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HISTORICAL TRENDS OF RECORD DAILY TEMPERATURES AT DENVER, COLORADO, 1872-2010

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1. Introduction

The highest and lowest temperatures ever recorded for each calendar day of the year at a location hold great interest for the public and the media. They serve as extreme milestones for comparing current-day weather conditions. Along with the daily normal high and low temperatures, these record temperatures have become routine fixtures in TV weather program graphics that present the current day's weather statistics. Record temperatures also have numerous more practical applications in engineering designs of outdoor facilities and in agricultural practices.

More recently, historical trends in record temperatures are being used as indicators of changing climate conditions. Meehl et al. (2009), for example, examined trends in daily record high and low temperatures at almost 2000 cooperative observer stations across the continental United States for the period 1950-2006, and showed that high temperature records are being broken increasingly more often than low temperature records. By the last decade of

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the 20th century, the ratio was approximately 2:1 in favor of new record high temperatures compared to new record lows. In statistical terms, the 2:1 ratio is a very wide margin. In contrast, for a stable climate, setting new record low and high temperatures should be equally likely to occur, and both become less likely events as more years of measurements accumulate. Thus, the recent preponderance of new record high temperatures is offered by Meehl et al. (2009) as evidence that the United States' climate has been warming.

In this study, we also investigate the historical trends of daily record temperatures. Unlike Meehl et al. (2009), however, we examine only one site (Denver, Colorado), but use a much longer period of record.

2. Data Analysis – Historical Trends

The record temperatures for all days (including February 29) of the year are available on the internet in tables from the Denver-Boulder office of the National Weather Service (NWS 2010). These are considered to be the "official" records for Denver. In addition to the temperatures, the year in which each record was set (or most recently tied) is also presented in the same NWS internet tables. Those years, extending back to 1872, are the primary data

of interest in this study, which used data updated through the end of 2010. Thus, 138 years of record are included.

A complicating factor for this study is the fact that the measurement site for the official Denver weather records moved substantial distances twice during the 138-year period of record. The NWS tables of record daily temperatures include data from all three sites, as if they were from a single, continuous measurement location. The three sites are similar but certainly not identical, in terms of weather conditions. Implications of the most recent site change in 1995 for assessing the long-term record temperature trends are examined in Section 3.

Figure 1 presents a plot of the record high and low temperatures[1] as a function of the 366 days of the year, along with the normal (1971-2000 averages) high and low temperatures, available from the same internet site (NWS 2010). The curve for the record low temperatures is more ragged than that for record highs, especially in winter months, indicating greater year-to-year variability in winter daily minimum temperatures.

Figure 2 shows a scatter diagram of the year in which the standing records were set[2], as a function of calendar day. The red dots represent record highs, and the blue triangles represent the record lows. Close inspection of Fig.2 reveals a greater number of red dots located near the top of the graph (recent years) and more blue triangles near the bottom (the more distant past). This indicates a recent preponderance of new record high temperatures compared to record lows. The newer records are mostly those of high temperatures, and those that have survived the longest are mostly record lows. An unexplained curiosity of Fig. 2 is the hole, or absence, of remaining summertime records that date back to the period of approximately 1915 to 1955.

The visual impression from Fig. 2 that there has been a preponderance of more recently broken record high temperatures compared to record lows is quantified in Table 1 and Figures 3 and 4. Table 1 shows the number or standing records that date back to each of the 14 decades since measurements began in Denver. The year-of-record numbers are plotted in statistical box-plot and histogram forms in Figs. 3 and 4, respectively. The most prominent differences between the high and low record temperatures involve the decades after 1980 and those before 1900, as indicated in Table 1 and Fig. 4.

Clearly, in the last three decades there have indeed been far more record high temperatures broken than record lows. In the 2001-2010 decade, for example, the ratio was 2.6 to 1 in favor of record highs. In 1991-2000 the ratio was 2.2, which agrees well with the 2.0 ratio reported by Meehl et al. (2009) for the continental United States. The Denver trend favoring record highs became established at the end of the 1970s. Figure 4 and Table 1 also show that the standing record-low temperatures remaining from the decades before the 20th century far outnumber the record highs that date back that far. In other words, most of the record-high temperatures from those early years

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[1] The NWS tables refer to the daily maximum and minimum temperatures as the daily "high" and "low" temperatures, respectively. We retain that terminology throughout the article for brevity.

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[2] Note that this paper addresses the year in which the standing record for each calendar day was most recently set, as of the end of 2010. This is a different approach from, but equivalent to, that of Meehl et al. (2009), who focused on how many daily records were set each year as time progressed, starting in 1950.

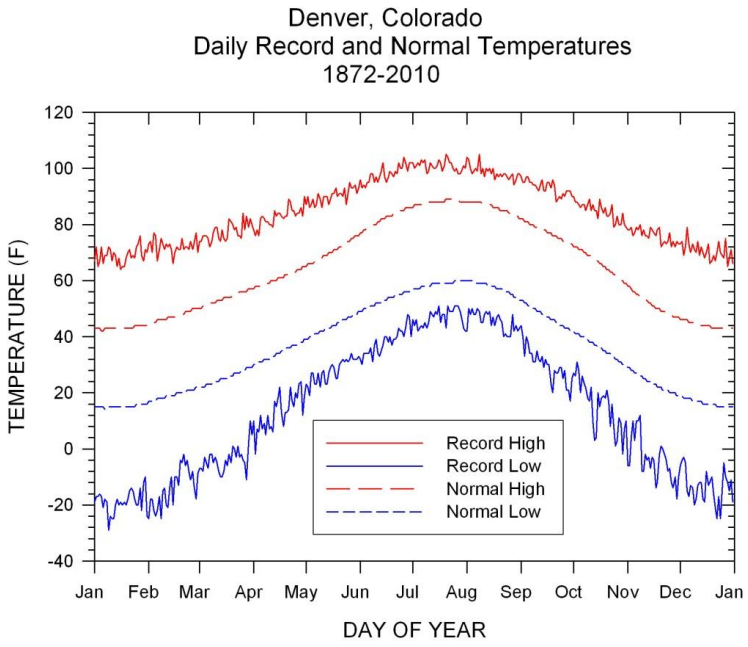

Figure 1. Daily record (1872-2010) and normal (1971-2000) temperatures for Denver, Colorado.

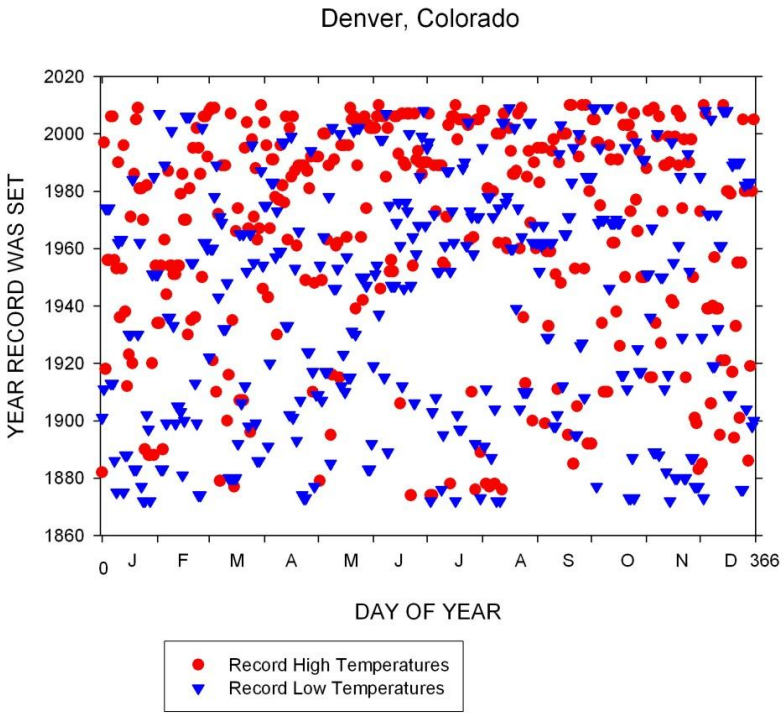

Figure 2. Scattergram showing the year in which the daily record temperatures were set at Denver, Colorado, for the period 1872-2010. Data are for standing records as of the end of 2010.

Table 1. Distribution of Denver's daily record temperatures by decade in which the record was set or most recently tied.

Decade	Number of Days With Record High Temperatures	Number of Days With Record Low Temperatures
2001-2010	79	30
1991-2000	51	23
1981-1990	52	27
1971-1980	26	31
1961-1970	24	45
1951-1960	30	32
1941-1950	17	16
1931-1940	19	12
1921-1930	8	15
1911-1920	14	26
1901-1910	13	27
1891-1900	11	22
1881-1890	10	22
1872-1880	12	38
Total	366	366
Mean year	1966.2	1940.9
Median year	1980	1951

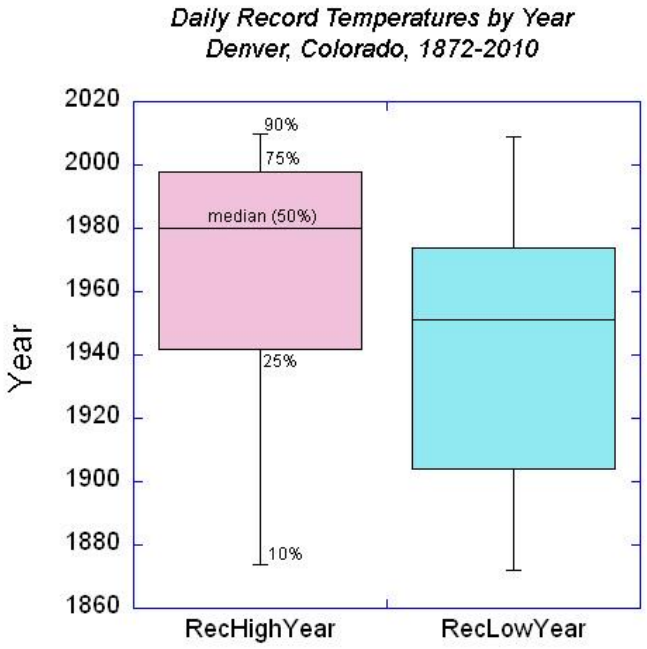

Figure 3. Statistical box-plot of years in which record temperatures were set in Denver, as of the end of 2010. Left side is for record highs; right for record lows. Horizontal markers are for 10, 25, 50, 75, and 90 percent of the cumulative number of cases.

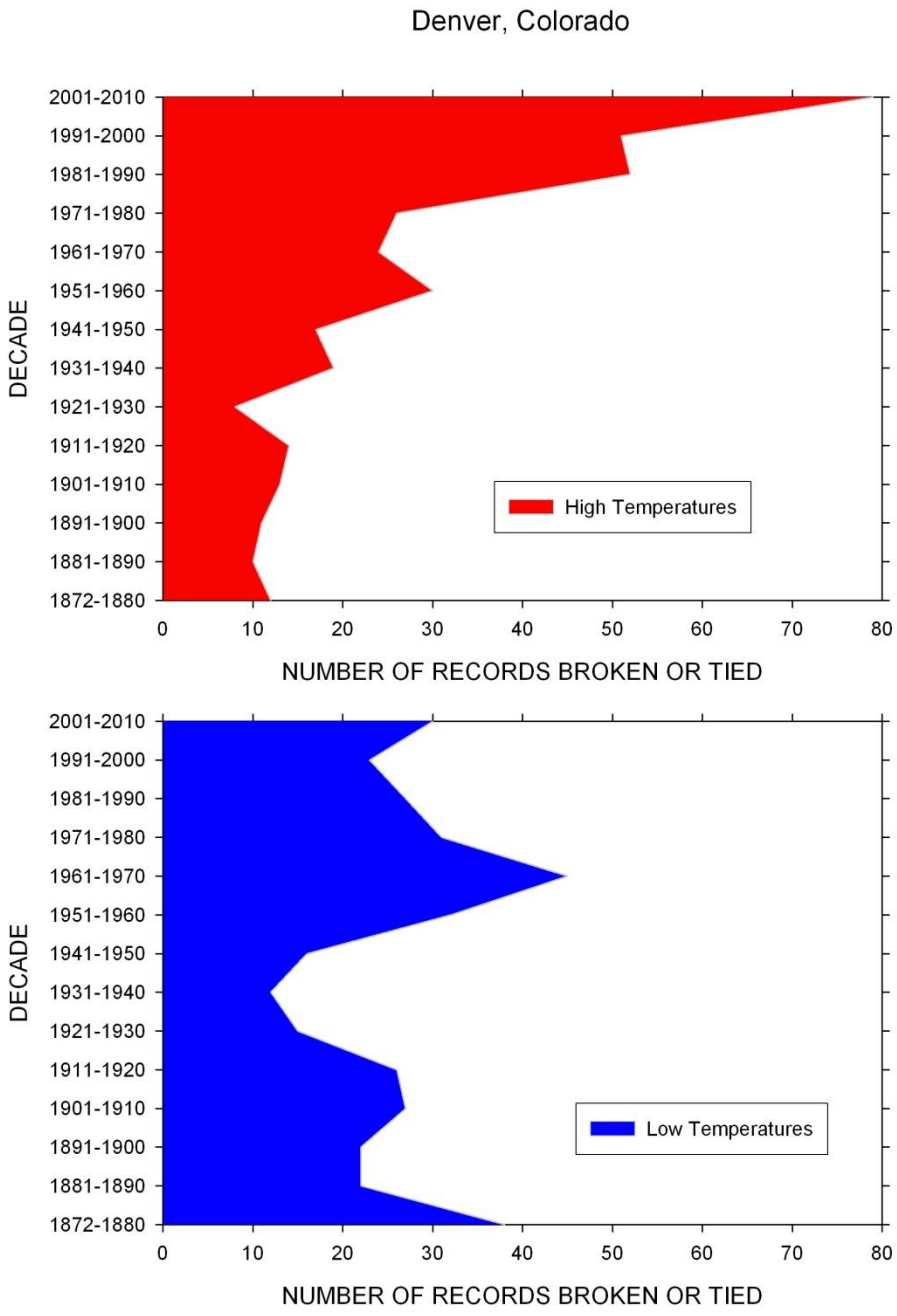

Figure 4. Histograms of the decades in which the standing daily record temperatures were set at Denver, plotted from the data of Table 1. Upper panel is for the record high temperatures; lower panel is for the record low temperatures.

have been surpassed, but many of the record lows from the 1800s remain on the books.

The results for Denver are in general agreement with those found by Meehl et al. (2009) in their study, which was far more spatially expansive but shorter in period of record. The results suggest that the climate of the Denver area has been warming since the 1970s.

3. Other Considerations – Stapleton versus DIA

The conclusion of the previous sentence would be even more convincing if the Denver measurements could be shown to be unaffected by other factors that might have significantly shifted the recorded daily temperatures up or down or changed their variability. Changes in instrumentation (for example, Quayle et al. 1991), time-of-day recording (Easterling 2002), and site location *could* produce such data discontinuities, and Denver has experienced all of these factors over the years. Change in site location is almost certainly the most important potential data-discontinuity factor in Denver's case.

The site of Denver's daily weather measurements has moved substantial distances twice since observations began in 1872. The record temperatures (NWS 2010) used in Section 2 include data sequentially from all three sites: downtown Denver (1872-1949), Stapleton Airport (STP, 1950-February 1995), and Denver International Airport (DIA, March 1995-present), as summarized in Table 2. The relocation to STP in 1950 involved only a minor altitude change, but the move to DIA in 1995 brought the instruments 128 feet higher above sea level. The altitude gain would favor slightly cooler weather at the new site, other factors aside. Both relocations moved the measurements farther away from the urban center and its possible heat-island effects, which should also favor lower temperatures at the new sites. A more quantitative assessment is possible, however, in the case of the 1995 move from STP to DIA because overlapping temperature data are available from both sites.

At the end of February 1995, Stapleton Airport closed and flight operations began at the new Denver International Airport. Measurements from a new Automated Surface Observing Station (ASOS) at DIA became the new NWS source of weather data for Denver, including the ongoing historical catalog of daily record temperatures. This was controversial because DIA was farther removed from Denver's population center and was therefore deemed unrepresentative by many people. Nevertheless, the more important question for this study is whether the move to DIA biased the new data toward higher temperatures.

Although the old airport was closed and later demolished, radiosonde launches and daily precipitation and temperature measurements continued at the STP site. Concurrent high and low temperatures from DIA and STP for the period of March 1995 through December 2010 are examined in this section. Both sites use the thermistor-based maximum-minimum temperature system (MMTS) instrumentation. The daily temperatures from DIA are available at the Denver-Boulder NWS internet site (NWS 2010) and the Stapleton data are available, without charge, at the National Climatic Data Center's internet site (NCDC 2010).

There is one major problem for making these comparisons, however. In 1999 the NWS staff at STP moved to new offices in

Table 2. Measurement sites from which the Denver record temperature data are compiled.

	downtown	Stapleton Airport (STP)	Denver International Airport (DIA)
Period	1872-1949	1950 – Feb. 1995	Mar. 1995 - present
Latitude/Longitude	39° 45' N 105° 00' W	39° 46' N 104° 52' W	39° 50' N 104° 39' W
Altitude (MSL)	5325 ft (approx.)	5286 ft	5414 ft
Distance and direction from previous site		7 miles east	12 miles northeast
Altitude change from previous site		- 39 ft	+128 ft
Identifier codes	Coop = 052225 WBAN = 93002	Coop = 052220 WBAN =23062 WMO =72469 Call signs = DEN, DNR (after 2/95)	Coop = 052211 WBAN = 03017 WMO = 72565 Call signs = DEN, KDEN

Table 3. Temperature comparisons for Stapleton and Denver International Airport based on the highest and lowest temperatures each month from 1995 to 2010.

Mean Values (°F) for the Period
March 1995 through December 2010

	-------- Monthly Extremes of Daily ---------			
	High Temperatures		Low Temperatures	
	DIA	STP	DIA	STP
WINTER	65.41	66.89	-2.5	0.13
SPRING	81.21	81.73	19.17	21.63
SUMMER	97.21	96.81	46.48	48.15
FALL	82.92	83.38	20.21	22.33
JAN	65.13	67	-3.13	0.2
FEB	65.67	66.87	-1.6	1.53
MAR	75	76	9.25	12.44
APR	79.81	79.69	19.06	21.81
MAY	88.81	89.5	29.19	30.63
JUN	94.81	94.38	40.06	42.56
JUL	99.69	99.38	51.13	52.13
AUG	97.13	96.69	48.25	49.75
SEP	91.44	91.63	34.69	35.44
OCT	83.69	83.94	21.13	22.5
NOV	73.63	74.56	4.81	9.06
DEC	65.44	66.81	-2.75	-1.25
ALL MONTHS	81.86	82.36	21.08	23.3

DIA = Denver Intl. Airport
STP = Stapleton

WINTER = DEC + JAN + FEB
SPRING = MAR + APR + MAY
SUMMER = JUN + JUL + AUG
FALL = SEP + OCT + NOV

DIA warmer than Stapleton
DIA cooler than Stapleton

Boulder, Colorado, leaving the STP site manned by contractors. This staffing change and economic considerations resulted in a time-of-day change for recording max/min temperatures. The recording time at STP changed from 2400 (midnight) local time to 0700 in the morning. The recording time at DIA remained 2400 throughout the overlap period.

The recording-time difference after the change caused one-day offsets between STP and DIA in some data. For example, STP's 24-hour high temperature recorded for the current day usually actually occurred the afternoon of the previous day, whereas the recorded high temperature at DIA occurred on the afternoon of the recording day. The morning recording time at STP also opens the possibility for double-minimums there (Easterling 2002). This complicates efforts to make direct day-to-day comparisons of maximum and minimum temperatures and record temperatures at STP and DIA. To minimize these problems, statistics of monthly temperature data from both sites are compared as a proxy for direct day-to-day comparisons. Extremes (the highest and lowest temperature recorded during a month) are more pertinent to this study of record-breaking temperatures than monthly means of the daily high and low temperatures.

Table 3 shows the statistics of the extremes data for the two sites, averaged by season and month of year, for the comparison period of almost 16 years (190 months). The table's color-coding highlights those seasons and months when DIA was warmer (pink), and cooler (blue), than STP. The right half of the table, which shows the monthly extremes of daily low temperatures, is entirely blue. This means that DIA had lower minimum temperatures than STP for each season and each month of the year. In terms of the extremes of daily high temperatures (left side of the table), DIA was warmer than STP only in the summer. (Thus, in summer, DIA had both hotter afternoons and cooler mornings than STP.) In all other seasons, both the afternoons and the mornings were cooler at DIA. The annual averages at the bottom of the table show that DIA was also cooler overall than STP. On an annual basis, its monthly extreme high temperatures averaged about 0.5° F lower than those of STP, and its extreme low temperatures were about 2.2° F lower than STP's.

These comparison results do not explain the unbalanced 2.6 ratio favoring the breaking of high temperature records found in Section 2. On the contrary, they suggest that the relocation to DIA in 1995 should have resulted in more record-breaking low temperatures following the move, if Denver's climate was not changing.

It should be noted that the DIA-STP temperature differences are small and involve large variabilities. Consequently, none of the site differences in Table 3 are statistically significant at the 95% confidence level, according to the Student T-test. Therefore, DIA is certainly not significantly warmer than the STP site, and the evidence indicates that it is actually cooler in all seasons except summer and slightly cooler overall.

The site-comparison shows that the move to DIA in 1995 is not a plausible explanation for the observed strong preference for breaking more record high temperatures than record low temperatures in recent years. Indeed, although the trend accelerated during the DIA years, it began approximately 15 years before the measurement site moved there (Table 1). Thus, a warming of Denver's climate

remains the most likely explanation for the observed recent preponderance of record-breaking high temperatures.

4. Summary and Conclusions

The National Weather Service maintains a compilation of the record temperatures for Denver, Colorado, for each calendar day, along with the year in which each record was set. The data span the period of 1872-2010. The record high and low temperature data were examined in this article with regard to the years in which the standing records were set. Analysis shows that far more daily record-high temperatures have been broken recently than record-low temperatures. This lopsided or disparate trend began at the end of the 1970s and accelerated through the last three decades. In the most recent decade of 2001-2010 new record-breaking high temperatures outnumbered new record lows by a ratio of 2.6 to 1. This evidence indicates that climate of the Denver area has been warming, at least since the 1970s.

Two major location changes occurred for the Denver temperature-measurement site since 1872. The most recent relocation from Stapleton Airport to Denver International Airport happened in 1995 during the period of accelerated apparent warming. Concurrent data of 1995-2010 from both sites were compared to determine whether a bias related to the location change, rather than climate change, could be responsible for the observed disparity in record temperature trends. In terms of the highest and lowest temperatures each month, the comparisons show that the new site (DIA) was cooler than the old site (STP) in all seasons except summer, and cooler overall on an annual-average basis. Thus, site relocation is not a plausible explanation for the observed recent trends in record temperatures.

5. References

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