air mass persistence has a more homogeneous pattern of increased persistence during summer than spring. In many cases, the changes at individual locations are rather profound. For example, the largest change in mean maximum summer air mass persistence occurred in Tampa, Florida, with an increase in the persistence of Moist Tropical air by 4.33 days from the first to second half of the period of record. Change in mean maximum air mass persistence for the summer exhibits a pattern that highlights the leeward side of the Rocky as areas of decreasing mean maximum persistence. In contrast, areas to the west of each the mountain systems were characterized by an increase in the mean maximum persistence.

The fall season is characterized by an inhomogeneous spatial pattern of change in mean air mass persistence, with increased persistence in the Midwestern United States through the Mid-Atlantic region, and with decreased persistence west of the Rocky Mountains. Change in mean maximum persistence exhibited a clear decrease east of the Rocky Mountains and an increase west of the Rockies. For the fall season, the Rocky Mountain range appears to be a delineator of increased and decreased air mass persistence. The winter season, much like the fall season, exhibited very little homogeneity in change in air mass persistence. However, in winter, decreased mean air mass persistence and mean maximum air mass persistence is present across much of CONUS, with the exceptions being southern Florida, and portions of California, Nevada, Idaho, and Oregon. This general pattern of decreasing persistence suggests that the frequency of synoptic scale systems that cycle air masses at the surface may have increased.

The most noticeable significant change in air mass persistence is in Florida. Three locations in Florida experienced statistically significant increases in mean air mass persistence or mean maximum air mass persistence over the two halves of the 60-year historical record. West Palm Beach experienced the largest statistically significant increase in mean and mean maximum air mass persistence for the spring, and the largest significant increase in mean maximum air mass persistence during fall. Miami experienced the largest statistically significant change in air mass persistence for the summer season, while Daytona Beach experienced the largest statistically significant change during fall. While Florida was the dominant area of significant increase in air mass persistence for the spring, summer, and fall, locations within the Pacific Northwest region experienced the largest statistically significant decreases in air mass persistence for winter. Seattle-Tacoma, Washington experienced the largest significant decrease in mean air mass persistence, while Boise, Idaho experienced the largest statistically significant decrease in mean maximum persistence for the winter season.

The analyses conducted here show that there has been a change in air mass persistence, both positive and negative depending on season, over the past 60 years.

Analysis of the two halves of the study period revealed multiple locations where a significant increase in air mass persistence has been observed, most commonly during the summer season. The analysis also revealed a pattern of decreasing air mass persistence across CONUS during the winter season between the two halves of the data.

While the results of this study seem robust there are two ways in which the work could possibly be improved moving forward. First, while the analysis was conducted for 140 SSC stations and there was at least one station in each of the 48 states, a greater station density would be helpful. If the study were to be conducted using only the most recent 30 years, during which time global warming was pronounced, more SSC stations could potentially be included. Second, a slightly different definition of air mass persistence could be applied within a future study. The nature of the SSC methodology requires definitive classification of a given day's weather as of a certain air mass type. In reality, it is likely that many days are not so clearly characteristic of one air mass type, such that either one of two types is a viable solution (e.g., Moist Tropical versus Moist Moderate). Further, as the SSC treats each day independently, modification of an air mass as it sits over a location may lead to an air mass change within the SSC (e.g., Dry Tropical-to-Dry Moderate) despite the fact that the broader synoptic air mass persists. In either case, a day-to-day change in SSC air mass may not truly reflect a wholesale change in the broader synoptic scale air mass. This obviously influences the characterization of air mass persistence as it is defined in this study.

This unique attempt to broadly quantify air mass persistence indicates that change has occurred over the past 60 years across the continental United States, particularly toward air mass stagnation in summer. Further solidified, this line of research could be used to examine large-scale climate system causes of inter-annual variability in persistence. It could also be used to study the role of air mass persistence in the global warming issue itself – the concept that increased air mass persistence, say in summer, perpetuates thermal inertia in the absence of more frequent air mass transitions. Going forward, the concept of air mass persistence holds promise as a potential indicator for climate change, although more research is required to definitively establish a direct link between air mass persistence and climate change.

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