Changing Temperature Inversion Characteristics in the U.S. Southwest and Relationships to Large-Scale Atmospheric Circulation

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ABSTRACT
Continental temperature inversions significantly influence air quality, yet little is known about their variability in frequency and intensity with time or sensitivity to dynamical changes with climate. Inversion statistics for six upper-air stations in the American Southwest are derived for the period 1994–2008 from radiosonde data reported by the Global Telecommunication System (GTS) and National Climatic Data Center (NCDC), which use different significant level standards. GTS data indicate that low-level elevated inversions have increased in frequency at four of six sites, consistent with enhanced regional stagnation projected by models. NCDC data, in contrast, show remarkable declines in weak, near-surface inversions through 2001, indicating local surface conditions may counteract atmospheric dynamics in regulating inversion activity and air quality. To further test the sensitivity of inversion activity to climate, associations between wintertime inversion frequency and large-scale circulation are quantified using the self-organizing map technique. Twenty-four representative circulation patterns are derived from North American Regional Reanalysis (NARR) 500-hPa geopotential height fields, and these patterns are correlated with inversion frequency at each site. Inversion activity in Salt Lake City, Utah, and Albuquerque and Santa Teresa, New Mexico, is found to correspond well with large-scale anticyclonic ridging; however, sensitivities to large-scale circulation in Denver, Colorado, and Flagstaff and Tucson, Arizona, are weak. Denver stands out in exhibiting a higher percentage of near-surface inversions in winter than the other southwestern sites. These findings indicate that dynamical changes with climate will not uniformly influence inversions and hence urban air quality conditions in the American Southwest.

1. Introduction
Temperature inversions are a common feature of high pollution episodes around the world (e.g., Haagenson 1979; Inceciik 1996; Kallos et al. 1993; Kukkonen et al. 2005; Malek et al. 2006; Reddy et al. 1995). Characterized by an inverted lapse rate, in which temperature increases with height in the atmosphere, inversions trap pollutants in a cold pool under a warmer layer of air. The resulting atmospheric stagnation inhibits pollutants from dispersing out of the region, resulting in higher pollution concentrations and longer periods of poor air quality than might otherwise be expected (e.g., Olofson et al. 2009; Romero et al. 1999).

In European cities, for instance, both elevated and ground-based temperature inversions have been found to coincide with periods of excessive particulate matter concentrations (Kukkonen et al. 2005). The root cause of these poor air quality episodes is undoubtedly anthropogenic emissions of particulates or the suspension of dust. Yet for every high pollution episode observed,
whether in a maritime or continental climate, in complex terrain or otherwise, a temperature inversion was also present and served to intensify poor air quality conditions by preventing the dilution of polluted air. Similarly, in the United States during January 2004, during one of the worst air pollution episodes on record, strong inversion activity helped drive particulate concentrations in Utah’s Cache Valley to 132.5 \( \mu g m^{-3} \), 2 times the 24-h standard then in use by the Environmental Protection Agency (EPA) (Malek et al. 2006). The stagnant conditions not only concentrated existing particles but also favored the formation of new aerosols (Silva et al. 2007). Inversions also effectively concentrate gaseous pollutants such as volatile organic compounds and nitrogen oxides that enable the photochemical production of ground-level ozone. Schnell et al. (2009) discovered that under inversion conditions, ozone concentrations exceeded 140 ppb in Wyoming’s Upper Green River Basin during the heart of winter. The ability of inversions to trap pollutants and their precursors at ground level has clear public health ramifications, and recent work suggests a direct link between human diseases and inversion activity (Abdul-Wahab et al. 2005). These findings affirm the role local stagnation plays in inducing unhealthy air quality, and they motivate a deeper understanding of the meteorological conditions that favor inversion formation.

Atmospheric inversions can be broadly categorized as advection, subsidence, or radiation inversions, which are described by Schnelle and Brown (2002) as follows. Advection inversions result when warm air advects over a cooler air mass. Subsidence inversions form as descending air warms adiabatically. Radiation inversions tend to occur during cold, cloudless conditions, when the ground cools rapidly and the resulting surface temperature drop halts vertical motion in the atmosphere. Notably, these categories reflect the sensitivity of inversion formation to atmospheric motion and to the surface energy balance, both of which may be shaped by larger-scale meteorological conditions, as demonstrated in the following studies.

Whiteman et al. (1999) found that over the expansive U.S. Colorado Plateau during wintertime, inversions form under high pressure systems, as warm air advection aloft caps the colder air that settles at night between the plateau’s high mountain ranges. Within this large basin, inversions can persist for several days, since diurnal heating is weak in wintertime. In nearby Denver, Colorado, four distinct surface synoptic patterns coincide with the worst air quality days (as described in Reddy et al. 1995). These consist of a double-centered high straddling Colorado’s Front Range, high pressure centered over the Great Plains, the intrusion of a shallow Arctic air mass over eastern Colorado, and a broad, poorly organized low pressure area in northern Colorado and Wyoming. Malek et al. (2006) reported that both radiation inversions and a persistent subsidence inversion created the stagnation that plagued Logan, Utah, and the surrounding Cache Valley during January 2004. Early in the month, low pressure brought storms and snowfall to the area, and snow cover lasted throughout the month, reflecting 80% of incoming solar radiation and promoting ground-level inversion formation. In the middle of the month, high pressure entered the region and lingered nearly two weeks, capping the cold valley air under an elevated inversion layer. Winds remained calm and no precipitation occurred during this period, enabling particulate matter concentrations to soar. Pollution levels finally subsided when a low pressure system passed through the region later in the month. Recent studies by Reeves and Stensrud (2009) and Gillies et al. (2010) also demonstrated links between persistent inversions in the U.S. West and synoptic-scale flow.

Seeking to quantify the connection between synoptic processes and inversion events more precisely, Milionis and Davies (2008a) tested statistical differences among mean inversion characteristics for three weather classes near England’s eastern shore. They found that inversion intensity—defined as the change in potential temperature between the top and bottom of the inversion—differs significantly among anticyclonic, westerly, and cyclonic circulation. An inversion activity index—based on the inversion intensity, the number of inversions per vertical profile, and the frequency of profiles containing inversions—also varies with the prevailing weather, such that for anticyclonic circulation, the mean activity index is 2 and 2.5 times greater than the mean activity index associated with cyclonic circulation for ground-level and elevated inversions, respectively. Additionally, the annual cycle of elevated and surface inversions near the coast explains approximately two-thirds of the annual cycle observed at a second, inland site, implying that synoptic conditions create a shared inversion history between these distinct locations (Milionis and Davies 2008b).

Quantifying the extent to which inversion activity responds to larger-scale meteorology is particularly relevant today, given the dynamic circulation changes expected as global climate warms. Indeed, evidence suggests that the Northern Hemisphere jet stream has been moving poleward since 1979, a shift that will likely influence synoptic activity in the future (Archer and Caldeira 2008). Climate simulations replicate this jet stream shift and suggest that both the number and intensity of midlatitude storms may change over the next century (Bengtsson et al. 2006). Geng and Sugi (2003),
for example, argued that increased concentrations of carbon dioxide and sulfate could influence baroclinicity by decreasing the Northern Hemisphere meridional temperature gradient and curb midlatitude cyclone density during the winter and summer seasons. Declines in the frequency of cyclonic activity would, in turn, likely enhance regional stagnation. Model studies also suggest that the meteorological conditions that favor poor air quality will occur more frequently as greenhouse gas concentrations climb. Mickley et al. (2004) projected the U.S. Northeast and Midwest could face more intense and longer-lasting pollution episodes due to changes in the frequency distributions of polluted air masses. The U.S. West could also experience up to 15 more days per season of stagnant conditions—periods characterized by minimal wind speeds and precipitation—by the mid-twenty-first century, with the Intermountain West, in particular, experiencing eight more days of stagnant conditions during the fall season and up to two additional unvented hours per day (Leung and Gustafson 2005).

These studies indicate changes in large-scale atmospheric dynamics could substantially affect air quality. Yet it remains unclear whether such projections of regional stagnation imply local inversion activity will also worsen. Furthermore, if poor air quality conditions are expected to occur more frequently as global temperatures increase, one might postulate that inversion characteristics should already be changing. The present study aims to address these questions by 1) quantifying inversion activity in the U.S. Southwest over a period of 15 years and 2) deducing the relationship between inversions and large-scale circulation using a continuous classification scheme that builds on previous investigations of inversion sensitivity to synoptic weather. In this manner, we further test associations between the large scale and local inversion activity and analyze inversion variability with time, in order to improve our understanding of how inversion characteristics could change with climate. This study focuses on six Southwestern cities: Tucson and Flagstaff, Arizona; Salt Lake City, Utah; Denver, Colorado; and Albuquerque and Santa Teresa, New Mexico. Population growth in the Southwest has largely outpaced average growth in the rest of the United States, precipitating rapid urbanization and dramatic increases in industrial and vehicular emissions, which have increased the sensitivity of the region’s air quality to stagnant conditions. Moreover, each of these cities lies within or in close proximity to the mountains, providing a test case for whether large-scale circulation can be used to effectively characterize inversion activity in more complex terrain.

2. Methods

a. Inversion characteristics

Inversion frequency and intensity were analyzed for six upper air stations in the U.S. Southwest: Tucson and Flagstaff, Arizona; Salt Lake City, Utah; Denver, Colorado; and Albuquerque and Santa Teresa, New Mexico. Inversions were defined as a temperature increase with height and calculated from the mandatory and significant levels reported from late afternoon (0000 UTC) balloon soundings. Early morning soundings (1200 UTC) were excluded from the analysis since they are dominated by frequent nighttime radiative inversions and provide little opportunity to study inversion frequency variability. Inversion frequency was defined as the number of days per month during which inversions were present, normalized by the number of available 0000 UTC temperature profiles per month. Following Milionis and Davies (2008a), intensity was defined as the difference in potential temperature between the top and bottom of the inversion. The inversion height was defined as the height above the local surface at which the bottom, or base, of the inversion formed. Inversion characteristics at all sites were investigated for the period 1994–2008, except at Flagstaff and Santa Teresa, whose earliest records begin in mid-1995.

Because of differences in significant level reporting and quality control practices among datasets, inversion presence and intensity were calculated from two sources: the online National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) Radiosonde Database (http://www.esrl.noaa.gov/raobs/), which spans 1994 to the present, and the University of Wyoming Department of Atmospheric Science’s Weather Web (http://weather.uwyo.edu/). One advantage of the ESRL dataset is that it is checked for hydrostatic and gross
errors (Schwartz and Govett 1992), while the University of Wyoming provides raw data reported through the Global Telecommunication System (GTS). However, the number of significant levels reported in the ESRL dataset changes abruptly in 2002 and therefore has the potential to significantly bias any trend analysis. For soundings launched prior to 2002, ESRL reports merged significant levels from GTS and the National Climatic Data Center (NCDC); for soundings launched since 2002, only GTS levels are reported. The change in reporting structure is relevant for inversion analysis because GTS and NCDC use different criteria for selecting significant temperature levels. Specifically, GTS determines significant levels in such a way that the linear interpolation between any two reported levels of a sounding differs by less than 1°C from observations. NCDC levels, in contrast, are based on a 0.5°C deviation from linear (Schwartz and Govett 1992). Containing only raw GTS data, the University of Wyoming radiosonde archive is consistent in its reporting structure for the period of interest for this study.

To focus the analysis on inversions in the lower atmosphere, only inversions whose base formed at or below 2000 m above the local surface were considered. This cutoff height was chosen to include lower-level elevated inversions, such as winter capping inversions, but to exclude inversions that formed above the 500-hPa level used herein to diagnose relationships between inversion formation and large-scale circulation. Inversion characteristics were analyzed for the entire 2000-m column, as well as for near-surface and elevated inversions within this column. Near-surface inversions were defined to include those that formed in the bottom 400 m of the atmospheric column. If more than one low-level inversion was present for a given sounding, the strongest inversion (largest temperature difference) in the column section considered was selected for analysis. Adjacent inversions were not combined.

b. Large-scale circulation

Associations between inversion frequency and large-scale circulation were investigated for the winter months [December–February (DJF)], when synoptic storms dominate local weather. Inversion activity also typically peaks during winter (Hosler 1961), and so focusing the analysis on this season ensured adequate sample sizes for statistical testing. Daily geopotential height records from the North American Regional Reanalysis (NARR), a product of the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center, were used to characterize circulation patterns from 1994 through 2008. The reanalysis provides 32 km × 32 km resolution data, available on monthly, daily, and 3-hourly time scales, spanning 1979 to the present. The 0000 UTC 500-hPa geopotential height anomalies were used to capture the large-scale atmospheric dynamics present during the 0000 UTC sounding launches. In contrast to the surface, the 500-hPa level provided a consistent level at which to analyze large-scale circulation (since the six Southwestern sites lie at varying elevations), allowing us to focus on similarities in circulation rather than on the differences that might occur because of topography or other confounding factors.

Daily geopotential height maps were organized into 24 groups using a neural network technique known as self-organizing maps, or SOMs (Kohonen 1998; SOM_PAK 1996 software package). This technique has been increasingly used to successfully study relationships between local meteorological conditions and larger-scale climatologies (e.g., Hewitson and Crane 2002; Cassano et al. 2007; Higgins and Cassano 2009; Schuenemann and Cassano 2010; Skific et al. 2009). The number of groups, or “nodes,” is subjectively chosen but with the goal of maintaining large enough sample sizes for statistical testing (fewer nodes comprising more historical records) while avoiding oversmoothing the representational climatological patterns (too few nodes).

The SOM nodes are organized in such a way that maximizes “between group” while minimizing “within group” differences. An advantage of this method is that nodes are distributed in a nonlinear fashion; as a result, a larger number of climatological groupings are created near areas of high-density data, allowing one to represent the variability in the original time series of geopotential height records more robustly. The way in which each daily record from the reanalysis is associated with 1 of the 24 nodes is here described briefly. To begin, the 24 representational patterns are linearly distributed across the data space. As each daily height record from the reanalysis is presented to the SOM, it is matched to its “best fit” pattern. Both the best fit and nearby nodes are subsequently updated through a self-learning process, which reduces differences between the newly presented record and the existing node distribution. A single record can thus help define several of the final representational patterns. The rate of this “learning” process (or the degree to which the nodes are adjusted) and the radius of the area affected by learning (which determines how many nearby nodes are updated each time a new record is considered) are user defined. Nodes are adjusted iteratively until no further changes in node distribution occur or until the number of training steps (the number of times the daily records are presented to the SOM) is maximized. User-defined parameters are chosen to minimize the overall quantization error. In this study, a minimal quantization error of 5947.14 was obtained by using a learning rate of 0.03, a radius of 3, and 500 000 training steps.
The SOM package objectively arranges the final 24 representational large-scale circulation patterns according to their similarities and displays them in a four by six array, referred to as the master SOM (Fig. 2). Since each of the final patterns is associated with daily records of known dates, local meteorological parameters can then be estimated for each pattern. In this manner, inversion frequencies were calculated for each representational pattern and tested against the total wintertime inversion frequency per site. A pooled variance $t$ test was used, after Cassano et al. (2007), to identify circulation patterns with anomalously high or low inversion activity. The null hypothesis—that the node inversion frequency is not different from the overall wintertime inversion frequency—was rejected if

$$1.645 < \frac{(p_1 - p_2) \sqrt{n_2}}{p_2(1 - p_2) + p_1(1 - p_1)} \sqrt{n_2},$$

where $n_1$ is the number of days mapped to the pattern of interest, $n_2$ is the total number of winter days included in the master SOM, $p_1$ is the inversion frequency for the pattern and site of interest, and $p_2$ is the total wintertime inversion frequency per site. The term on the left of the inequality is for the 0.10 significance level. The 0.05 level, used elsewhere in the study, proved too restrictive.

3. Results

a. Inversion characteristics

Monthly inversion frequencies, calculated as the percentage of the month during which at least one low-level (base $\leq 2000$ m) inversion was present during the late afternoon sounding, are shown for the ESRL and University of Wyoming radiosonde archives (Fig. 3). The records are closely aligned from 2002 through 2008, when both datasets report GTS significant levels exclusively. Pearson correlation coefficients exceed 0.98 for all sites, suggesting that differences between the raw and quality-checked GTS data are minimal. However, substantial differences are apparent for the first eight years of the comparison, likely resulting from ESRL’s inclusion of both NCDC and GTS significant levels during this earlier period. For the period 1994–2001, correlations between the two time series are reduced to 0.69 at Tucson, 0.85 at...
Flagstaff, 0.86 at Salt Lake City, 0.83 at Denver, 0.71 at Albuquerque, and 0.92 at Santa Teresa. Since NCDC significant temperature levels are based on smaller temperature deviations than GTS levels, the NCDC record likely captures weak temperature inversions not reported by GTS. Figure 4 supports this hypothesis by clearly showing changes in the frequency distributions of inversion intensity, calculated for soundings with inversions present, between the late 1990s and 2000s in the ESRL record. A much larger probability of weak inversions is associated with the 1994–2001 period, when the NCDC and GTS data were merged. Figure 5 also shows a much higher frequency of surface inversions during this time. Together, these results suggest that the NCDC–GTS merged records include a much higher number of weak, near-surface inversions than the GTS records alone.

Because the change in reporting structure appears to affect the continuity of the inversion record calculated from the ESRL database, and because differences between raw and quality-checked GTS data appear to be minimal, the University of Wyoming archive is used to analyze the full 15-yr period in an unbiased manner. Monthly mean inversion frequencies from this archive are plotted in Fig. 6 for 1994–2008 for all low-level, near-surface, and elevated inversions. All sites exhibit much higher low-level inversion activity during the winter than summer, although the four southern sites experience a peak in near-surface inversions during July and August.

**FIG. 3.** Monthly inversion frequencies calculated from the NOAA–ESRL (gray) and University of Wyoming (black) radiosonde archives at (a) Salt Lake City, (b) Denver, (c) Flagstaff, (d) Albuquerque, (e) Tucson, and (f) Santa Teresa. The vertical dashed line at 2002 marks the time at which the ESRL database stopped merging NCDC and GTS significant levels.
possibly as a result of evaporative cooling following convective storms.

To account for this strong seasonal cycle, inversion frequency time series are plotted as monthly anomalies for all low-level, near-surface, and elevated inversions (Fig. 7). Tucson and Albuquerque exhibit no significant changes in inversion frequency at any height. In contrast, Flagstaff, Santa Teresa, Salt Lake City, and Denver show significant increases in elevated inversions. Slopes from linear regressions that differ from zero at the 0.05 significance level are reported in Fig. 7. These increases, in absolute percent, represent changes for the 15-yr period of 13.5% at Salt Lake City, 10.5% at Flagstaff, 6% at Santa Teresa, and 1.5% at Denver. For an average 30-day month, these are equivalent to increases of 4.0, 3.2, and 1.8 inversion days per month at Salt Lake City, Flagstaff, and Santa Teresa, respectively. Although Salt Lake City experienced the largest increase in low-level elevated inversions, no significant change is apparent when the entire 2000-m column above the surface is considered, due to opposing, though insignificant, declines in near-surface inversions. The increase in low-level elevated inversions at Denver, while significant, is small, amounting to less than half a day increase per month over the 15-yr period. The more striking change in inversion frequency at Denver is the significant decline in near-surface inversions, equivalent to a change in absolute percent of \(-10.5\%\) over the 15-yr period, or \(-3.2\) inversion days per month. Changes in inversion intensity were not significant at any of the Southwestern sites.

In comparison, the ESRL record suggests that all six sites experienced substantial declines in inversion frequency through 2001 (Fig. 3). Linear regressions, based on the ESRL monthly anomaly time series for 1994–2001,
exhibit slopes significantly different than zero at the 0.05 significance level (not shown). In contrast to the increasing trends from the GTS data, they show changes (in absolute percent) of $-4.3\% \text{ yr}^{-1}$ at Tucson, $-2.8\% \text{ yr}^{-1}$ at Flagstaff, $-3.2\% \text{ yr}^{-1}$ at Salt Lake City, $-2.8\% \text{ yr}^{-1}$ at Denver, $-4.8\% \text{ yr}^{-1}$ at Albuquerque, and $-1.4\% \text{ yr}^{-1}$ at Santa Teresa. These changes are much larger than any in the 15-yr University of Wyoming record. Because these substantial declines are unique to the period when NCDC–GTS significant levels were merged, they must reflect changes in very weak, near-surface inversions. It is worth noting, however, that the weakest inversions captured by the early ESRL record are defined by temperature differences close to the expected precision of radiosonde temperature sensors (Luers 1997), and so we cannot rule out the possibility that some of these apparent declines are affected by changes in instrument accuracy. This possibility further supports our use of the University of Wyoming GTS record in analyzing inversion statistics for the full 15-yr period.

b. Large-scale circulation

Recent increases in elevated inversion frequency, evident in GTS records, are consistent with projections of regional stagnation driven by large-scale conditions. To investigate this mechanism further, the SOM method was used to test the sensitivity of inversion activity at each southwestern upper air station to large-scale circulation during the winter season. Wintertime circulation for the period 1994–2008 was characterized by constructing 24 representational patterns from daily 500-hPa geopotential height anomaly maps for the area spanning approximately $20^\circ$–$50^\circ$N, $80^\circ$–$130^\circ$W. These representational patterns are shown in the master SOM (Fig. 2) and are further categorized by type for the purpose of facilitating discussion. SOM analysis was also repeated for a smaller domain, $26^\circ$–$45^\circ$N, $96^\circ$–$121^\circ$W; however, the results were qualitatively similar and thus only the larger domain is described here in detail. Circulation patterns associated with anomalously high or
low inversion frequencies were identified for all low-
level inversions (Fig. 8) and for elevated inversions
(Fig. 9) at each site. Inversion frequencies associated
with a particular circulation pattern that significantly
differed from the overall wintertime frequency for the
site at the 0.10 significance level are shaded in Figs. 8
and 9. The discussion below focuses on the University of
Wyoming record, although results based on the ESRL
record were qualitatively similar.

Salt Lake City experienced low-level inversions on
57% of winter days between 1994 and 2008. Yet the city
experienced inversions at a much higher frequency
(often exceeding 70% of days) when ridges centered
over the Southwest or Pacific coast, but not when the
ridge axis was positioned far west of the coastline, as was
the case for ridge patterns 13 and 19. Salt Lake City also
experienced anomalously high inversion activity for
zonal pattern 15, which, though representing largely
zonal flow, is also characterized by a weak ridge over the
northwestern United States. Significantly below normal
inversion activity occurred for most trough patterns, as
well as for zonal patterns 20 and 21. Positive inversion
frequency anomalies were significant for nine of the
patterns and negative inversion frequency anomalies
were significant for seven, showing a strong association
between Salt Lake City’s inversion activity and the
prevailing circulation.

Elevated inversion activity at Salt Lake City was also
strongly associated with large-scale conditions, and ele-
vated inversions occurred on 42% of winter days during
the 1994–2008 period. Elevated inversion frequency
anomalies (Fig. 9) mapped to many of the same patterns
as low-level frequency anomalies (Fig. 8), with a few
exceptions. For instance, zonal pattern 15, which was
FIG. 7. Time series of monthly inversion frequency anomalies (absolute percentage) for (top) low-level, (middle) elevated, and (bottom) near-surface inversions at (a) Salt Lake City, (b) Denver, (c) Flagstaff, (d) Albuquerque, (e) Tucson, and (f) Santa Teresa. Slopes of linear regressions that are significantly different from zero at the 0.05 level are labeled.
associated with significantly high inversion activity when considering the entire 2000-m atmospheric column, was associated with low, but not significantly anomalous, elevated inversion activity. This implies that most of the inversions associated with this pattern were surface-based. In contrast, trough pattern 6, which exhibited an insignificant but slightly negative frequency anomaly when considering all low-level inversions, was characterized by significantly high elevated inversion activity. This pattern was likely associated with more subsidence or frontal inversions than radiation inversions. Frequency anomalies associated with patterns 9, 16, 17, and 19 also changed significance but not sign.

Inversion frequency anomalies at the New Mexico sites also corresponded well with large-scale circulation. At Albuquerque, inversions occurred significantly more frequently than the wintertime average (35% of the time) when the strongest southwestern ridges were present, such as was the case with ridge patterns 1–4 and 7. Inversions occurred significantly less frequently when troughs extended into the Southwest. Some 200 miles to the south, Santa Teresa experienced inversion activity on 45% of winter days, with significant positive frequency anomalies occurring for three ridge patterns and significantly low inversion activity occurring when trough patterns were present. Significant frequency anomalies for elevated inversions at Albuquerque mapped identically to significant frequency anomalies for all low-level inversions with two exceptions. Trough pattern 6 was still associated with low elevated inversion activity but was no
longer significant at the 0.10 level, while zonal pattern 15 exhibited significantly low activity for elevated inversions only. As with Salt Lake City, most inversions affiliated with this pattern appeared to be ground-based. No differences between elevated and low-level inversions were evident in the mapping of significant frequency anomalies at Santa Teresa. Mean elevated inversion frequencies for the winter months were 32% and 43% at Albuquerque and Santa Teresa, respectively.

In contrast, inversion frequency at Denver, Flagstaff, and Tucson showed little dependence on large-scale circulation. At these sites, both positive and negative frequency anomalies occurred for a variety of geopotential height patterns. In Denver, where low-level inversions occurred on 48% of winter days between 1994 and 2008, significantly higher than expected inversion activity was associated with three zonal patterns and trough 24, which corresponded with significantly low inversion activity at neighboring sites Salt Lake City and Albuquerque. Denver inversion activity was significantly low for just two patterns. Notably, inversion frequencies associated with the majority of circulation patterns, especially ridge patterns, deviated little from the average wintertime inversion frequency for the site, demonstrating a high degree of insensitivity to large-scale circulation. Similar insensitivity to large-scale conditions was found for elevated inversion activity, which affected Denver on 25% of winter days.

Anomalous inversion activity at the Arizona sites also mapped poorly to the circulation patterns of the master SOM; and although Flagstaff and Tucson are approximately the same distance apart as Albuquerque and Santa Teresa, they failed to show a similar degree of coherence. At Flagstaff, where low-level inversions occurred on 53% of winter days between 1994 and 2008, the weak dependence on large-scale circulation is illustrated by the fact that oppositely signed inversion frequency anomalies occurred for nearby or closely related circulation patterns. At Tucson, few patterns exhibited inversion activity different from the wintertime average.
for the site (26% of the time), which was the lowest of the region. Significant elevated inversion anomalies at Tucson mapped identically to low-level anomalies, with the mean elevated wintertime inversion frequency being just 24%. Flagstaff experienced more significant frequency anomalies for elevated inversions than low-level inversions, but the congruity with wintertime circulation did not improve. Flagstaff’s mean elevated inversion frequency was 45% for the winter season.

To summarize the relationship between site inversion frequencies $I$ and SOM circulation patterns, a simple linear regression model was applied:

$$I = aZ_x + bZ_y + c.$$  

Each circulation pattern was characterized by differences in geopotential height anomalies along east–west ($Z_x$) and north–south ($Z_y$) transects bisecting the region of interest (Fig. 10). The $Z_y$ height difference was used to approximate the zonal index of wind strength, while the $Z_x$ height difference provided an estimate of the longitudinal position of troughs and ridges. Together the two approximate the geostrophic circulation near the region of interest, in this way distinguishing one SOM circulation pattern from the next. Height differences for each circulation pattern are listed in Table 1.

The $R^2$ values (Table 2) suggest that 62.9% of the variance in Salt Lake City’s low-level inversion activity and 84.1% of the variance in elevated inversion activity were captured by the 24 circulation patterns. At Santa Teresa, 57.2% of the variance in low-level inversions and 56.8% of the variance in elevated inversions were captured. At Albuquerque, the variance explained was 43.1% and 49.0% for all low-level and elevated low-level inversions, respectively. Although the SOMs captured just 25% of the variance in Tucson’s low-level inversion activity, an $F$ test suggests the regression parameters were significant for the site, indicating that inversion activity in Southern Arizona is at least weakly correlated with large-scale conditions. Regression models were insignificant at Denver and Flagstaff for all low-level and elevated inversions, supporting the interpretation that inversion activity was poorly characterized by large-scale circulation at these sites.

Salt Lake City and Santa Teresa were thus the only two sites that exhibited both significant changes in elevated inversion activity and strong associations between inversion activity and large-scale circulation. To test whether changes in the large-scale circulation regime were responsible for the observed inversion activity increases at these sites, differences in the frequencies of individual circulation patterns between the first (January 1994–February 2001) and second (December 2001–December 2008) halves of the period of analysis were calculated. Figure 11 shows that in the latter half of the period, circulation patterns were more often affiliated with the left- and right-hand sides of the master SOM. These “edge” patterns were more representative of strong ridges and troughs, conditions that favored anomalously high and low inversion activity in both Utah and New Mexico.
Multiplying these circulation changes by the mean elevated inversion frequencies associated with each pattern for each site results in a net positive change in inversion activity at Salt Lake City but a net negative change at Santa Teresa, which is inconsistent with observations. It is thus unlikely that changes in winter circulation pattern frequencies alone were responsible for the observed changes in elevated inversion statistics. Subtle variations in the daily records represented by each circulation pattern may also have been important, as might have changes outside of the winter season. At Salt Lake City, for instance, significant increases in elevated inversions occurred during January but also during October and November, indicating that the fall season may be particularly important for inversion statistics.

4. Discussion

Previous studies suggest that air quality conditions will deteriorate in response to dynamical changes brought about by a warming climate, and GTS radiosonde records indicate that low-level elevated inversions are indeed increasing in frequency at four of six Southwestern upper air stations. However, GTS records also show that near-surface inversions are declining at Denver and possibly at Salt Lake City, the two northern sites of the study region. The ESRL record, which contains finer significant temperature level structure for soundings launched prior to 2002, indicates that declines in weak, surface-level inversions were actually widespread in the mid- and late 1990s and highlights the substantial influence of radiosonde archiving practices on inversion statistics. If these observations of small temperature deviations are accurate, they suggest remarkable declines in the frequency of weak, ground-based inversions in the Southwest.

Such declines are not necessarily inconsistent with the increases in elevated inversions evident in the University of Wyoming record. Ground-based inversions, which often result from radiative cooling, are particularly sensitive to surface temperature and albedo, while elevated inversions, if subsidence-induced, respond largely to adiabatic warming during calm conditions. One could certainly imagine a situation in which regional high pressure, associated with subsidence, also produces sunny, cloud-free conditions that enhance warming at the surface. Surface temperatures could also be affected by factors independent of meteorology, such as land use change and urban heat island effects. This raises an interesting and important question about the relative importance of microscale climate and large-scale circulation in determining the direction of future air quality conditions.

Although increases in elevated inversion frequency are consistent with projections of meteorological stagnation, the SOM analysis highlights considerable variations in inversion sensitivity to large-scale circulation from one Southwest city to the next. Of the six sites considered, Salt Lake City, Utah, exhibited the strongest link between local inversion activity and large-scale circulation, consistent with the findings of previous investigations (Gillies et al. 2010). Inversion activity at Albuquerque and Santa Teresa, New Mexico, though corresponding well with the large scale, was not nearly as sensitive as elevated inversion activity at Salt Lake City. At these three locations, inversions occurred most frequently when ridges were present, conditions expected to favor high pressure subsidence. These findings are consistent with the results of Milionis and Davies (2008a,b), Reeves and Stensrud (2009), and Whiteman et al. (1999). In contrast, inversion activity at Denver, Colorado, and Flagstaff and Tucson, Arizona, was poorly characterized by large-scale circulation, although a weak correlation was evident at Tucson when considering all low-level inversions.

We speculate that this geographically disparate response to large-scale circulation may be a result of the

<table>
<thead>
<tr>
<th>Inversion type</th>
<th>Tucson</th>
<th>Flagstaff</th>
<th>Salt Lake City</th>
<th>Denver</th>
<th>Albuquerque</th>
<th>Santa Teresa</th>
</tr>
</thead>
<tbody>
<tr>
<td>All low-level</td>
<td>0.250</td>
<td>0.024</td>
<td>0.629</td>
<td>0.145</td>
<td>0.431</td>
<td>0.572</td>
</tr>
<tr>
<td>Elevated</td>
<td>0.220</td>
<td>0.072</td>
<td>0.841</td>
<td>0.105</td>
<td>0.490</td>
<td>0.568</td>
</tr>
</tbody>
</table>

**Table 2.** The $R^2$ values from multiple linear regressions of inversion frequencies on the 24 SOM circulation patterns. Models significant at the 0.05 level are shown in boldface.
unique topography near the six study sites. Salt Lake City lies in a large basin rimmed by the Wasatch Range to the east and smaller ranges to the north, west, and south of the Great Salt Lake. Albuquerque and Santa Teresa both lie along the Rio Grande, with elevated landmasses to the east and west. Whiteman et al. (1999) noted that inversion activity in the large basinlike area of the Colorado Plateau is particularly sensitive to synoptic circulation during wintertime. Perhaps the basin topography at Salt Lake City and the valley-like topography at the New Mexico sites favor the entrapment of cold air near the surface, facilitating inversion persistence when stagnant conditions are present at the large scale.

The topography near Denver, on the other hand, is characterized by high mountains to the west and extensive plains to the east, which facilitates the drainage of cold, polluted air masses eastward, out of the urban area along the Platte River valley (Riehl and Herkhof 1972). Inversion formation often occurs when these cold air masses return westward by way of short-range flows, which can develop under low pressure regimes (as described by Reddy et al. 1995). The SOM analysis confirmed above-normal inversion activity at Denver when trough patterns were present. Furthermore, Denver was unique in experiencing a higher percentage of near-surface inversions than elevated inversions during December and January, indicating surface conditions may be particularly important in determining wintertime inversion statistics at this site. Indeed, winter inversion frequencies show some degree of correlation with National Weather Service (NWS) monthly snowfall statistics (Fig. 12), and Denver’s largest monthly declines in surface inversion frequency occurred in November, the beginning of the Front Range snow season. Surface radiation changes might be expected to have a particularly strong effect during the fall–winter transition by altering the number of days when snow cover is present. There remains a need to assess the sensitivity of inversion activity to the surface energy balance, complementing previous work by Savoie and McKee (1995) in rural Colorado.

Flagstaff’s mountainous setting may also thwart simple associations between local inversion activity and large-scale circulation. A second possibility is that the relationship between Flagstaff’s inversion activity and the large-scale circulation is obscured by other dynamics. Even though Flagstaff’s inversion frequency anomalies mapped poorly with SOM circulation patterns, Flagstaff nevertheless exhibited the second highest number of significant frequency anomalies for elevated inversions in association with large-scale circulation. Using a 3-yr bandpass filter to eliminate shorter time-scale variability, Flagstaff’s low-level inversion frequency was compared with the Southwest Monsoon Index (NOAA–ESRL Climate Indices) on a 6-month lag, resulting in a correlation of 0.96 (Fig. 13). It is thus possible that summertime circulation patterns are equally or more important in setting up Flagstaff’s wintertime inversion activity, or that the Pacific teleconnections that favor a stronger Southwest monsoon (Grantz et al. 2007) also favor winter circulation regimes that induce inversion formation.

Tucson, in contrast, lies within a distinct valley and would, according to the above reasoning, be expected to exhibit a strong association with large-scale circulation. Yet the city’s warm climate may play a role in decoupling afternoon inversion frequency from the large scale. For instance, Tucson experienced significant negative inversion frequency anomalies for two ridge patterns. These patterns were associated with high mean surface temperatures. Tucson also experienced the lowest overall frequency of inversions during the wintertime. Perhaps, then, Tucson’s warmer climate, including a general lack of snow cover, favors strong diurnal heating, which erodes inversions by the time the 0000 UTC soundings (1700 local time) are launched, regardless of the prevailing large-scale conditions.

In a region of complex terrain, inversion activity appears most sensitive to large-scale circulation at sites with basin or valley features. Yet this association may be compromised in warmer climes, as a result of local diurnal heating, if inversion activity is measured late in
the day. This demonstrates a need for future work to quantitatively evaluate the effects of local topography and urban development on the sensitivity of inversion activity to large-scale conditions. Importantly, these findings indicate that individual urban areas in the U.S. Southwest will respond quite differently to large-scale dynamical changes expected with climate. Meso- and microscale factors may play particularly significant roles in influencing inversion activity at select sites.

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