A DETERMINATION OF CHARACTER AND FREQUENCY CHANGES IN AIR MASSES USING A SPATIAL SYNOPTIC CLASSIFICATION

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ABSTRACT

Of the numerous climate change studies which have been performed, few of these have analyzed recent trends using an air mass-based approach. The air mass approach is superior to simple trend analysis, as it can identify patterns which may be too subtle to influence the entire climate record. The recently-developed 'spatial synoptic classification' (SSC) is thus used to identify trends over the contiguous United States for summer and winter seasons from 1948 to 1993. Both trends in air mass frequency and character have been assessed.

The most noteworthy trend in frequency is a decline in air mass transitional days (TR) during both seasons. In winter, decreases of up to 1% per decade are noted in parts of the central U.S. Other notable trends include a decrease in moist tropical (MT) air in winter, and an increase in MT in summer over the southeastern states.

Numerous national and local air mass character changes have been uncovered. A large overall upward trend in cloudiness is noted in summer. All air masses feature an overnight increase, yet afternoon cloudiness increases are generally limited to the three 'dry air masses'. Also in summer, a significant warming and increase in dew point of MT air has occurred at many locales. The most profound winter trend is a large decrease in dew point (up to 1.5°C per decade) in the dry polar (DP) air mass over much of the eastern states. © 1998 Royal Meteorological Society.

KEY WORDS: synoptic climatology; USA; climate change; climate trends; air mass frequency; air mass character; spatial synoptic classification

1. INTRODUCTION

Recent climate trends have been analyzed using a number of distinct methods. The ubiquitous mean annual global temperature trendline (IPCC, 1996) shows an irregular rise of less than 1°C in temperature over the past 130 years. Numerous other studies have produced mean temperature trends for parts of the globe or parts of the year, with differing results (Hansen and Lebedeff, 1987; Jones, 1988; Spencer and Christy, 1990; Balling and Christy, 1996). Karl *et al.* (1993) split the temperature record into maximum and minimum temperature components, and discovered a significant increase in minimum temperature with a lesser change in maximum temperature. Using a different data set, Michaels *et al.* (1988) analyzed trends in upper-level heights over the North American Arctic for a 40-year period and suggested no statistically significant trend over time.

Few studies have been conducted which attempt to assess recent climate trends using a synoptic climatological method. The synoptic approach to evaluate climate change has distinct advantages over utilizing raw or adjusted long-term temperature data. For example, the character of some air masses might be undergoing alteration conducive to warming, but these changes might be too subtle to be detected through evaluation of mean annual temperatures, which does not discriminate between air masses (Ye *et al.*, 1995). Kalkstein *et al.* (1990), using a clustering analysis (TSI) routine, analyzed data

for four stations in the Yukon and Alaska, where some of the highest mean temperature increases have been reported. They noted that the frequency of the warmest air masses increased at the expense of the colder air masses. Also, the coldest air masses were shown to be warming during the 1953–1986 period of study. An updated study (Ye *et al.*, 1995), which included several Russian Arctic stations as well, and accounted for 'residence time' of air masses, produced significant results at fewer stations. Schwartz (1995) developed a synoptic classification scheme based on 850 hPa temperature and dew point data for stations in the north central U.S. using data from 1958 to 1992. He discovered several frequency and character changes over the region in all seasons, and he suggested that increased frequency of 500 hPa troughs in the western U.S. has led to a slight but steady increase in hot, humid conditions over the region during the warm season.

The goal of this paper is to evaluate character and frequency changes in air masses for over 100 cities in the United States for the period 1948–1993 using a newly developed air mass-based synoptic classification. This new classification identifies the same air masses over a continental-sized region, something that our previous scheme (the TSI) was not able to do. Thus, direct comparisons between regions are now possible, and systematic changes in character and frequency over large areas can be noted if such changes, in fact, do exist.

2. DATA AND METHODOLOGY

The Spatial Synoptic Classification (SSC) utilized in this research (Kalkstein *et al.*, 1996) is an air mass-based system which is concerned more with the meteorological characteristics of the air mass rather than the geographical source region. Unlike most existing air mass-based techniques such as the TSI, the SSC requires initial identification of the major air masses that traverse the nation, as well as their typical meteorological characteristics. The final result is identification of more air masses than the four historical categories (mT, mP, cT, and cP) developed by Bergeron (1930). For example, air mass characteristics of dry, adiabatically warmed Pacific air on the lee side of the Rocky Mountains represents an important category in the SSC, although its character at the source region is much different.

The SSC thus defines six air mass types for the continental United States, although some are not present at certain stations at particular times of the year. They are:

(i) DP (dry polar) is synonymous with the traditional cP air mass classification. This air mass is generally advected from Canada through circulation around a cold-core anticyclone, and is usually associated with the lowest temperatures observed in a region for a particular time of year, as well as clear, dry conditions;

(ii) the DT (dry tropical) air mass is generally the same as the cT air mass; it represents the hottest and driest conditions found at any location. There are two modes of development for this air mass: either it is advected from the southwestern U.S. or Sonoran Desert of Mexico, or it is produced by rapidly descending air, such as the Chinook or Santa Ana winds;

(iii) DM (dry moderate) air is mild and dry. It is typically found in the eastern and central U.S. associated with zonal flow aloft, when adiabatically-warmed and dried air moves eastward after crossing the Rocky Mountains. It may also be found in the southeastern U.S. when polar air is advected around a surface anticyclone with a long trajectory over the Atlantic Ocean;

(iv) MP (moist polar) air is a large subset of the mP air mass; weather conditions are typically cloudy, humid, and cool. MP air appears either by inland transport from a cool ocean, or as a result of frontal overrunning well to the south of the region;

(v) MM (moist temperate) air is considerably warmer and more humid than MP. The MM air mass typically appears in a zone south of MP air, still in an area of overrunning, but with the responsible front much nearer. This air mass may persist for many days if frontal movement is particularly lethargic;

(vi) MT (moist tropical), analogous to mT, is warm and very humid. It is typically found in warm sectors of frontal cyclones or in a gulf return flow on the western side of an anticyclone in the eastern and central U.S.

The foundation for the development of the SSC is the proper selection of 'seed days' for each of the air masses above. A seed day for each air mass represents a day with the typical meteorological character of each air mass at a location; seed days are employed to classify all other days within an air mass category. Criteria are set up to ensure that each seed day belongs in that category; there are limits to the diurnal range of several parameters (e.g. dew point) to eliminate days of air mass transition, and there are limits to values of certain parameters whose characteristics for a given air mass are generally established (e.g. afternoon temperature less than a certain threshold for a dry polar air mass).

Discriminant function analysis is then used to produce equations for each air mass based on the chosen seed days. These equations evaluate each day in a given record, and assign a classification based on which group the day resembles most from a meteorological standpoint. Air mass transition days are initially incorrectly assigned by this system, and a second seed day procedure is then done to separate transition from non-transition days. Days which are not transitional retain their original assignment; those which are, become reclassified as Transition (TR). Thus, every day in the period of record is classified as one of the major air mass types or as a transition situation. Please refer to Kalkstein *et al.* (1996) for a much more detailed explanation of SSC development.

In this study, trends in air mass frequency and character are evaluated to determine statistically significant changes through time. The data used in this project are 6-hourly airport observations of temperature, dew point, cloud cover, sea level pressure, and *u*- and *v*-components of the wind. A total of 118 stations for summer and 109 stations for winter have been examined (selection is based on completeness of record; refer to Figure 4 (summer) and Figure 6 (winter) for station location). All available days from the months June–August (summer) and December through February (winter) from 1948–1993 have been included in the frequency and character evaluations. However, in the trend data, only years in which greater than 80% of the data are available have been included in the calculations. All trends are determined using a standard least squares regression formula, and the level of statistical significance is $\alpha = 0.05$.

3. RESULTS

3.1. Air mass frequency: patterns and trends

An evaluation of air mass frequencies for the period 1948–1993 reveals spatial coherence and systematic changes across the country. Some of these have been documented previously for the eastern U.S. using the SSC (Kalkstein *et al.*, 1996), and have been expanded for the entire country here (Figures 1 and 2).

During both summer and winter, DM air is most prevalent in and directly east of the Rocky Mountains. Mean winter frequencies range from 25–50% in this area, with slightly higher values in summer. Much of the southeastern U.S. is influenced by this air mass between 20 and 30% of the time in winter, but it occurs considerably less frequently in summer, when weak upper level flow diminishes the possibility of its intrusion. However, farther north, DM air is more prevalent in summer, and frequencies in the Northeast and Midwest can exceed 30% during this season.

DP air shows a pronounced north-south frequency gradient during both seasons. In winter, a marked decrease in DP frequency occurs around the Great Lakes, a result of frequent overcast conditions and associated low dew point depressions. In summer, DP air occurs less than 20% of the time almost everywhere, and is absent along the Gulf Coast and Florida.

The DT air mass has a range generally limited to the western United States. During winter, it is most common in an area from the Desert Southwest eastward to Texas. Frequencies exceed 30% in the deserts, and diminish to around 10% in parts of Texas. During summer, DT air extends northward to the

Canadian border, with frequencies greater than 20% as far north as Idaho and Montana. Much of the DT air at these latitudes is a result of downsloping winds creating very hot, dry conditions. Even in summer, DT is rare in the East, occurring on less than 2% of days.

MM air is exclusively confined to the eastern half of the U.S. and the immediate Pacific coast. During winter, there is virtually no spatial gradient in the East, where it occurs about 5 to 15% of the time. Interestingly, greatest frequencies of this air mass are found along the Pacific coast in winter, due to frequent Pacific storms with moderate thermal regimes. In summer, spatial gradients are also weak, with frequencies of between 12 and 25% east of the Mississippi River. The summer influence of this air mass is less along the Pacific coast, except in southern California where frequent fog and low dew point depressions create MM conditions.

MP air is most frequent in the upper Midwest in winter, due to the localized effect of the Great Lakes. Farther east, MP is generally associated with the passage of adjacent mid-latitude cyclones, while in the Midwest, it is often a function of overrunning conditions. MP is found almost everywhere during winter,
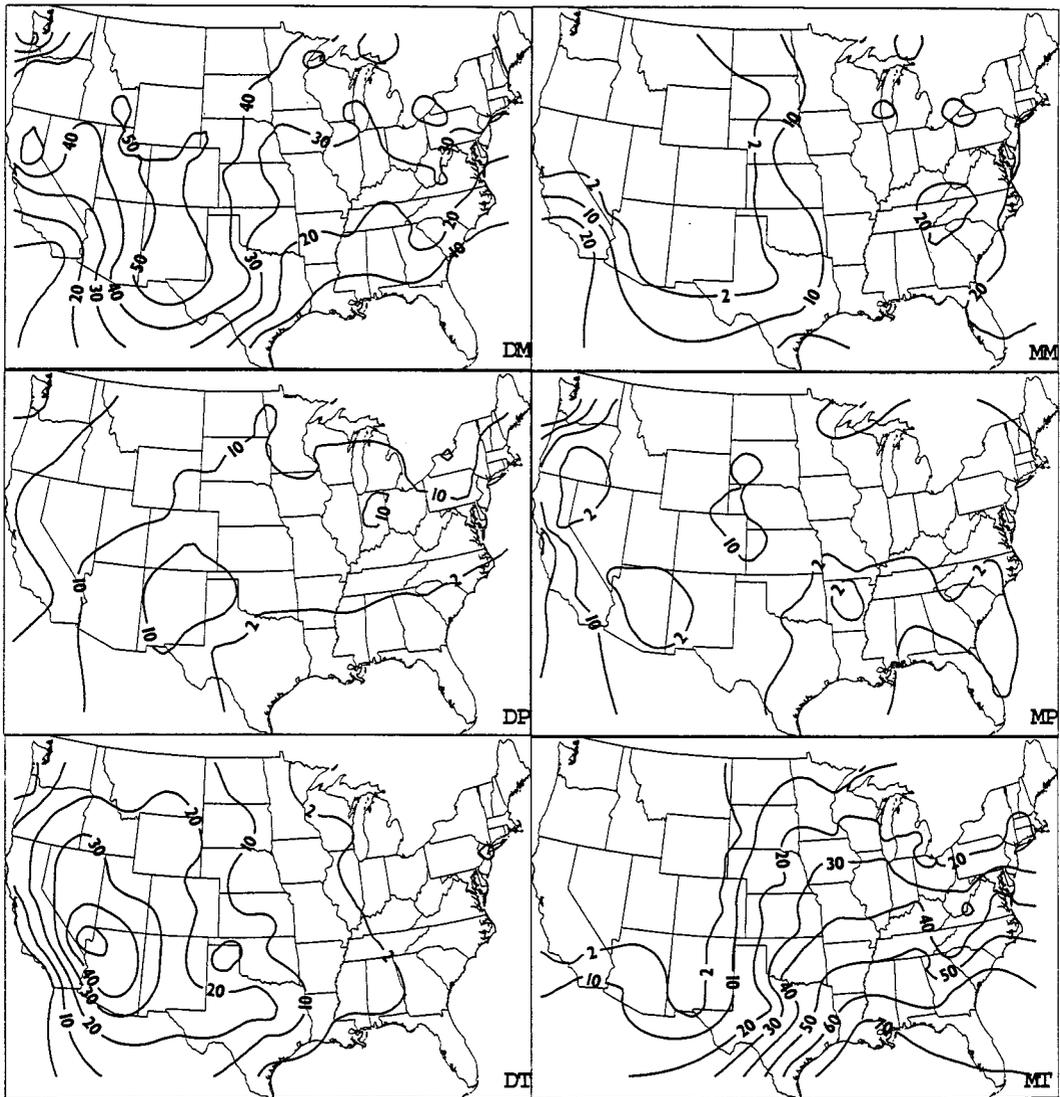

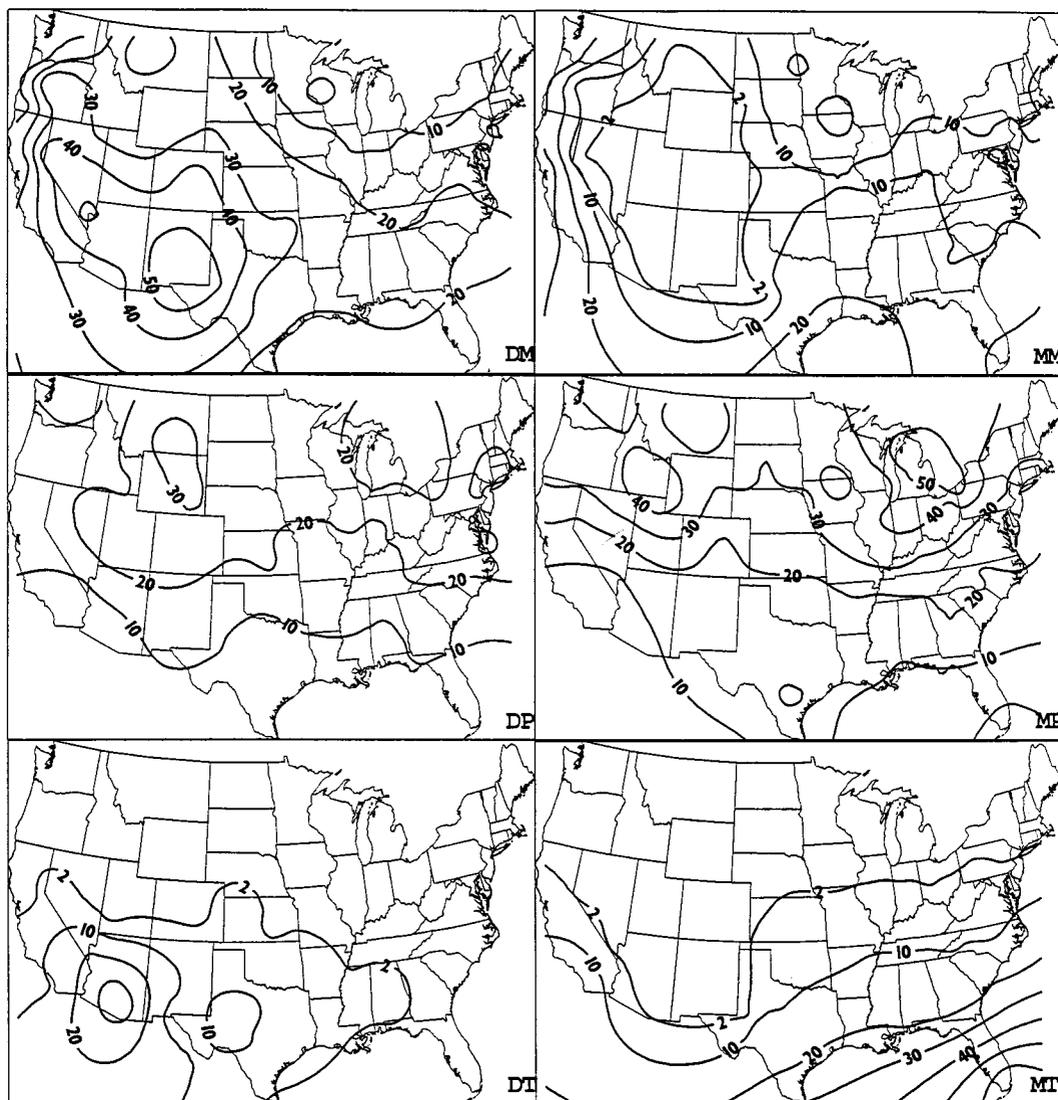Figure 1. Mean air mass frequency for summer

Figure 2. Mean air mass frequency for winter

although frequencies are small along the Gulf Coast and in the Southwest. During summer, it is much less common, with frequencies generally less than 10% throughout the country.

MT frequencies show a strong latitudinal gradient in the eastern U.S. during both seasons. In winter, it occurs more than 10% of the time south of a line from Norfolk, VA to Little Rock, AR. Frequencies exceed 20% near the Gulf Coast and approach 70% in southern Florida. During summer, MT frequencies are greater than 50% throughout much of the Southeast, and the air mass occurs on about one-third of summer days in large mid-Atlantic cities.

TR frequencies show a remarkably consistent pattern throughout the country, especially in winter. Frequencies average in the 'teens across the entire U.S. during winter, and are slightly lower in summer, especially in the southern tier of the nation.

Temporal trends in air mass frequency have been analyzed in terms of changes in annual frequency of the air mass (percentage of days within season) through the period of record. During winter, several trends are apparent (Table I). The most noteworthy is a dramatic decrease in air mass transition

Table I. Trends in air mass frequency over the continental U.S. 1948–1993

	Winter			Summer		
	+	−	Δ	+	−	Δ
DM	10	5	0.36	3	21	−0.16
DP	6	1	0.30	0	5	−0.32
DT	1	0	−0.08	5	0	0.18
MM	2	1	0.05	5	1	0.58
MP	12	7	0.20	5	1	−0.79
MT	0	7	−0.53	15	3	0.37
TR	0	24	−0.62	0	12	−0.71

+ and − represent the total no. of statistically significant increases and decreases, respectively, at $\alpha = 0.05$.
Δ indicates mean change in frequency in % per decade at all stations, weighted by frequency.

frequency, which is observed at 94 of the 109 stations and is statistically significant at 24. Areas with the greatest frequency declines (greater than 1% per decade) include a large region stretching from the Great Basin to Texas and Oklahoma, and a portion of the Ohio River Valley (Figure 3). Most of the statistically significant declines are west of the Mississippi River, with the greatest (over 2% per decade) in Nevada. While the declines in the west are generally gradual, those farther east demonstrate a sharp drop over a short period. For example, at Indianapolis, IN transition frequencies averaged between 20–25% of days during the winter from the late 1940s through the mid-1950s; since the late 1970s these frequencies have averaged between 10–15%. This coincides with a period of more persistent non-zonal flow, leading to more frequent large-amplitude troughs in the East. This circulation pattern change has been well-documented by others (Trenberth, 1990; Rogers and Rohli, 1991; Leathers and Palecki, 1992).

In balancing the decline in transition frequency, most other air masses show an increase over the 45-year winter period. DM and DP show the greatest gains, with 75 and 72 of the 109 stations, respectively, showing increases. However, only a small number of these upward trends are statistically significant. DM increases are particularly strong across the northern Great Plains, where frequencies rise by up to 3.6% per decade. DP increases are of smaller magnitude, and extend from the Great Lakes to the Carolinas.

MT air shows a decline at 52 of the 68 stations at which it is identified in winter, although only seven of these declines are significant. The largest decreases cover Alabama, Georgia, the Carolinas, and northern Florida, where 1.5–3.0% per decade declines are observed. In several cases, this is complemented
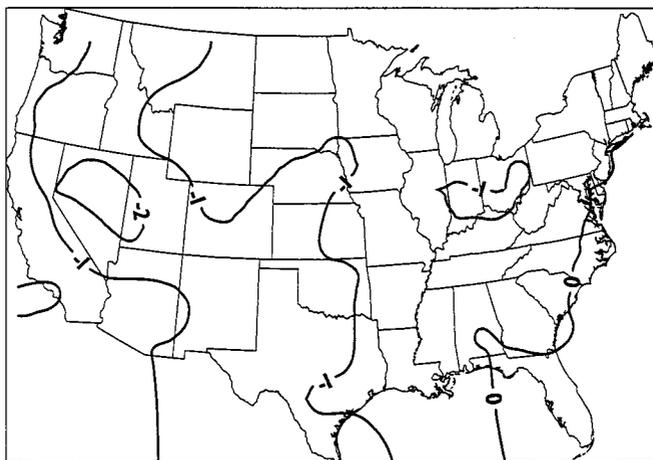

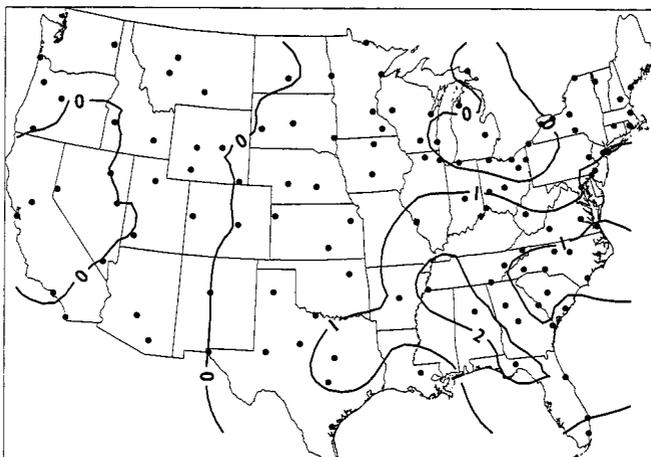Figure 3. Frequency change for winter TR air mass (%/decade)

Figure 4. Frequency change for summer MT air mass (%/decade). Dots represent stations used in summer analyses (this map only)

by an increase in MP air. Over the entire country, the increases (59; 12 significant) and decreases (50; 7 significant) in MP frequency nearly balance out. However, most of the increases are in the Southeast and most of the decreases are in the West. The MP increases (at the expense of MT) in the Southeast may be related to the recognized increase in upper-level meridional flow.

During the summer, a decrease in transition frequency is also apparent. However, in contrast with winter's highly regionalized decrease, the summer decrease is neither as dramatic nor concentrated in any particular region. A mean decrease of 0.7% per decade is noted nationwide, with 82 of the 119 stations showing declines.

Of greater importance is the increased presence of MT air masses during summer (Figure 4). Upward frequencies are noted at 76 of the 94 stations (15 significant), with very high increases (2–4% per decade) across the interior Southeast. Much smaller increases have occurred in the midwestern US, where Schwartz (1995) notes a significant increase in his T air mass (analogous to MT) between 1958 and 1992. Much of the MT gain comes at the expense of the DM air mass, which exhibits decreases of 1–3% per decade in this same region (Figure 5). DM also shows a significant decline at many stations in the Northeast and Great Lakes area (1–3% per decade), and for many sites, it is clear that when MT frequencies are high during a particular summer, DM frequencies are low. This may reflect an increase in the frequency of semi-permanent ridging in the eastern U. S. and western Atlantic since the early 1950s (Davis *et al*., 1997). It is also possible that a slight warming of DM air through the period could permit more days to be captured within the SSC as MT. Sensitivity tests need to be performed to determine if such air mass capture is occurring, as the climate change implications of this are important.

The largest change in frequency of any air mass in either season is for Phoenix DT air during the summer, where a 6.4% per decade increase has occurred. This increase is offset by frequency declines in DM (− 5.3% per decade) and DP (− 1.2% per decade). It seems likely that this reflects a significant land-use change in the area, which will be discussed more fully below. While a similar trend occurs in Tucson, no such DT trend is found in Las Vegas, in spite of considerable land-use changes there.

3.2. Air mass character trends

In virtually all cases, the within-air mass meteorological variability is significantly less than the between-air mass variability. However, there are some cautions involved in air mass character evaluation. First, a very large temporal character change in an air mass might shift a number of days from one air mass category to an adjacent category. If this occurs, the magnitude of the change over time would likely be underestimated, as extreme days within one air mass would be classified within another air mass. Considering the number of significant character changes described below, we suggest that the results

presented here may be rather conservative. Second, air mass character alterations attributed to equipment changes (such as hygrothermometer replacement of HO-63 with HO-83 instruments), station movements, or other non-climatological factors could influence results (Karl *et al.*, 1995). However, any such changes should be indicated by abrupt character or frequency shifts, which are not apparent within our evaluated cities.

A summary of the trends in meteorological data for several characteristics of all six air masses shows a number of statistically significant results (Table II). During the summer, by far the most prominent 45-year trend is the increase in cloudiness, especially during the overnight hours. This overnight cloud increase is very apparent within all six air masses. The most consistent areas of increase are the northern Rockies (where spatial homogeneity was surprisingly good despite the terrain variations) and the southern Great Lakes. In these regions, increases for all air masses average near 0.2 tenth per decade, a nearly 1.0 tenth increase in cloud cover over the entire period. Several cities in each of these regions, such as Buffalo, NY, Cleveland, OH, and Spokane, WA have statistically significant overnight cloudiness increases in three or four air masses. The most important cloudiness increases occur within the DM air mass in summer, and about 30% of all stations evaluated show statistically significant increases. The 'moist air masses' (MM, MP, and MT) show large increases as well.

Afternoon cloudiness demonstrates a general increase as well, although the pattern is not as consistent among all air masses. The three 'dry air masses' (DM, DP, DT) are all increasingly cloudy at most stations, with mean increases of around 0.05 tenths per decade. The moist air masses have a much lower mean increase; MT days actually show an overall slight decrease over the period. The maximum afternoon cloud increase is again in the northern Rockies, with secondary maxima in the Great Lakes and Middle Atlantic regions.

This upward trend in cloudiness has been noted by others (Karl *et al.*, 1993, Jones and Henderson-Sellers, 1992), but an analysis which discriminates by air mass has never been attempted. It is noteworthy that the DM air mass, usually associated with minimal cloudiness, appears most affected. Another rather cloudless air mass, DP, shows a much smaller increase in cloudiness, especially overnight. The reasons for this differential are unclear, but might be related to changes in the surfaces across which these air masses are transported.

There are a number of statistically significant trends in temperature, especially during summer. Minimum temperature appears particularly affected, and general upward trends are noted. It is interesting that most of the minimum temperature increases occur within the moist air masses: 20 locales show statistically significant minimum temperature increases for MT air (mostly in the East and the West Coasts), while only five decreases are detected (three of these are cities in Texas; Table III). Some of the
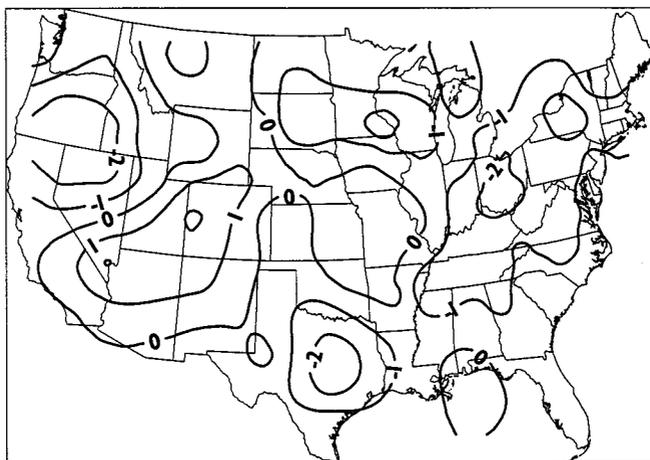

Figure 5. Frequency change for summer DM air mass (%/decade)

Table II. Trends in air mass character over the continental U.S., 1948–1993

	Summer																	
	DM (118)			DP (115)			DT (81)			MM (84)			MP (118)			MT (93)		
	+	−	Δ	+	−	Δ	+	−	Δ	+	−	Δ	+	−	Δ	+	−	Δ
Maximum temperautre	5	9	−0.03	6	2	0.04	8	1	0.07	9	0	0.02	7	1	0.10	7	1	0.03
Minimum temperature	21	19	0.07	12	10	0.03	9	9	0.04	11	2	0.00	7	1	0.18	20	5	0.21
Dew point	13	4	0.06	3	5	0.06	8	1	0.23	4	1	0.03	5	1	0.12	17	2	0.10
0300 h clouds	33	1	0.12	10	2	0.07	13	1	0.09	22	1	0.10	13	1	0.16	19	1	0.08
1500 h clouds	28	4	0.06	10	1	0.05	10	1	0.07	9	6	0.03	8	5	0.03	7	16	−0.03
	Winter																	
	DM (109)			DP (109)			DT (31)			MM (89)			MP (109)			MT (68)		
	+	−	Δ	+	−	Δ	+	−	Δ	+	−	Δ	+	−	Δ	+	−	Δ
Maximum temperautre	4	0	0.05	0	7	−0.09	0	0	0.13	7	1	0.04	4	2	0.01	1	0	−0.01
Minimum temperature	14	5	0.04	6	7	−0.09	2	3	0.19	9	1	0.11	7	0	0.06	3	2	0.02
Dew point	6	8	0.00	0	29	−0.28	1	1	0.10	1	1	−0.03	2	5	−0.03	1	1	−0.02
0300 h clouds	5	1	0.01	11	4	0.06	2	3	−0.01	4	1	0.04	9	2	0.05	4	1	0.08
1500 h clouds	7	1	0.02	9	5	0.03	1	2	−0.04	6	3	0.01	14	2	0.04	5	1	0.06

+ and − represent the total no. of statistically significant increases and decreases, respectively, at $\alpha = 0.05$.
Δ indicates mean change in value per decade over all stations, weighted by frequency. Temperatures and dew points are in °C, clouds in tenths.

Table III. Locations and values (°C/decade) for statistically significant changes in minimum temperature for the MT air mass during summer

Increases					Decreases	
MT air mass–minimum temperature changes (°C/decade)						
Akron, OH	0.21	Miami, FL	0.22		Corpus Christi, TX	−0.24
Allentown, PA	0.27	Milwaukee, WI	0.39		Knoxville, TN	−0.28
Asheville, NC	0.28	Newark, NJ	0.33		Midland, TX	−0.41
Buffalo, NY	0.20	Norfolk, VA	0.22		Tallahassee, FL	−0.16
Charleston, SC	0.33	Phoenix, AZ	0.72		Wichita Falls, TX	−0.33
Daytona Beach, FL	0.11	Portland, ME	0.24			
Des Moines, IA	0.22	San Diego, CA	0.39			
Erie, PA	0.25	St. Louis, MO	0.33			
Hartford, CT	0.35	Tulsa, OK	0.37			
Memphis, TN	0.39	Wilmington, DE	0.17			

increases exceed 0.3°C per decade, and a particularly large value is uncovered for Phoenix. This is consistent with findings of local climate modification uncovered in Phoenix by Balling and Brazel (1986), and suggests that synoptic-scale differentiation may be helpful to determine exactly which air masses are being altered by local modifications.

The statistically significant trends in summer for the three dry air masses are rather evenly split between increases and decreases. Most of the increases in DP minimums are found in the West (including Phoenix, AZ, San Diego, San Francisco, and Los Angeles, CA), while the decreases are concentrated in the East (including Knoxville, TN, Augusta, GA, Columbia and Charleston, SC). Sizable DM minimum temperature decreases of up to 0.5°C per decade are found from Florida to Texas. Thus, it is important to note that the relatively large minimum temperature increases noted here and elsewhere (Karl *et al.*, 1993) are mostly related to changes in moist air masses during summer.

There are some statistically significant changes in summer maximum temperature as well, but a lesser number than for minimum temperature. With the exception of the DM air mass, the vast majority of statistically significant maximum temperature changes show a warming, although the magnitude is frequently less than minimum temperature (refer to Table IV for an MT comparison). One air mass with a stronger maximum temperature signal is DT, where virtually all of the Rocky Mountain sites evaluated display statistically significant increases. These include Ely and Elko, NV, Casper, Lander, and Rock Springs, WY, Colorado Springs and Grand Junction, CO, and Pocatello, ID. Most of these increases in maximum temperature are near 0.2°C per decade. Interestingly, those cities nearer the source region (Phoenix and Tucson) do not show statistically significant increases in DT maximum temperature. The reasons for this regional disparity are difficult to explain, but it appears that DT air in the more northerly locales is influenced and modified by downsloping processes which do not occur farther south.

Summer mean daily dew point changes have also demonstrated large increases, with the greatest magnitudes occurring within the moist air masses. MT is particularly noteworthy, with 17 statistically

Table IV. Same as Table III except for MT maximum temperature

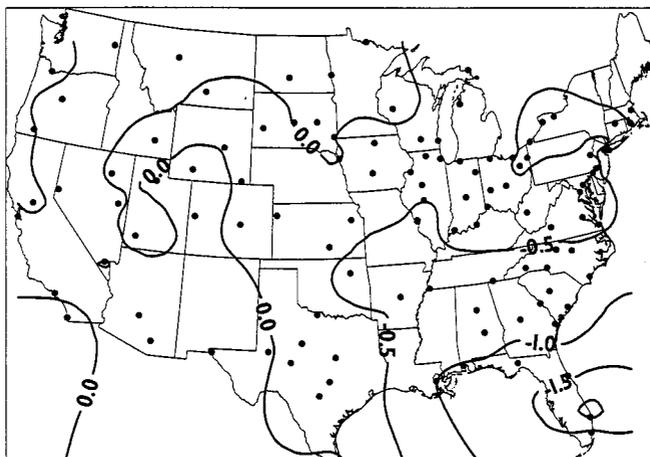| Increases					Decreases	
MT air mass–maximum temperature changes (°C/decade)						
Charleston, SC	0.20	Tallahassee, FL	0.19		Midland, TX	−0.34
Daytona Beach, FL	0.14	Traverse City, MI	0.25			
Newark, NJ	0.16	Tulsa, OK	0.22			
Phoenix, AZ	0.43					

Figure 6. Dew point change for winter DP air mass (°C/decade). Dots represent stations used in winter analyses (this map only)

significant increases. About half of these sites are in the northeastern U.S., and the magnitudes of the increases are similar to those uncovered for minimum temperature. DM and DT also demonstrate sizable increases in summer, which do not seem to be concentrated within any particular part of the country. Little change in summer dew point is evident for DP and MM air masses. Dew point trends seem to be somewhat similar to the cloud cover trends described earlier. The air masses with the greatest dew point increases all demonstrated sizable increases in overnight cloudiness.

Most of the winter character trends uncovered in this study are less significant than those during summer. For example, all air masses (except DT) contain an overall increase in overnight winter cloud cover (Table II); however, the magnitude of increase and spatial extent is generally less in winter than in summer. Most of the winter cloudiness increases are confined to the East, with polar air masses being particularly affected. Several cities near the Great Lakes (Cleveland, OH, Erie, PA, Youngstown, OH, Buffalo, NY, Dayton,OH) show statistically significant increases in MP cloudiness.

The single largest trend uncovered for winter is the remarkable decrease in DP dew point. Figure 6 shows the spatial pattern of this trend; declines are largest in the southeastern U.S., where a decrease of greater than 0.5°C per decade is found at nearly every station. Declines of greater than 0.3°C per decade cover almost the entire eastern half of the country. Figure 7 depicts the year-by-year mean for Atlanta, GA, which is typical for most southeastern stations. It appears that most of the decline occurred from the start of the period through the mid-1970s. This coincides with the more persistent non-zonal flow, referred to earlier. Such a pattern would reduce the modification of DP air, lessening the ability of the air mass to gain moisture as it more rapidly traverses a moist (possibly snow-covered) land surface. This is reflected, to a much lesser degree, in maximum and minimum temperature trends for DP air. Seven stations show statistically significant decreases in maximum temperature, while none show increases. For minimum temperature, there is an even split between a modest number of statistically significant increases and decreases. It is interesting to speculate why this decrease in DP air mass modification would be manifested in dew point changes, but not in thermal character. One possibility might involve changes in snow cover over the northern U.S.; however, recent research suggests that snow cover has changed minimally over the period of record we are evaluating (Hughes and Robinson, 1996; Leathers and Luff, 1997). Another suggestion relates to potential warming which may be associated with the negative vorticity advection on the windward side of larger-amplitude troughs. It is also possible that the thermodynamics of the DP air mass have changed at the source region, possibly attributed to increased Arctic haze or increased concentrations of trace gases (Kalkstein *et al.*, 1990).

The other common dry wintertime air mass, DM, features some increases in temperature (especially minimum) and decreases in dew point. A statistically significant minimum temperature increase is noted

at stations in the upper Midwest (e.g. Eau Claire, WI, Mason City, IA, Sault St. Marie, MI, Bismarck, ND) and West Coast (e.g. Los Angeles, San Diego, San Francisco). The third dry air mass, DT, occurs rarely throughout much of the U.S. in winter. Phoenix does feature a large increase in minimum temperature with the DT air mass (1.1°C per decade), although this increase is also observed with most other air masses at this site. As mentioned previously, recent urban/agricultural expansion is probably the cause.

The moist air masses have also undergone much less character alteration in winter than in summer. MT air shows very few statistically significant changes, although Florida and Gulf Coast stations have experienced a moderate increase in maximum and minimum temperature and dew point of around 0.2°C per decade. MM and MP both show overall increases in minimum temperature, but minimal changes in dew point and maximum temperature. No particular spatial patterns are evident for these changes.

3.3. Discussion and conclusions

It is apparent that a discrimination of weather by air mass type is a useful means to determine changes in climate over a long time period. Synoptic differentiation permits a more detailed evaluation than a simple time-series of a particular meteorological variable, such as temperature or dew point. As this study suggests, many of the changes are limited to particular air masses, and if a synoptic categorization is not performed, these changes are dampened or, at worst, indeterminable.

The following important climate changes were uncovered for the summer and winter seasons within this analysis.

Seasonal air mass frequencies demonstrate systematic spatial patterns which are intuitive. For example, a pronounced north-south frequency gradient in DP air is noted for both seasons. This spatial integrity suggests that the SSC is working properly in assigning days within air mass categories for the large number of sites evaluated in this study.

A large number of air mass frequency trends were uncovered for the period of record. These include:

 (i) a dramatic decrease in winter air mass transition frequency, especially in the middle of the nation. This appears to correspond to a pattern shift in upper-tropospheric flow from zonal to increasingly meridional;

 (ii) an increase in winter DM and DP frequency, although most of these are not statistically significant;

(iii) a decrease in winter MT frequency in the southeastern U.S., and a concomitant increase in MP frequency within this region;

(iv) a significant increase in summer MT frequency, also in the southeastern U.S., approaching 2–4% per decade. Much of this gain comes at the expense of the DM air mass, which decreases sharply in frequency within this same region;

 (v) very large frequency increases in summer DT for Phoenix and Tucson, possibly reflecting significant land-use changes in the area.
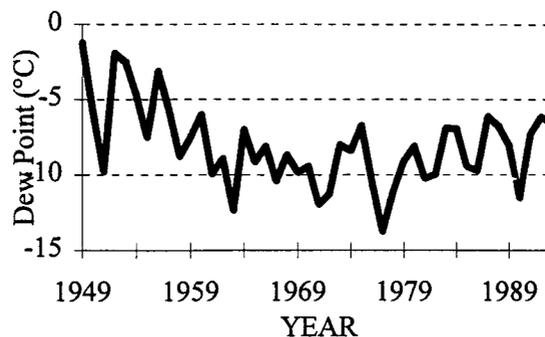

Figure 7. Mean annual dew point for the DP air mass, Atlanta, Georgia

Significant summer character changes were found, and one of the most important was the large increase in cloud cover for most air masses. Overnight cloud cover increases were particularly notable for the DM air mass, although large increases were also apparent for MM and MT air. Afternoon cloudiness, while showing a general increase, was less affected. Most of the afternoon increases were confined to the three dry air masses.

Summer minimum temperature showed large increases, but these were generally confined to the moist air masses. MT air was particularly affected, with some increases exceeding 0.3°C per decade. In fact, the SSC has isolated moist air masses as the major contributor to general increases in minimum temperature.

Summer maximum temperature also demonstrated increases, but these were less dramatic than for minimums. The most important summer maximum increases were noted for DT air, especially in the Rocky Mountains (not in Phoenix or Tucson). Summer dew points showed large increases, especially within the MT air mass. Many of the statistically significant increases occurred in the northeastern U.S.

Winter air mass character trends were, in general, less significant than those during summer. The most important trend was the striking decrease in DP dew point. In the southeastern U.S., these decreases generally exceeded 0.5°C per decade. Most of the decline occurred before the mid-1970s, and corresponded with a period of greater meridional flow at upper altitudes. Interestingly, thermal character of DP air did not show a persistent trend.

Although it has been attempted to discuss some possible reasons for the numerous changes noted in air mass character and frequency, the authors are quite uncertain about the physical explanations underlying most of these changes. Some are clearly related to phase changes in upper level flow, but further analysis is necessary to determine whether surface features, such as snow cover or surface moisture content, are responsible for many of these changes. In addition, it is not certain whether human-induced climate change plays a major role in these long-term trends. The strong increases in summer minimum temperature within the moist air masses, changes in cloud cover, summer dew point increases, and winter DP dew point decreases are all provocative findings, but the role of anthropogenic activities in possibly affecting these changes needs much further investigation. It is also important to develop the SSC for spring and fall so an annual continuum of changes can be assessed. This task is currently being undertaken.

It is also uncertain how increasing urbanization may have biased these results. However, it is noteworthy that there is spatial continuity in the findings, even though the first order weather station sites are at locations exhibiting various levels of urbanization. This spatial cohesiveness suggests that urbanization is not playing a significant role in altering these results; nevertheless, more research is necessary in the comparative evaluation of urban-rural air mass differences.

It is clear that a synoptic evaluation reveals much more about climate change than does a trend analysis of various meteorological variables. Most of the character and frequency changes occur within particular air masses, and these have been isolated. It is hoped to expand this analysis to a number of additional sites in North America. The authors are also interested in the possible role that ENSO events, and associated teleconnections, might play in altering air mass character and frequency. In addition, it is planned to determine, in a more quantitative manner, the relationship between air mass changes and upper tropospheric flow patterns. If air mass character alterations appear to occur independently of changes in zonality (thus eliminating transport speed and associated modification, as well as vorticity influences, as major reasons for air mass character changes), this might implicate anthropogenic factors more directly.

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