THE JULY 2005 DENVER HEAT WAVE: HOW UNUSUAL WAS IT?

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Abstract

In mid July 2005, very hot temperatures developed over the Rocky Mountains and western Great Plains. This paper summarizes the heat wave and places it in historical perspective. The core of the heat wave was centered near Denver where several weather stations approached or exceeded their all-time record high temperatures on 20-21 July. Denver International Airport rose to 105°F on 20 July and two National Weather Service (NWS) Cooperative stations in the Denver metro area reached 108°F exceeding any previous records for the city. Based on 5-day running mean temperatures, this heat wave ranks first for Denver, Edgewater/Lakewood, and Fort Collins. For July as a whole, the month was not the warmest on record, however, due to sharply cooler weather shortly after the heat wave. An alternative method for evaluating heat waves - moist enthalpy which combines temperature and humidity - provides a markedly different perspective and shows the Denver heat wave to be less extreme due to very low humidity accompanying the event.

1. Introduction

Extremely hot weather developed over the Western U.S. during July 2005. Numerous high temperature records were broken from California and Arizona eastward into Colorado and New Mexico as cited in the *Weekly Weather and Crop Bulletin* [United States Department of Agriculture (USDA) 2005]. An unusually late onset of the summer monsoon played a large role in the hot weather. For example, the NOAA/National Weather Service (NWS) Weather Forecast Office (WFO) in Tucson, AZ recorded 2005 as the second latest arriving monsoon (1987 is the latest) since 1949 (NOAA 2005b). This nearly record breaking late arrival of the monsoon was associated with Tucson tying its record for the longest string of 100°F+ readings (39 days; op. cit.).

Meanwhile brief episodes of extreme heat, beginning on 13 July, were observed over the northern Rockies (Wyoming and Montana). Then from 19-23 July, temperatures soared daily to 100°F and above from the Front Range of Colorado across the northern and central Great Plains as reported in the *Weekly Weather and Crop Bulletin* (USDA 2005). The Denver-Boulder WFO (NOAA 2005a) summarized July 2005 as the second hottest (the hottest average month remains July 1934) and the third driest since 1872. This assessment was based on data collected at Denver International Airport (DIA) where six record high temperatures were set, each at or above 100°F (Fig. 1). The high of 105°F observed on 20 July 2005 tied 8 August 1878 for the all-time highest temperature ever recorded at Denver's primary weather station. There were 25 days with maximum temperatures at 90°F or higher, which tied with the third most since 1963 (1964 had 27 days). Were it not for a strong cold front and sharply cooler temperatures later in the month, July could have been the hottest on record. The 500 hPa analysis for the five-day average from 20 July through 24 July is shown (Fig. 2) to illustrate the average synoptic pattern with this event. The upper level ridge over Colorado was anomalous by more than 70 gpm, which reflects the warmth of the air column underneath this level rather than surface pressure anomalies.

This heat wave resulted in considerable news coverage and some public debate regarding just how extreme this event was and the integrity of the data used to assess it (Denver Channel 7 2005; Rocky Mountain News 2005). One question regarding the hot temperatures at DIA is whether the instrument is properly sited. This is not always the case (Davey and Pielke 2005). The DIA site's exposure (Fig. 3) was examined for this study and shown to have a good exposure, such that its record high temperatures cannot be attributed to local conditions. The DIA site (lat 39°49'58"N and long 104°39'27"W) began taking observations in March 1995. The temperature sensor was moved one-quarter mile north in June 2003 from the original location and another 1 mile north in 2004 to make room for a new runway (personal communication, Byron Louis, National Weather Service, 2006).

The purpose of this paper is to examine the heat wave in greater detail to better assess its place in Colorado cli-

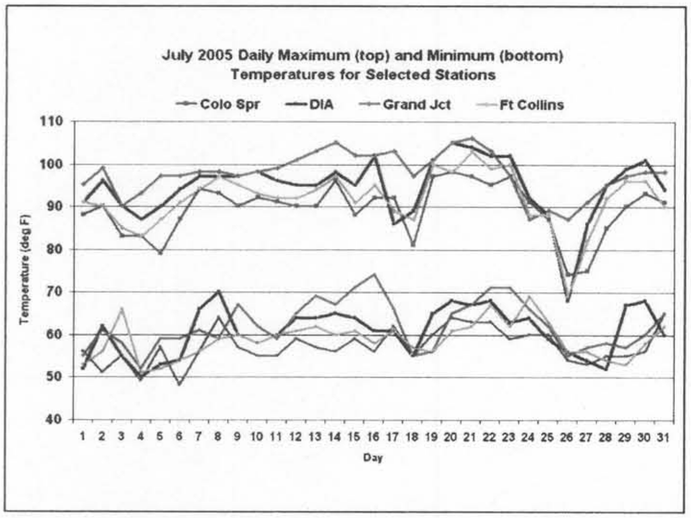

Fig. 1. Daily high and low temperatures for July 2005 from four official weather stations Colorado - Colorado Springs (airport), Denver (airport), Fort Collins (Colorado State University) and Grand Junction (airport).

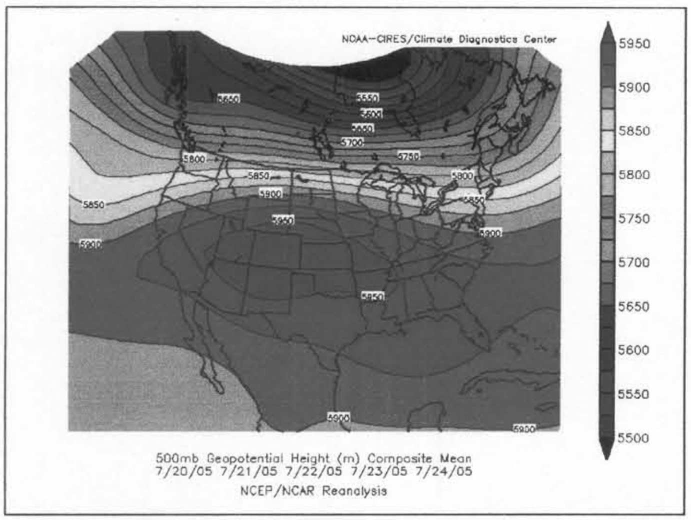

Fig. 2. Five-day average 500 hPa geopotential height map for 20-24 July 2005. Image was provided by the NOAA-CIRES Climate Diagnostics Center in Boulder, Colorado, from their web site (http://www.cdc.noaa.gov).

mate history. Several different approaches to assessing heat are presented below, including the monthly average temperature surrounding the heat wave, the number of days above commonly used temperature thresholds, the highest daily temperature, the five-day running average of mean daily temperatures, and the highest value of moist enthalpy.

The evaluation of moist enthalpy (also known as the "effective temperature") is a new approach to assess heat waves, and permits the incorporation of the contribution of water vapor content to the heat of the air in units of Joules. Although historic records of surface water vapor content are comparatively short, they allow for a revealing perspective on recent Colorado heat waves. It should be noted that the occurrence of a single extreme heat

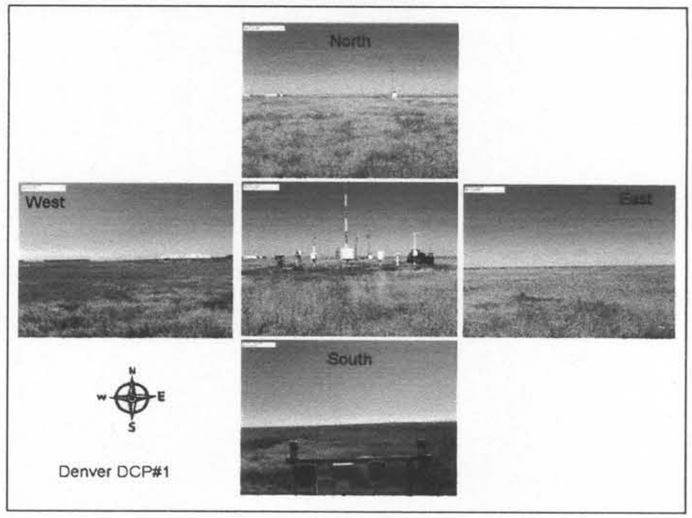

Fig. 3. Denver International Airport ASOS Site photos, courtesy of the NOAA/National Weather Service, Denver/Boulder Office.

wave in a limited geographic region cannot be used to prove or disprove the existence of a recent "global warming" fingerprint, even though moist enthalpy is a better metric for measuring heat content change than surface temperature alone.

2. Climatological Analysis

a. Monthly mean, maximum, and minimum temperature

Table 1 displays the July 2005 monthly maximum, minimum and mean temperatures and period of record across Colorado for selected long-term stations. The locations of these long-term weather stations are shown in Fig. 4. The rank for the period of record is also given.

Despite selecting the best of Colorado's long-term climate monitoring stations in Table 1, nearly all of them have experienced station moves, changes in thermometers and changes in the landscape and environments around the station all of which can impact rankings. Nevertheless, it is apparent that 2005 July monthly temperatures were hot statewide but were most anomalous in the Denver area and the Front Range urban corridor from Fort Collins to Pueblo.

b. Number of days above a temperature threshold

Table 2 presents the number of days during July 2005 with daily maximum temperatures greater than or equal to 90°F and 100°F, respectively, and where these rank in the period-of-record for each available station. The information we have is more limited than for the monthly averages, but it does show that in terms of days greater than or equal to 100°F, Denver Stapleton tied and Lakewood exceeded the record number. Both sites, however, had fewer days at this level than DIA.

While it was clearly hot statewide, the number of days with temperatures of 90°F or higher were not exceptional. The number of days of 100°F or greater were more

Table 1. Monthly average maximum, minimum and mean temperatures for selected stations for July 2005 for period of record. Most stations are NWS Cooperative Stations (Coop), but for the larger cities data come from the NWS Automated Surface Observing Sites (ASOS).

Climatic Stations	Elevation (feet)	Type of Station	Period of Record (POR)	July 2005 Temperature Max (Rank)	Min (Rank)	Mean (Rank)
Akron 4E	4550	Coop	1905-2005	93.3(5+)	61.0(2)	77.2(2)
Alamosa	7533	ASOS	1948-2005	86.9(1)	45.7(47)	66.3(8)
Aspen / 1SW combined*)	7936/8163	Coop	1914-2005	81.1(16)	48.7(5)	64.9(6)
Boulder	5484	Coop	1893-2005	91.6(4)	58.5(53)	75.1(21)
Buena Vista	7946	Coop	1905-2005	87.2(5)	50.8(2)	69.0(3+)
Center 4 SSW	7673	Coop	1942-2005	84.1(7)	46.5(28)	65.3(5)
Cheesman	6880	Coop	1902-2005	87.7(9)	52.5(11)	70.1(4)
Cheyenne Wells	4250	Coop	1897-2005	93.1(26+)	59.4(54+)	76(34+)
Cochetopa Creek	8000	Coop	1947-2005	86.1(3)	41.4(33+)	63.8(6+)
Collbran / 2SW (combined*)	5980/6100	Coop	1901-2005	92.0(8)	52.3(40)	72.1(14+)
Colorado Springs WSO	6181	ASOS	1948-2005	89.3(5)	57.2(26)	73.3(9)
Del Norte 2E	7864	Coop	1920-2005	79.6(32)	45.8(77)	62.7(52)
Denver Intl Airport	5414	ASOS	1995-2005	94.5(1)	60.8(4)	77.7(1)
Denver Stapleton	5286	Coop	1948-2005	92.6 (3)	60.1(13)	76.4(6+)
Denver (combined*)	5325/5286	C/A	1872-2005	94.5(1)	60.8(33)	77.7(2)
Dillon	9065	Coop	1910-2005	78.2(6)	37.4(42+)	57.8(11)
Fort Collins	5001	Coop	1895-2005	91.7(2+)	58.8(10+)	75.4(3)
Fraser (combined*)	8560/8563	Coop	1910-2005	78.7(3)	35.8(27+)	57.3(8)
Grand Junction WSO	4858	ASOS	1900-2005	97.7(3+)	62.2(93+)	80.0(21)
Grand Lake 1NW	8720	Coop	1940-2005	80.9 (5)	39.8(16)	60.2(6)
Kassler	5587	Coop	1918-2005	91.9(2)	61.3(12+)	76.6(5)
Lakewood	5640	Coop	1962-2005	93.5(1)	60.0(7)	76.8(2)
Lakewood/Edgewater (combined*)	5640/5453	Coop	1902-2005	93.5(5)	60.0(11)	76.8(5+)
Las Animas	3890	Coop	1893-2005	97.5(24+)	62.8(23)	80.1(22)
Leadville	9938	Coop	1976-2005	74.6(6)	39.4(4+)	57.0(15+)
Leadville (combined*)	9941/9938	Coop	1949-1982	74.6(6)	39.4(24+)	57.0(14+)
Leroy 7WSW	4470	Coop	1893-2005	93.5(7)	60.3(14+)	77.0(8)
Meeker	6180	Coop	1894-2005	89.3(10)	48.1(22)	68.7(12+)
Mesa Verde NP	7115	Coop	1923-2005	88.5(23+)	59.0(15)	73.8(17)
Montrose No. 2	5785	Coop	1896-2005	92.7(5+)	54.1(80+)	73.4(32+)
Pueblo WSO	4720	ASOS	1954-2005	97.7(2)	58.9(37+)	78.3(12)
Rocky Ford 2SE	4170	Coop	1892-2005	98.7(1)	54.2(111)	76.5(44)
Sedgwick	3990	Coop	1959-2005	94.7(4)	60.9(14)	77.8(8+)
Taylor Park	9206	Coop	1941-2005	74.7(4+)	41.7(17+)	58.2(7+)
Waterdale (Loveland)	5230	Coop	1902-2005	91.6(6)	57.0(9)	74.3(6)

+ means that temperature tied previous years

* Data combined for Aspen 1914-1979; Aspen 1SW 1980-2005

* Data combined for Collbran 1901-1999; Collbran 2SW 2000-2005

* Data combined for Denver City 1872-1950; Denver Stapleton 1950-1994; DIA 1995-2005

* Data combined for Fraser 1910-1973; 1989-2005

* Data combined for Edgewater 1908-1961; Lakewood 1962-2005

* Data combined for Leadville 1949-1975; Leadville 1976-2005

Table 2. The number of days during July 2005 where daily maximum temperatures equaled or exceeded 90°F and 100°F for selected weather stations in Colorado. The rankings, with respect to the period of record, are shown in parentheses.

Climatic Stations	Elevation (feet)	Period of Record (POR)	Number of Days .GE. 90 (Rank)	.GE. 100F (Rank)
Akron 4E	4550	1905-2005	21(12+)	6(4+)
Alamosa	7533	1948-2005	9(2+)	0
Aspen / 1SW (combined*)	7936/8163	1914-2005	0	0
Boulder	5484	1893-2005	22(6+)	1(7)
Buena Vista	7946	1905-2005	11(5)	0
Center 4 SSW	7673	1942-2005	3(4)	0
Cheesman	6880	1902-2005	12(10)	0
Cheyenne Wells	4250	1897-2005	22	5
Cochetopa Creek	8000	1947-2005	6(3+)	0
Collbran/2SW (combined*)	5980/6100	1901-2005	23(8+)	0
Colorado Springs WSO	6181	1948-2005	20(2+)	0
Del Norte 2E	7864	1920-2005	0	0
Denver Intl Airport	5414	1995-2005	25(2)	7(1)
Denver Stapleton	5286	1948-2005	22(6+)	5(1+)
Denver (combined*)	5325/5286	1872-2005	25(3+)	7(1)
Dillon	9065	1910-2005	0	0
Fort Collins	5001	1895-2005	22(2+)	3(2)
Fraser (combined*)	8560/8563	1910-2005	0	0
Grand Junction WSO	4858	1900-2005	28(12+)	10(5+)
Grand Lake 1NW	8720	1940-2005	0	0
Kassler	5587	1918-2005	20(5+)	3(3+)
Lakewood	5640	1962-2005	22(2)	6(1)
Lakewood/Edgewater (combined*)	5640/5453	1902-2005	22(7+)	6(3+)
Las Animas	3890	1893-2005	27(33+)	12(26+)
Leadville	9938	1976-2005	0	0
Leadville (combined*)	9941/9938	1949-1982	0	0
Leroy 7WSW	4470	1893-2005	22(11+)	6(6+)
Meeker	6180	1894-2005	13(17+)	0
Mesa Verde NP	7115	1923-2005	12(32+)	0
Montrose No. 2	5785	1896-2005	23(12+)	2(4+)
Pueblo WSO	4720	1954-2005	28(7+)	12(2+)
Rocky Ford 2SE	4170	1892-2005	29(8+)	16(3)
Sedgwick	3990	1959-2005	25(4+)	8(3+)
Taylor Park	9206	1941-2005	0	0
Waterdale (near Loveland)	5230	1902-2005	22(7+)	3(4+)

+ means that temperature tied previous years
* Data combined for Aspen 1914-1979; Aspen 1SW 1980-2005
* Data combined for Collbran 1901-1999; Collbran 2SW 2000-2005
* Data combined for Denver City 1872-1950; Denver Stapleton 1950-1994; DIA 1995-2005
* Data combined for Fraser 1910-1973; 1989-2005
* Data combined for Edgewater 1908-1961; Lakewood 1962-2005
* Data combined for Leadville 1949-1975; Leadville 1976-2005

impressive with most locations ranking in the top 5 years. The only stations showing the most days ever recorded with temperatures of 100°F or higher were in the immediate Denver area (DIA, Stapleton and Lakewood).

c. Highest daily temperature

Table 3 presents the highest maximum temperature reached in July 2005, the date of occurrence and its ranking with respect to previous highest July temperatures. Also shown is the highest recorded temperature for any day in July and the year it occurred. For stations where July 2005 was the highest, the previous highest temperature and date of occurrence are shown. The absolute (or the all-time record) highest recorded temperature and the date it occurred is also shown, and for some stations this occurs in late June or early August. In addition to DIA, several sites reported their highest temperature ever (Denver Stapleton, Fort Collins, Grand Junction, Leroy, Waterdale, and Lakewood). Fort Collins, Waterdale, Leroy, and Grand Junction have temperature records that extend back through the 20th century.

The highest temperatures in Colorado during major heat waves are usually found at lower elevation stations east of the Rockies and in the Colorado River valley of western Colorado near the Utah border. This was generally the case in July 2005, but of note were the very high temperatures at the base of the Rockies from Fort Collins to Pueblo (Fig. 4). At the same time that DIA reported the record-tying 105°F, two stations within urbanized areas hit 108°F: Denver Water Department and Northglenn (Fig. 5). These are the highest temperatures ever measured in the Denver metropolitan area but these two stations have only been in existence since 1997 and 1984, respectively.

d. Running five-day averages of mean daily temperatures

There are arguably better ways to define heat waves than with mean monthly temperatures or with individual daily extreme values. The impacts from heat waves are often cumulative - the result of consecutive days of extreme heat. A centered 5-day running average computed from daily maximum and minimum temperatures captures these cumulative effects (Fig. 6).

For a few selected stations near Denver, CO, July mean daily temperatures were computed for the available record. For each day with a mean daily temperature greater than or equal to an extreme threshold value, a centered 5-day average was computed (Figs. 7-9). This value was chosen based on local experience to represent only days of extreme heat. Since 1950, for example, Fort Collins has only had one mean daily temperature of 83°F or above while the combined Denver and Lakewood stations have had 33 and 21 such days, respectively. Therefore, we picked 80°F for the Fort Collins threshold to show periods of extreme heat, while an 83°F threshold was used for Denver and Lakewood.

This analysis shows the July 2005 heat wave as the most extreme on record for these stations when applying

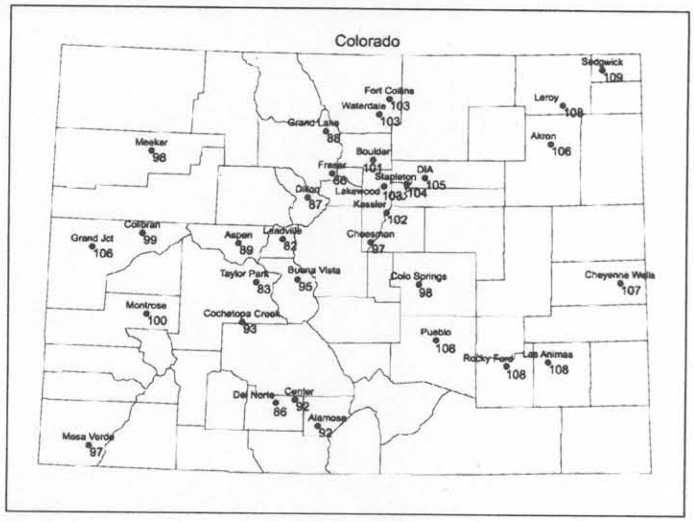

Fig. 4. Locations of the weather stations used in this study and their highest recorded daily maximum temperature for July 2005.

this particular criterion. The number of days above the local threshold was comparable to other heat waves at each station, but the highest 5-day running mean exceeded any previous values for all three stations. For the combined Denver station, the highest 5-day running mean of 84.8 was nearly 1.5°F higher than any previous record.

3. An Alternative Metric for Evaluating the July 2005 Heat Wave

The surface air temperature is often used to quantify how hot it is. However, temperature is not actually a measure of heat, since heat is energy, and energy is measured in Joules, not degrees. To obtain the *heat content* of the surface air, one should compute the moist enthalpy, which requires three standard observed quantities: the air temperature, dew point temperature (or relative humidity), and the surface pressure (Pielke et al 2004; Davey et al 2005). Moist enthalpy is expressed as:

$$H = c_p T + L_v q \qquad (1)$$

where c_p is the specific heat of air at constant pressure and was approximated as 1005 J kg^{-1} K^{-1}, T is the observed air temperature (in K), L_v is the latent heat of vaporization and is equal to 2.430x10^6 J kg^{-1} (at 30°C), and q is the specific humidity (in kg kg^{-1}), which can be found from the dew point temperature and surface pressure via the following relation:

$$q = \frac{0.622e}{p - 0.378e}, \text{ where } e = 6.112\exp\left(\frac{17.67T_d}{T_d + 243.5}\right). \qquad (2)$$

In the previous equations, e is the saturated vapor pressure (in hPa), p is the surface pressure (in hPa), and T_d is the dew point temperature (in °C). To scale the enthalpy

Table 3. The highest maximum temperature, the rank for its period-of-record, the date it occurred and time of observation for July 2005 compared to the highest recorded temperature for all July's and the year it occurred or for stations where July 2005 was the highest, then the previous highest temperature and date of occurrence are shown. The last two columns show the absolute highest temperature for the station and date(s) of occurrence.

Climatic Stations	Period of Record (POR)	Time of Obs LST	Record Temperature					Absolute Temperature	
			July 2005 Highest Max Temp	July 2005 Highest Max Temp	Date of July Tmax	Highest Recorded Temp or Previous Record	Year	Absolute Tempurature	Month and Year
Akron 4E	1905-2005	08	106	2+	21st	107	1989	107	1989/07/09
Alamosa	1948-2005	24	92	4+	17,19, 21, 21	96	1989	96	1989/07/05
Aspen / 1SW (combined*)	1914-2005	08	89	12+	22nd	94	1917	94	1917/07/27
Boulder	1893-2005	17	101	3+	21st	104	1954	104	1954/06/23
Buena Vista	1905-2005	08	95	5+	22nd	102	1927	102	1927/07/13
Center 4 SSW	1942-2005	24	92	4+	20th	94	1954	95	1954/06/21
Cheesman	1902-2005	07	97	6+	22nd	99	1936, 1939	99	1954/06/23; 1936/07/23; 1939/07/12
Cheyenne Wells	1897-2005	17	107	3	20th	109	1936	109	1936/07/24
Cochetopa Creek	1947-2005	08	93	3+	23rd	94	2002, 2003	94	2002/07/14; 2003/07/19
Collbran / 2SW (combined*)	1901-2005	08	99	2+	21st	100	2003	100	1902/08/02; 2003/07/14
Colorado Springs WSO	1948-2005	24	98	5	20th	100	1954, 2003	100	1954/06/23; 2003/07/24
Del Norte 2E	1920-2005	07	86	32+	15/20th	91	1940, 1951	91	1940/07/24; 1951/07/07
Denver Intl Airport	1995-2005	24	105	1	20th	101	2000, 01, 03	105	2005/07/20
Denver Stapleton	1948-2005	06	104	1	21st	103	1973, 1989	104	1994/06/26; 2005/07/21
Denver (combined*)	1872-2005		105	1	20th	103	1973, 1989	105	1878/08/08; 2005/07/20
Dillon	1910-2005	07	87	2	21st	89	1939	89	1939/07/12
Fort Collins	1895-2005	19	103	1	21st	102	1925	103	2005/07/21
Fraser (combined*)	1910-2005	16	86	5+	21st	94	1939	98	1969/08/01
Grand Junction WSO	1900-2005	24	106	1	21st	105	1925, 1971, 1976, 2002, 2003	106	2005/07/21

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Table 3 Continued.

Climatic Stations	Period of Record (POR)	Time of Obs LST	Record Temperature					Absolute Temperature	
			July 2005 Highest Max Temp	July 2005 Highest Max Temp	Date of July Tmax	Highest Recorded Temp or Previous Record	Year	Absolute Tempurature	Month and Year
Grand Lake 1NW	1940-2005	16	88	7+	12th	92	1978	92	1978/07/15
Kassler	1918-2005	07	102	3+	21/22nd	103	1990	105	1994/06/27; 2005/07/21
Lakewood	1962-2005	07	103	1	21st	101	1989	104	1994/06/27
Lakewood/ Edgewater (combined*)	1902-2005		103	4+	21st	106	1939, 1954	106	1954/06/23; 1938/08/01; 1939/07/20
Las Animas	1893-2005	24	108	12+	20th	114	1933	114	1933/07/01
Leadville	1976-2005	17	82	5		85	1963, 2003	86	1954/06/23
Leadville (combined*)	1949-1982		82	8+		85	1963, 2003	85	2003/07/18; 1963/07/19
Leroy 7WSW	1893-2005	07	108	1+	21st	108	1990, 2005	108	1990/07/02; 2005/07/21
Meeker	1894-2005	08	98	5+	22nd	103	1900	103	1900/07/11
Mesa Verde NP	1923-2005	08	97	12+	21st	102	1936	102	1936/07/24
Montrose No. 2	1896-2005	08	100	5+	21/22nd	103	1931	106	1947/08/01
Pueblo WSO	1954-2005	24	108	2	20th	109	2003	109	2003/07/13
Rocky Ford 2SE	1892-2005	17	108	1	20th	107	1960, 2003	108	2005/07/20
Sedgwick	1959-2005	07	109		20th	114	1954	114	1954/07/11
Taylor Park	1941-2005	17	83	2+	21st	86	1942	86	1942/07/15
Waterdale (near Loveland)	1902-2005	08	103	2	22nd	104	1934	104	1934/07/13

+ means that temperature tied previous years
* Data combined for Aspen 1914-1979; Aspen 1SW 1980-2005
* Data combined for Collbran 1901-1999; Collbran 2SW 2000-2005
* Data combined for Denver City 1872-1950; Denver Stapleton 1950-1994; DIA 1995-2005
* Data combined for Fraser 1910-1973; 1989-2005
* Data combined for Edgewater 1908-1961; Lakewood 1962-2005
* Data combined for Leadville 1949-1975; Leadville 1976-2005

into degrees for easy comparison to air temperature, divide by c_p:

$$\frac{H}{c_p} = T_E = T + \frac{L_v q}{c_p} \tag{3}$$

Here, T_E is called the effective temperature and has units of Kelvin. It is clear that the effective temperature will always be greater than or equal to the air temperature. The two are only equal when there is no moisture in the air, and the difference between the two becomes greater as the humidity increases. In other words, T_E has contributions from both sensible and latent heat, and the latter should not be ignored when evaluating the intensity of heat waves.

The NWS adopted a "heat index" (Steadman 1979) to assess the severity of predicted heat waves, but this measure is different from the effective temperature that is used in our study. In particular, the NWS heat index is designed to model the human response to heat, and requires additional observations of radiation and wind speed to be properly computed. It is therefore much more

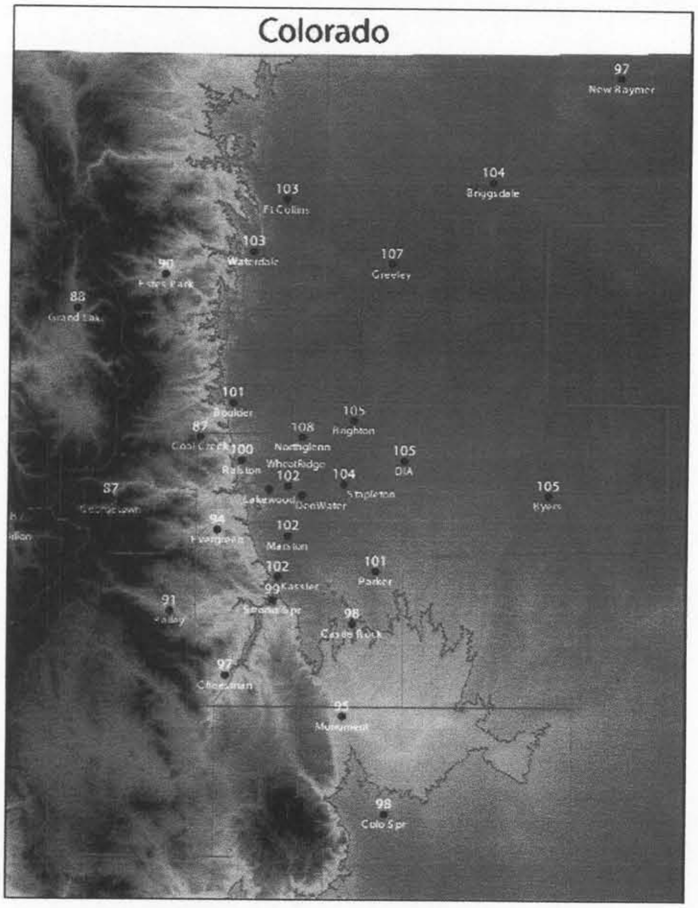

Fig. 5. Highest daily maximum temperatures (°F) for July 2005 for selected stations in northern Colorado. Background shading shows topography. Thick contour highlights 6500-foot elevation.

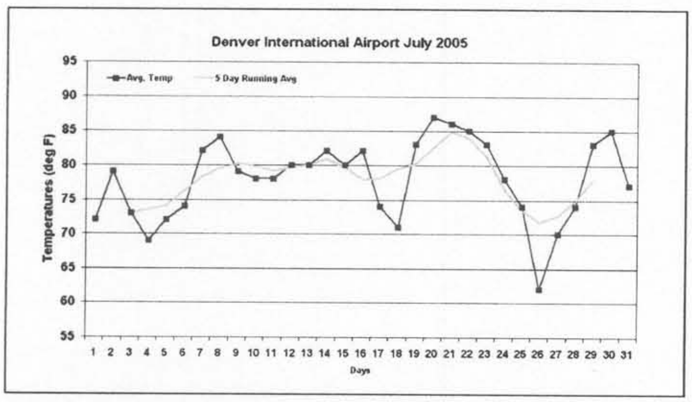

Fig. 6. Centered 5-day running average of mean daily temperature for Denver International Airport for July 2005.

complicated than the effective temperature, which is based solely on heat content in Joules.

Using automated hourly observations at two stations encompassing three recent heat waves, one will see that there is a difference in the heat waves when effective temperature is used as the metric instead of air temperature. The two stations used in this section are Fort Collins, CO, and Denver International Airport, CO (FCL

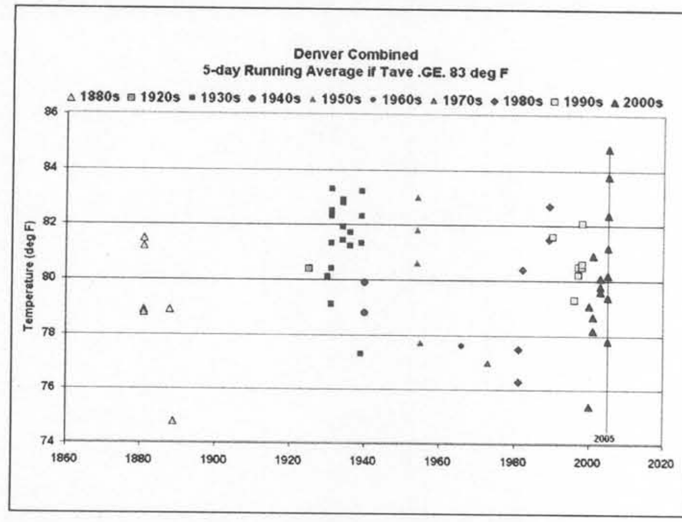

Fig. 7. Time series, 1872-2005, of 5-day centered mean daily temperatures (°F) for each day with a mean temperature (average of the high and low for the day) of 83°F or higher. This time series incorporates data from the original downtown Denver weather station from 1872-1950 with Denver Stapleton data (1950-1995) and Denver International airport (1995-2005).

and DIA), and the three heat waves occurred during July of 2002, 2003, and 2005. It should be noted that the data presented here are the automated hourly observations, not the official observations. The FCL station is located amidst irrigated grass, some trees, and further away are parking lots and buildings. The DIA station is in an open field near the airport's runways. In Fig. 10a-c, only the peak values of T and T_E are plotted on each day during July 2002, 2003, and 2005 (hourly data not shown). The average of each curve is given in the legend.

Although not as obvious in 2002 and 2003, one feature that stands out in 2005 is that T is typically higher at DIA, but T_E is typically higher at FCL. This is actually true in all three years if one considers the average values provided in the legends, and is likely due to the different environments in which the two sensors record (irrigated grass versus open prairie), as mentioned earlier.

There is a notable difference in the heat waves depending on which metric one uses, air temperature or effective temperature. Table 4 reveals that the days with highest T are typically not the days with highest T_E, and vice versa. All times are Mountain Daylight Time, and T and T_E are in °F. In each month, the top five days with highest air temperature are shown, along with the date and time at which the peak occurred, as well as the effective temperature at that time. The second set of numbers for each month is the top five days with highest effective temperature, along with the date and time at which the peak occurred, as well as the air temperature at that time. To put the effective temperatures in context, the highest value observed at FCL during a ten-year period (1996-2005) was 150.4°F, which occurred on 6 July 1999.

The time at which the air temperature reaches a maximum and the time at which the effective temperature reaches a maximum often do not coincide due to boundary layer mixing in the late afternoon. In fact, the maxi-

Table 4. In each of the three recent heat waves – July 2002, July 2003, July 2005 – the top five days with highest air temperature are given. The date and time at which those temperatures occurred are given, followed by the effective air temperature at that time. Similarly, the top five days with highest effective temperature are given. The date and time at which those temperatures occurred are given, followed by the air temperature at that time. Times are in MDT, and temperatures are in °F. Rarely do the two sets of records coincide.

FCL JULY 2002				DIA JULY 2002			
Highest T	Date	Time	T_E	Highest T	Date	Time	T_E
99.4	7/1	1500	117.7	98.0	7/31	1553	123.3
96.8	7/31	1700	117.5	98.0	7/1	1353	125.3
95.8	7/24	1600	121.7	95.0	7/19	1653	124.6
94.9	7/30	1600	116.0	94.0	7/30	1353	118.2
94.3	7/16	1700	119.3	94.0	7/29	1553	117.3
Highest T_E	Date	Time	T	Highest T_E	Date	Time	T
144.5	7/10	1600	82.9	145.3	7/10	1253	86.0
142.8	7/7	1300	84.5	133.9	7/7	1653	86.0
142.3	7/3	1300	84.2	133.5	7/6	1353	76.0
141.0	7/4	1300	81.1	131.6	7/21	1653	78.0
138.2	7/6	1400	79.2	130.8	7/8	1953	80.0

FCL JULY 2003				DIA JULY 2003			
Highest T	Date	Time	T_E	Highest T	Date	Time	T_E
99.0	7/24	1400	123.5	100.0	7/24	1353	131.9
98.8	7/8	1700	119.8	99.0	7/16	1153	124.1
97.5	7/16	1600	129.0	98.0	7/13	1253	125.3
97.3	7/13	1400	116.9	98.0	7/17	1253	131.0
97.2	7/21	1500	123.8	97.0	7/8	1453	121.4
Highest T_E	Date	Time	T	Highest T_E	Date	Time	T
149.5	7/18	1300	90.0	145.7	7/19	1653	84.0
145.7	7/28	1600	78.5	145.1	7/27	1053	79.0
142.0	7/19	1300	83.1	143.3	7/18	0953	86.0
140.8	7/27	1400	85.0	141.6	7/26	1653	90.0
140.7	7/25	1500	92.1	138.5	7/28	1253	77.0

FCL JULY 2005				DIA JULY 2005			
Highest T	Date	Time	T_E	Highest T	Date	Time	T_E
101.3	7/21	1700	128.3	103.0	7/21	1353	123.6
98.5	7/19	1700	116.7	102.0	7/20	1053	118.9
98.2	7/22	1700	130.5	101.0	7/23	1353	127.3
98.1	7/23	1500	136.7	101.0	7/22	1253	122.5
95.8	7/14	1500	132.4	101.0	7/16	1353	120.1
Highest T_E	Date	Time	T	Highest T_E	Date	Time	T
145.5	7/22	1400	92.3	135.7	7/12	1153	88.0
145.4	7/25	1200	77.6	134.0	7/14	1453	97.0
140.9	7/13	1300	86.5	133.9	7/15	1253	94.0
140.9	7/15	1500	88.6	130.2	7/24	1053	84.0
140.6	7/12	1400	86.8	129.9	7/22	1053	93.0

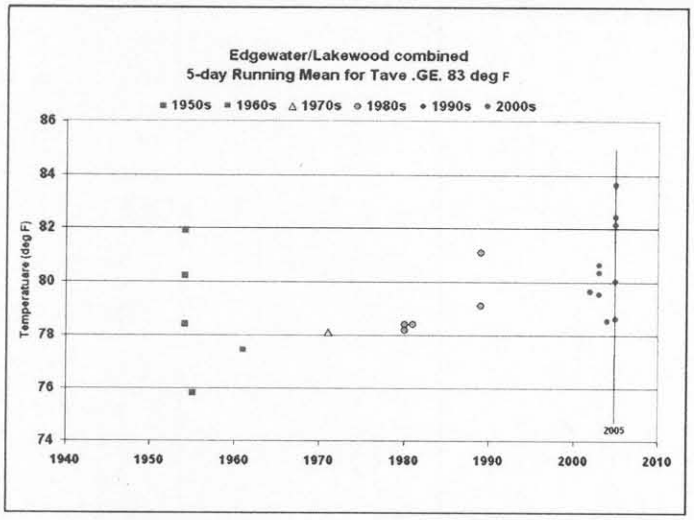

Fig. 8. Time series of 5-day centered mean daily temperatures (°F) for each day with a mean temperature (average of the high and low for the day) of 83°F or higher. This time series incorporates data from the Edgewater, CO cooperative weather station 1948-1962 and the nearby Lakewood, CO cooperative station from 1962-2005.

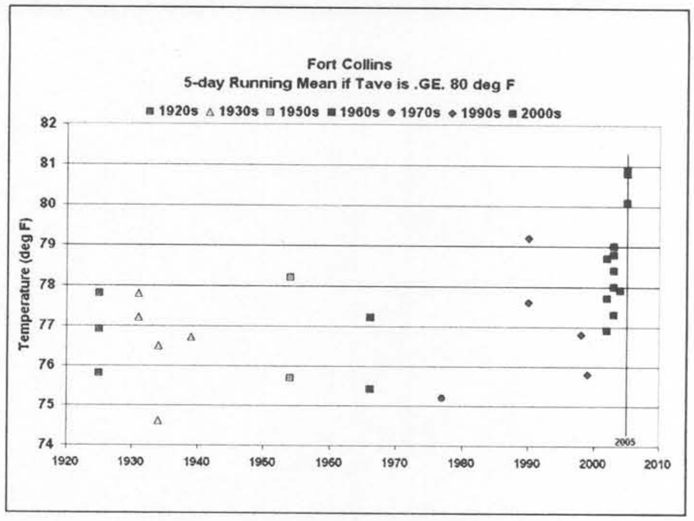

Fig. 9. Time series, 1889 – 2005, of 5-day centered mean daily temperatures (°F) for the Fort Collins, CO weather station for each day with a mean temperature (average of the high and low for the day) of 80°F or higher. The threshold of 80°F or higher was used because there were no days above 83°F.

mum T_E typically occurs a few hours before the maximum T. Figure 11 shows this temporal difference very clearly. It is a composite of the top five hottest days in each of the three years considered here, for FCL (see the left side of Table 4 for the fifteen days that go into making this composite). Both quantities have a minimum just before sunrise, but the effective temperature peaks at approximately 1100 Local Time, while the air temperature peaks at approximately 1500 Local Time.

4. Conclusions

Several different metrics are shown here for comparing heat wave severity and ranking the recent July 2005 Colorado heat wave: monthly temperatures, frequency of temperatures above specified threshold values, daily temperature extremes, 5-day running means and moist enthalpy. Based on daily temperature extremes, July 2005 was a record heat wave for several locations. New all-time records included 108°F at Northglenn and Denver Water Department, 105°F on 20 July 2005 at DIA (tying an old record previously set in 1878), and 103°F at Fort Collins on 21 July. The heat wave was persistent, and record or near-record 5-day running means were observed near Denver. Also, several stations reported the greatest number of days of 100°F or higher.

However, in terms of frequency of monthly temperatures and daily temperatures of 90°F or above, July 2005 was not exceptional. Cooler weather earlier in the month, and a notable cold front in late July cut the duration of this heat wave short. Finally, a new metric for assessing heat, moist enthalpy, showed significantly different results. Very low humidities reduced the peak moist enthalpy values of the July 2005 heat wave compared to earlier heat waves in 2002 and 2003, despite higher temperatures. Cooler but more humid locations (like Fort Collins) actually have greater heat (effective temperature) when compared to the relatively hot but dry conditions observed at DIA. Based on the moist enthalpy diagnostic, the 2005 heat wave was not exceptional.

The diversity of observations of the heat wave suggests that we need to address the question, should we record temperatures that register the full impact of heat waves that affect people both in terms of human health impacts (mortality) and electrical power consumption (air conditioning) inside the "urban heat island," or should we keep the observing sites out at airports where we get a more objective record of regional temperatures that are often substantially lower than those affecting the majority of the population? Over the past 50 years, data have been collected at airports, but the value of also retaining urban observation sites is clear.

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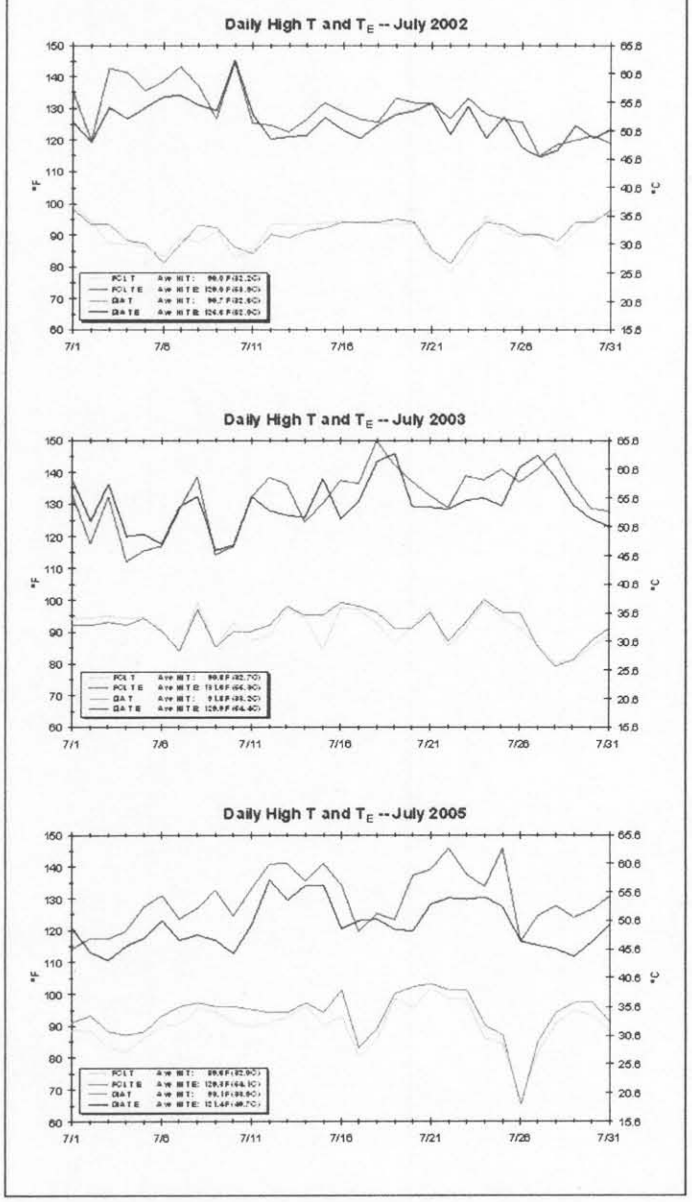

Fig. 10. Hourly data from automated weather stations at FCL and DIA are used to pick and calculate the highest air temperature and effective temperature for each day in July 2002 (a), July 2003 (b), and July 2005 (c). In all three months, the average high air temperature is higher at DIA, while the average high effective temperature is higher at FCL.

Ph.D.degrees from The Pennsylvania State University in 1969 and 1973 respectively.

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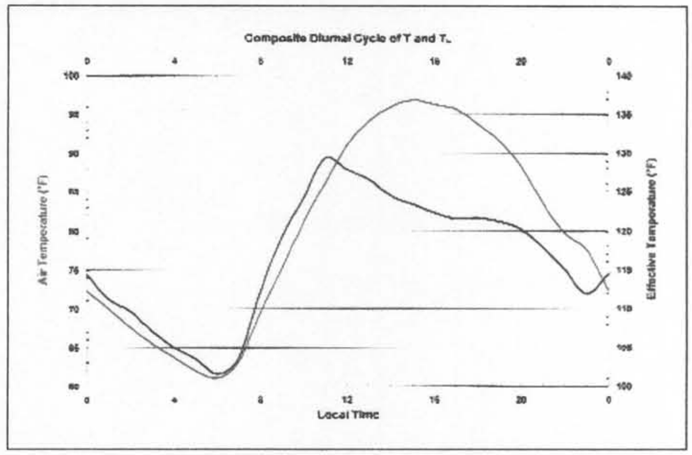

Fig. 11. A daily composite of air temperature (red line) and effective temperature (blue line) for Fort Collins. The composite is created by averaging hourly data during the five days with highest air temperature in each of the three years considered in this section – fifteen days total. This shows the pattern of heating and cooling on the station's extreme hottest days. Note how the effective temperature peaks approximately four hours before the air temperature peaks. Typically, the hottest days are characterized by exceptionally low relative humidity in the late afternoon, which explains the premature drop in effective temperature.

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References

Davey, C.A., and R.A. Pielke Sr., 2005: Microclimate exposures of surface-based weather stations – implications for the assessment of long-term temperature trends. *Bull. Amer. Meteor. Soc.*, 86, 497–504.

______, ______, and K.P. Gallo, 2006: Differences between near-surface equivalent temperature and temperatures trends for the eastern United States – Equivalent temperature as an alternative measure of heat content. *Global and Planetary Change*. 54, 19-32.

Denver Channel 7, cited 2005: Denver ties all-time record of 105 degrees, July 20, 2005. [Available online at http://www.thedenverchannel.com/weather/4746329/detail.html.]

NOAA/NWS WFO Denver/Boulder, 2005a: Denver Monthly Summary (July, 2005). [Available online at http://www.crh.noaa.gov/bou/?n=climo.]

____________, Tucson, 2005b: Year-by-Year Monsoon Statistics for Tucson (1949-2005). [Available online at http:www.wrh.noaa.gov/twc/monsoon/monsoon.php.]

Pielke Sr., R.A., C.A. Davey, and J. Morgan, 2004: Assessing "global warming" with surface heat content. *Eos, Trans. Amer. Geophys. Union,* 85, No. 21, 210-211.

Rocky Mountain News, cited July 26,2005: Hot streak has experts divided. [Available online at http://www.highbeam.com/browse/NewsLocal+Interest+Rocky+Mountain+News+(Denver,+CO)/July-2005-p14]

Steadman, R.G., 1979: The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. *J. Appl. Meteor.*, 18, 861-873.

U.S. Department of Agriculture, 2005: Weekly Weather and Crop Bulletin, Vol. 92, No. 30, 39 pp. [Available online at http://www.usda.gov/oce/weather/pubs/Weekly/Wwcb/index.html.]