6.3

PRELIMINARY OBSERVATIONS OF EXTREME TEMPERATURES AND HEAT-RELATED ILLNESSES IN A HIGH PLAINS CANYON ENVIRONMENT

T. Todd Lindley*, Nicholas Fenner, Tabatha Seymore, Kurt Buffalo, Andrew Moulton, and Kristin Scotten
NOAA/National Weather Service – Amarillo, Texas

Stephen Kersh
KVII-TV – Amarillo, Texas

Mark Hassell
Texas Parks & Wildlife Department/Palo Duro Canyon State Park – Canyon, Texas

1. INTRODUCTION

Palo Duro Canyon is the largest of several eroded canyonlands along the eastern terminus of the southern High Plains Caprock escarpment in western Texas. Nearly 100 km in length, Palo Duro is the second longest canyon system in the U.S. and home to Palo Duro Canyon State Park, a nature conservatory which topped Fodor's Travel 2014 list of America's 10 Best State Parks (Fodor's Travel, cited 2014). The park attracts more than 300,000 outdoor enthusiasts annually, most of which visit during the summer tourist season. Between 2011 and 2014, 106 incidents of heat-related illnesses and/or deaths were reported in Palo Duro Canyon State Park.

This study analyzes preliminary temperature observations recorded by two meteorological instruments deployed on the canyon floor during the summer of 2014. These thermometers are the first to document temperatures near park trailheads, where a majority of heat-related incidents occur. The relationship between daytime high temperatures on the canyon floor and those observed at established sites on the adjacent High Plains is shown to be linear (R^2=0.92) with differentials frequently reaching 5° to 6° C. Rim-to-floor temperature lapse rates within the canyon were measured to be as much as 1.8 to 2.6 times those attributable to the 232 m elevation change via adiabatic processes. Correlations in these data are used to determine approximate temperatures associated with past heat-related health incidents. Linear regression models support temperatures of 49° C during a record setting heat wave in June 2011 when 25 persons were treated for heat exhaustion. Such temperatures, estimated to occur at 867 m ASL in Palo Duro Canyon, are comparable to record high temperatures of 49° C observed at the 776 m Phantom Ranch in Grand Canyon National Park.

*Corresponding author: Todd Lindley, National Weather Service, 1900 English Road, Amarillo, TX 79108. todd.lindley@noaa.gov

2. GEOGRAPHY & METHODOLOGY

Palo Duro Canyon is a system of technicolor gorges comprised of eroded pinnacles, hoodoos, and slots carved through Triassic sandstone by the waters of the Prairie Dog Town Fork of the Red River (Flores 2010) (Fig. 1). The canyon begins its descent into the vast southern High Plains tableland plateau, known as the Llano Estacado, at the confluence of Palo Duro and Tierra Blanca Creeks near the town of Canyon, Texas (MacLeod 2007). From there the Palo Duro system deepens and widens as tributary side canyons of the Prairie Dog Town Fork of the Red River erode deep crevasses and badlands along a 95 km trough of the Caprock escarpment, the dramatic eastern edge of the southern High Plains.

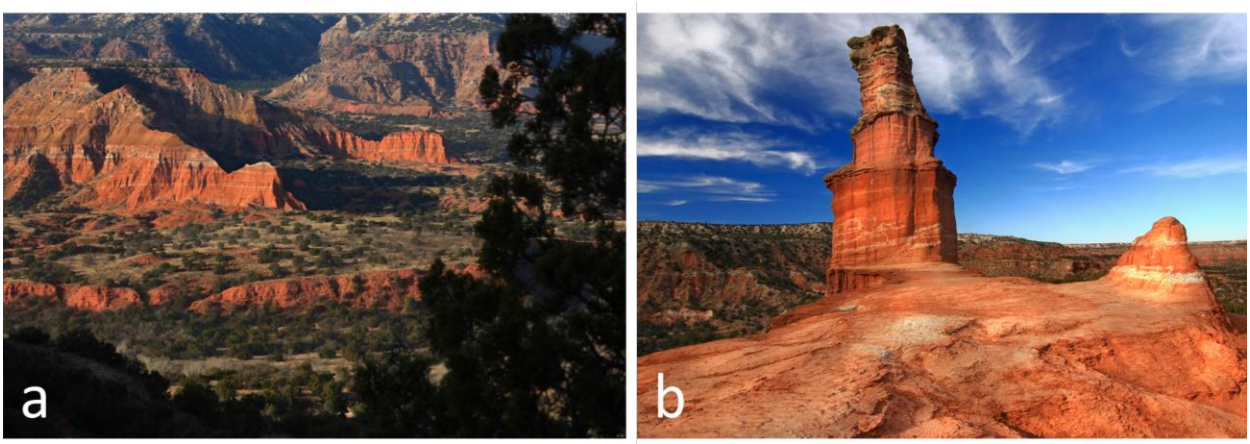

Figure 1: Landscapes of the Palo Duro Canyon environment including: a) a canyon gorge, and b) a sandstone pinnacle.

Prior to the summer of 2014, weather instrumentation in the canyon was limited to simple analog thermometers mounted on wooden poles near park trailheads. These thermometers were neither sheltered nor sited according to conventional meteorological standards, and occasionally showed extreme temperatures of 50° to 55° C (Fig. 2).

In recent years, efforts have been made to increase remote meteorological sensing of the Palo Duro Canyon environment. This has included Texas Tech University's deployment of West Texas Mesonet (WTM) sites (Schroeder 2005) and installation of KVII-TV Schoolnet instruments. Due to limited telecommunications in the canyon, most of these platforms were deployed on the rim. In early 2014, however, KVII-TV Schoolnet and official National Weather Service (NWS) Nimbus thermometers were deployed to measure 2-m temperatures along the canyon floor (Figs. 3 and 4). For this study, temperatures recorded by these instruments were compared to the Amarillo, Texas, Automated Surface Observing System (ASOS), located on the adjacent plains 19 km north of Palo Duro Canyon.

3. TRENDS IN VISITATION & HEAT-RELATED INCIDENTS

Palo Duro Canyon State Park welcomes more than 300,000 people each year, and registered 305,800 visitors in Fiscal Year 2014 (FY14). The number of people engaged in physically strenuous outdoor activities within the park, such as hiking and mountain biking, or susceptible to prolonged heat exposure at the park's popular outdoor amphitheater, is typically highest during the peak summer travel season. In FY14, nearly half of all visitation (44%) occurred during the hottest summer months of June, July, and August (Fig. 5).

In addition to the state park, there are additional private recreational areas and two

Figure 2: Analog thermometer in Palo Duro Canyon State Park indicating a temperature near 55° C (132° F) in July 2011.

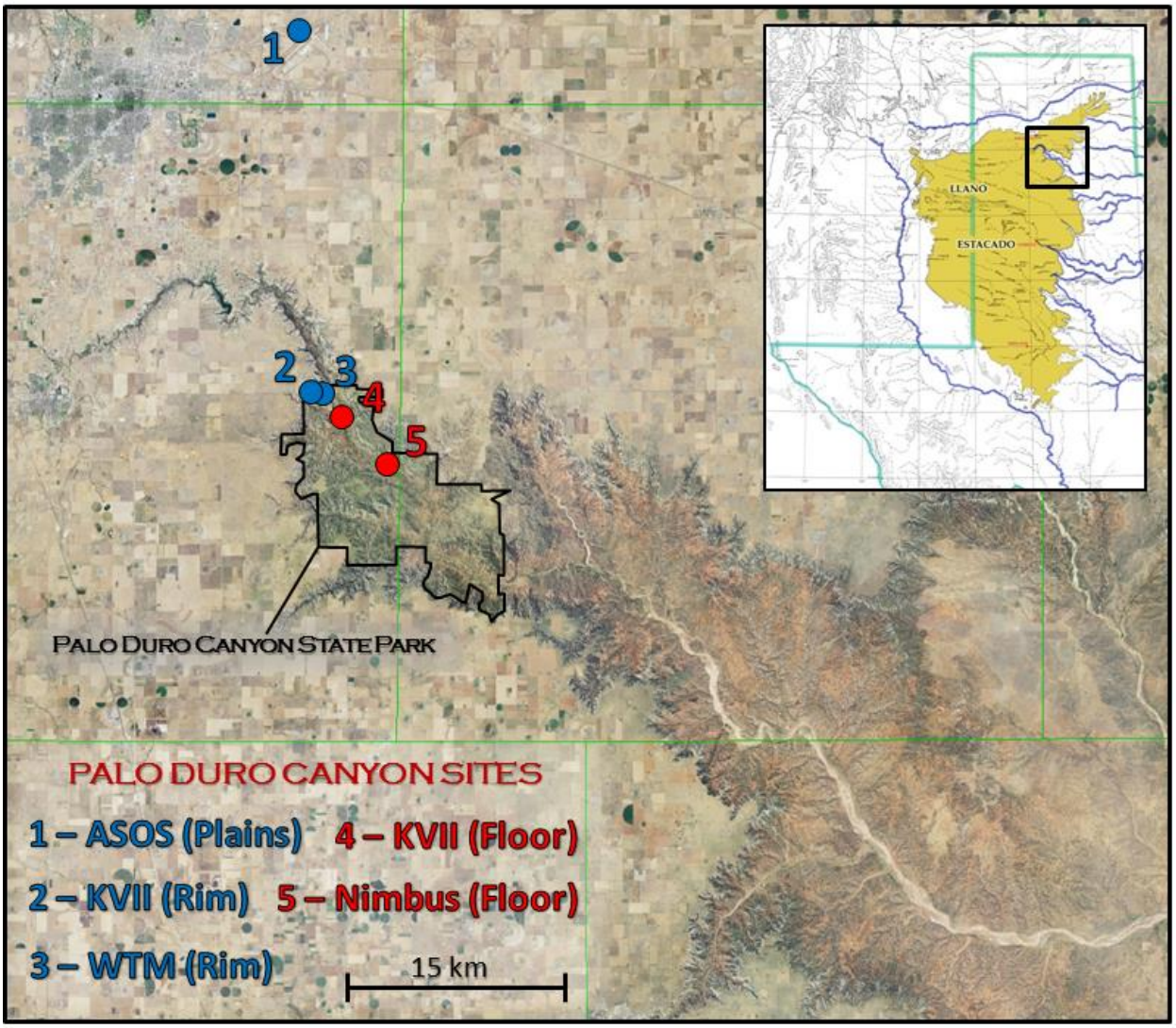

Figure 3: Satellite imagery of the Palo Duro Canyon system depicting the location of weather stations used in this study. The boundaries of Palo Duro Canyon State Park are shown. Inset shows the location of Palo Duro Canyon in west Texas relative to the Llano Estacado.

Figure 4: Topographical cross-section of Palo Duro Canyon with the location and elevation of meteorological instruments utilized in this study noted.

youth church camps located within the Palo Duro Canyon system. The fact that the canyon environment is a popular summer-time outdoor use area increases the likelihood of heat-related illness incidents. While this potential exists at many outdoor venues and natural attractions with high rates of summer visitation, the health risks are amplified within Palo Duro Canyon due to the occurrence of extreme temperatures within the canyon's microclimate. Between 2011 and 2014, 106 incidents of heat-related illnesses involving state park visitors (97 human and 9 pet animals) were reported to Texas Parks & Wildlife Department (TP&WD). This record only includes heat-related emergencies treated within the park, and does not represent incidents involving patients that either refused medical assistance or sought treatment outside of Palo Duro Canyon State Park. A categorization of heat-related illnesses included in the dataset is detailed in Fig. 6.

An examination of the temporal trends of heat-related illnesses within Palo Duro Canyon State Park can help identify high risk periods for incidents. Between 2011 and 2014, heat incidents peaked dramatically during the month of June. This signal is amplified by the occurrence of a three-day heat wave in June 2011. The 24-26 June 2011 heat wave on the southern High Plains resulted in an all-time record high temperature of 44° C (111° F) at the Amarillo ASOS on the plains adjacent to Palo Duro Canyon on the 26th (NWS cited 2015) and contributed to 25 human heat exhaustion incidents in Palo Duro Canyon State Park. Still, even in the absence of this particular high-impact event, the month of June still ranks as the most common month of occurrence for heat-related illnesses in the park. The risk of incidents remains high, however, through the remainder of the summer with 81% of all 2011-2014 heat-related illnesses occurring in the same three-month period as peak visitation of June, July, and August (Fig. 7).

Analysis of heat-related illnesses in Palo Duro Canyon State Park relative to days of the week reveals that a majority of incidents occur on weekends (Fig. 8). While this result is not surprising, an interesting signal for a higher occurrence of incidents on Sunday was observed. Park rangers have noted that outdoor enthusiasts tend to begin trail activities at a later time of day on Sunday compared to other days of the week, when hikers and cyclists are more likely to begin hikes and mountain bike rides during the early morning hours (Londenberg 2014). This tendency for starting extraneous trail activity during the midday or early afternoon hours on Sunday exposes park visitors to a relatively higher risk from excessive heat during the hottest time of day.

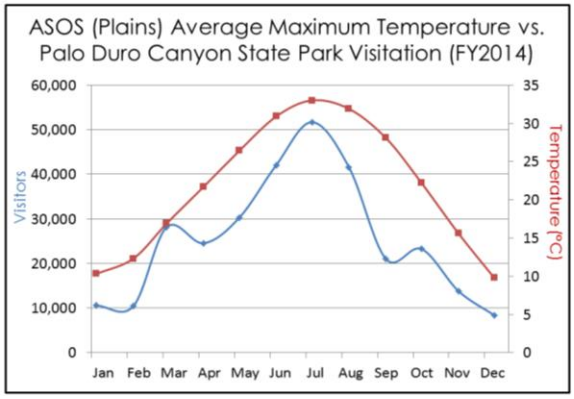

Figure 5: Average monthly maximum temperature on the adjacent plains (red) and FY14 monthly Palo Duro Canyon State Park visitation (blue).

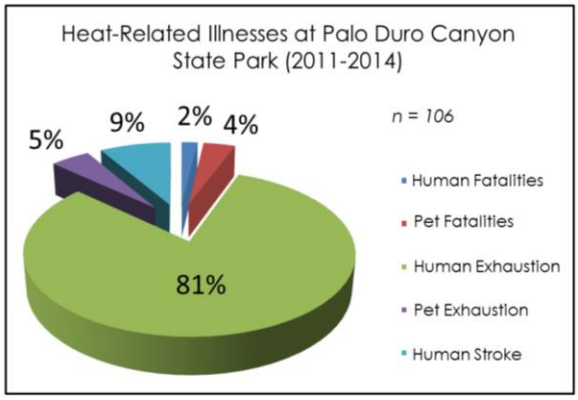

Figure 6: Categorization of 2011-2014 heat-related illnesses in Palo Duro Canyon State Park.

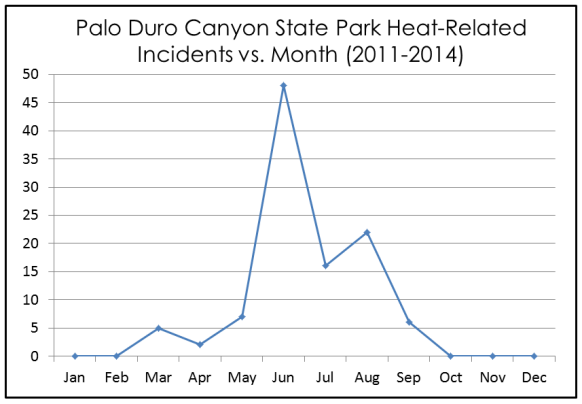

Figure 7: Palo Duro Canyon State Park heat-related incidents (2011-2014) relative to month.

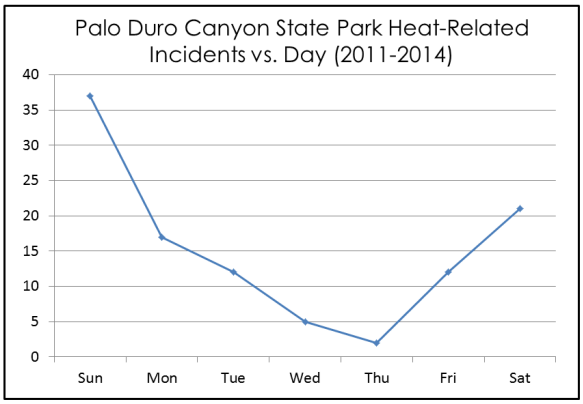

Figure 8: Palo Duro Canyon State Park heat-related incidents (2011-2014) relative to day.

4. OBSERVATIONS

a. Summer 2014 observed temperatures

Daily maximum temperatures were recorded at five observation sites between 11 June and 3 September 2014, representing conditions on the plains adjacent to Palo Duro Canyon, the canyon rim, and the canyon floor (detailed in Section 2). During the summer 2014 study period, daily maximum temperatures reached or exceeded 38° C (100° F) 27 times at the KVII (floor) site and 38 times at the Nimbus (floor) thermometer, or on a total of 39 unique days. This constitutes 46% of all days sampled and compares to observed temperatures ≥38° C (100° F) during only 6% of sampled days on the canyon rim and 5% on the adjacent plains (Fig. 9). A geographical plot illustrating the number of days with temperatures ≥38° C (100° F) during the study period shows an apparent heat island effect (American Meteorological Society 2014), or microclimatological influence of the Palo Duro Canyon system on summertime maximum daytime temperatures (Fig. 10).

Of the temperature observation sites used in this study, the Amarillo ASOS (plains) site is the only sampled location with an established climatological record, and is the most commonly referenced forecast point in the Palo Duro Canyon vicinity. It is likely that most visitors to Palo Duro Canyon State Park plan their visits based upon the widely publicized forecast for the immediate Amarillo (plains) area without considering local effects of the canyon environment in any quantitative way. Thus, in order to understand the typical temperature variance between the urbanized plains adjacent to Palo Duro Canyon and conditions experienced by outdoor enthusiasts within the canyon environment, it is appropriate to consider comparisons of observed Amarillo ASOS (plains) temperatures to those measured at the Nimbus (floor) site (Fig 11). Temperatures at these two sites showed a strong linear correlation (R^2=0.92).

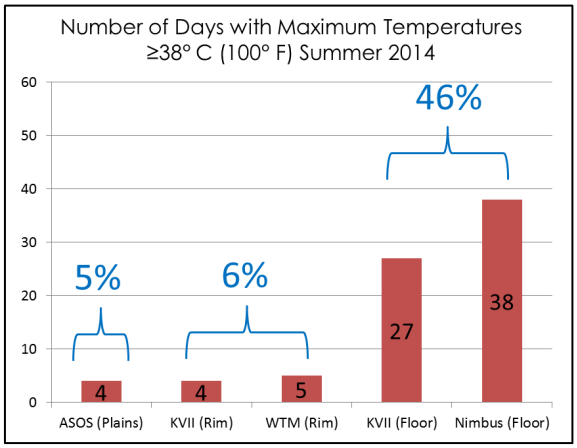

Figure 9: Number and cumulative percentage of days with maximum temperatures ≥38° C (100° F) at the plains, rim, and floor observation sites in the vicinity of Palo Duro Canyon during summer 2014.

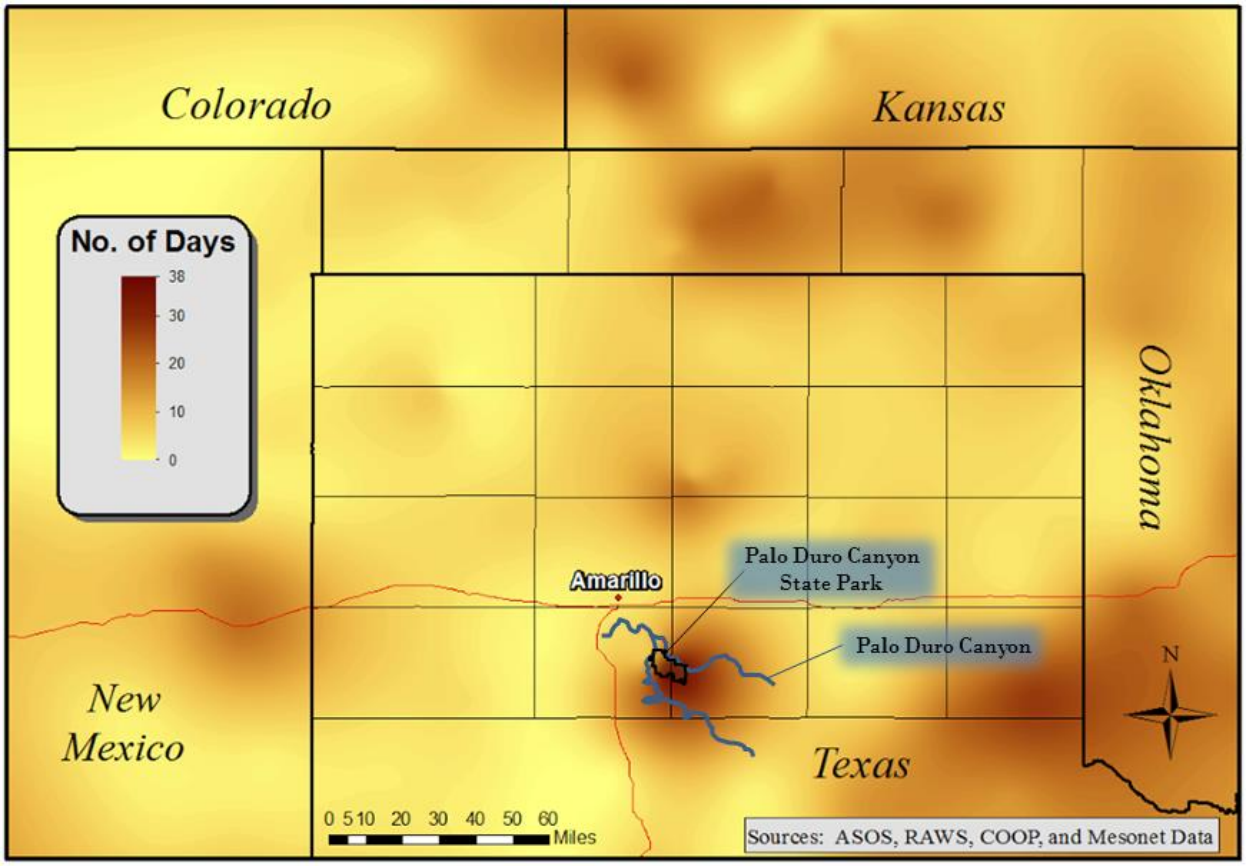

Figure 10: A geographical plot of summer 2014 days with maximum temperatures ≥38° C (100° F) across the Texas Panhandle illustrating Palo Duro Canyon's heat island effect.

Temperature differentials between all of the plains, rim, and canyon floor sites averaged 3.7° C warmer on the canyon floor, but exceeded 5° to 6° C on 25% of the sampled days. A maximum variance of 6.7° C was observed between the ASOS (plains) and Nimbus (floor) site on 17 August.

b. Linear regression applied to historic heat-related illness incidents

In order to develop more meaningful heat advisory criteria that are effective in improving safety for outdoor activities, including those at Palo Duro Canyon State Park, it is useful to compare the occurrence of heat-related health incidents to accompanying weather conditions. The correlation of temperatures at the ASOS (plains) site to those observed at the Nimbus (floor) during the summer of 2014 is well suited for estimating maximum temperatures associated with past incidents. The summer 2014 temperature observations were applied to a database of 104 heat-related illnesses spanning 52 dates between 2011 and 2014 using linear regression for the best fit trend line (Eq. 1).

$$y=1.1247x-0.2754 \quad (1)$$

Conditions associated with two additional heat-related illnesses that occurred on 31 August 2014 were directly observed during the study period, and were well correlated to the best fit trend line (Fig. 12). These estimates and observations suggest that 75% (first quartile ranking) of all heat-related illnesses in Palo Duro Canyon State Park occur when temperatures on the canyon floor exceed 40° C (104° F) (Fig. 13). Although estimated canyon floor temperatures associated with heat-related illnesses ranged from 33° C (91° F) to 49° C (120° F), the first

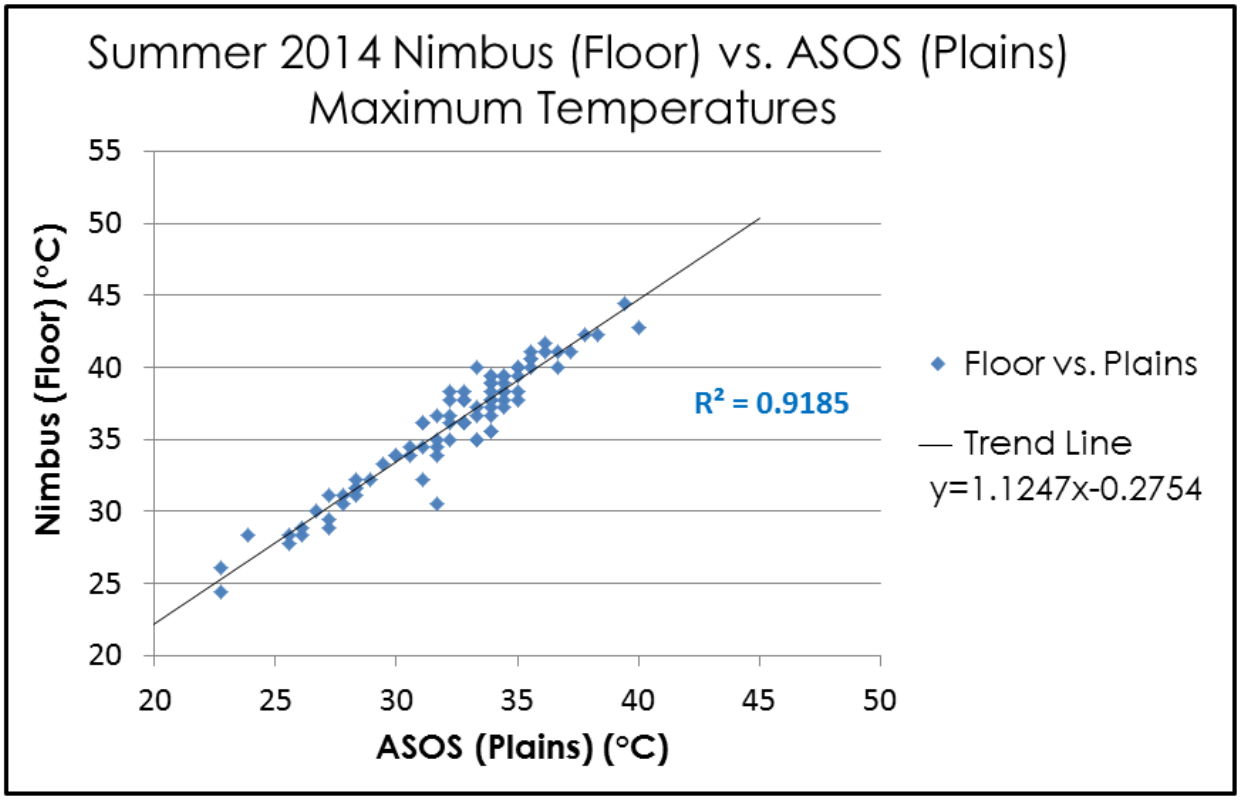

Figure 11: Summer 2014 Nimbus (floor) temperatures plotted relative to observations at the Amarillo ASOS (plains).

quartile value may represent a threshold of increased risk for people of average physical ability and fitness to succumb to the effects of extreme heat in the Palo Duro Canyon environment. Estimated mean and median canyon floor temperatures associated with heat-related illnesses in the park were found to be 42° C (108° F).

c. Temperature lapse rates

The strong temperature variances between plains/rim sites and canyon floor thermometers observed during the summer of 2014 support lapse rates that exceeded those attributable to elevation change via dry adiabatic processes. These temperature lapse rates were estimated to reach 1.8 to 2.6 times dry adiabatic (Fig. 14). Preliminary analyses of super-adiabatic lapse rates in the canyon indicate that they are of short temporal duration during peak diurnal heating, generally persisting for one to three hours (Fig. 15). Lapse rates were noted to be less intense during periods of higher wind speed. This indicates that stronger mixing of air in the canyon environment with the ambient airmass reduces the canyon's influence on heating. It is hypothesized the source of these anomalous temperatures and super-adiabatic lapse rates is tied to radiative heating effects emanating from the canyon's red sandstone walls; however, diagnosing the physical cause of Palo Duro Canyon's heat island is beyond the scope of this preliminary observational study.

To illustrate the magnitude of heating observed within Palo Duro Canyon, it is useful to compare temperatures indicated by this study to temperatures at the Grand Canyon (Fig. 16). Record high temperatures observed at three established sites in Grand Canyon National Park (National Park Service cited 2014) include 33° C on the North Rim (2525 m), 38° C on the South Rim (1934 m), and 49° C (120° F) at Phantom Ranch (776 m) on the canyon floor. When plotted relative to elevation, the sloped trace

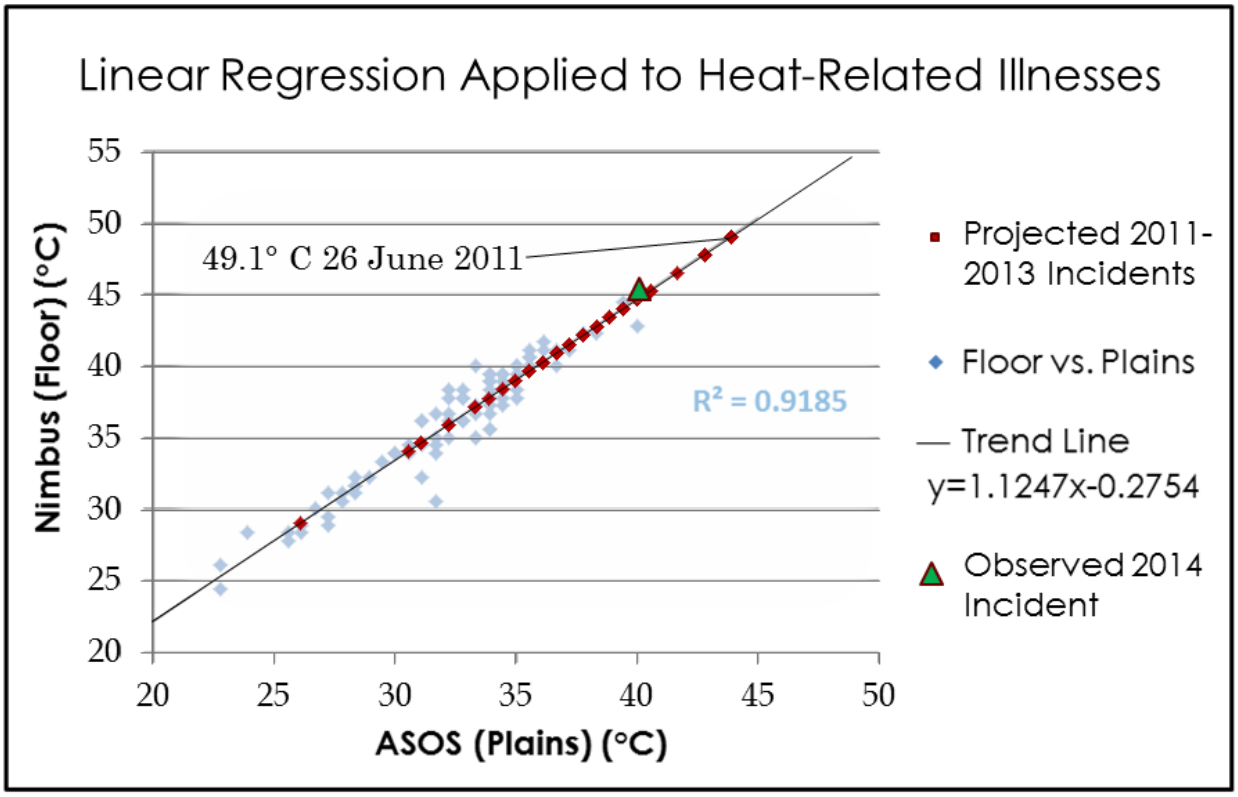

Figure 12: Regression of summer 2014 plains and floor temperatures applied to 2011-2014 heat-related health incidents. ASOS (plains) temperatures for dates of incidents were known and Nimbus (floor) temperatures estimated per linear relationship. Observations for a 2014 case are additionally shown.

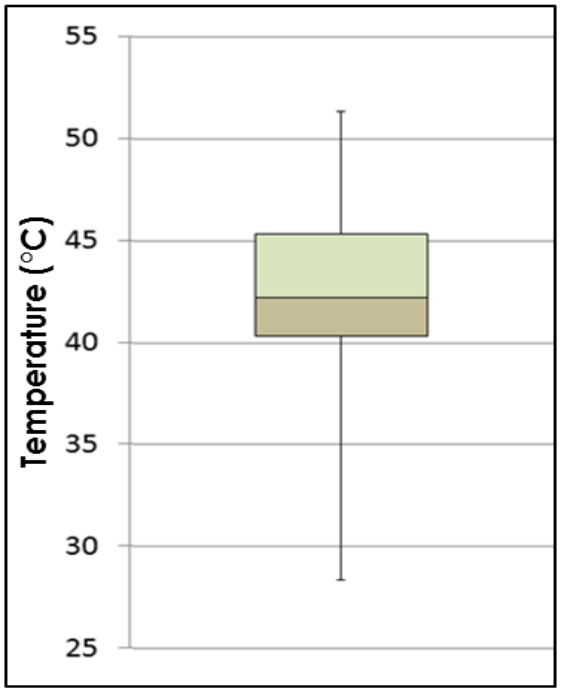

Figure 13: Box-and-whisker of estimated canyon floor temperatures for 2011-2014 heat incidents.

of these temperatures is comparable to the dry adiabatic lapse rate. Applying the same linear regression method used in Section 4c to the all-time record temperature at the Amarillo ASOS (plains, 1099 m) of 44° C (111° F) on 26 June 2011 results in a lapse rate 2.2 times dry adiabatic and an approximated canyon floor temperature of 49° C (120° F). Excessive temperatures on that date were part of a three-day heat wave which contributed to dangerous conditions and 25 reported incidents of human heat exhaustion within Palo Duro Canyon State Park from 24 to 26 June 2011. It is notable that the all-time highest maximum temperature observed in Texas is 49° C (120° F) at Seymour on 12 August 1936 and at Monahans on 28 June 1994 (Bomar 1983, p. 207 and Texas Office of the State Climatologist cited 2015). Therefore, the data suggest that extreme temperatures within Palo Duro Canyon, unmeasured prior to summer 2014, have the potential to reach state record levels.

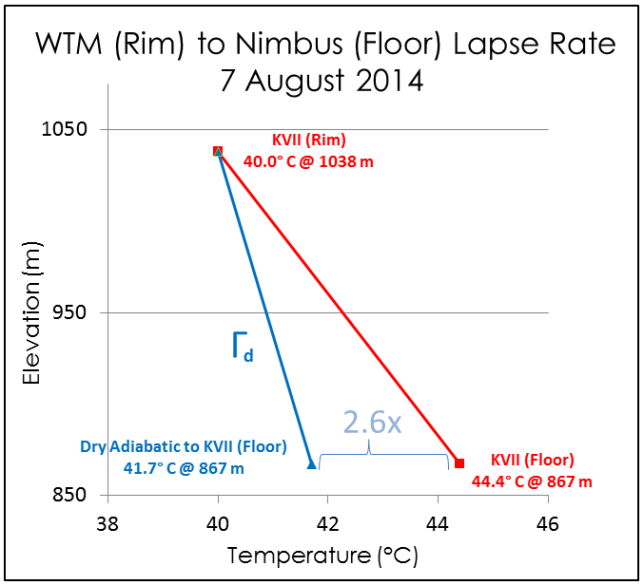

Figure 14: Rim-to-floor temperature variances on 7 August 2014 relative to the dry adiabatic lapse rate.

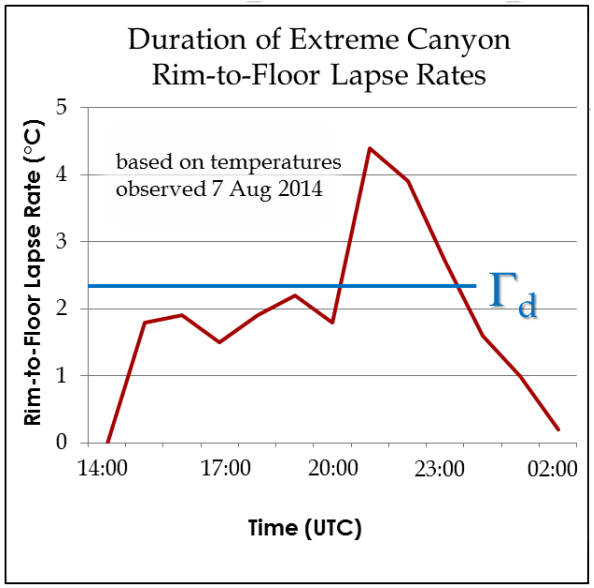

Figure 15: The duration of rim-to-floor super adiabatic lapse rates on 7 August 2014.

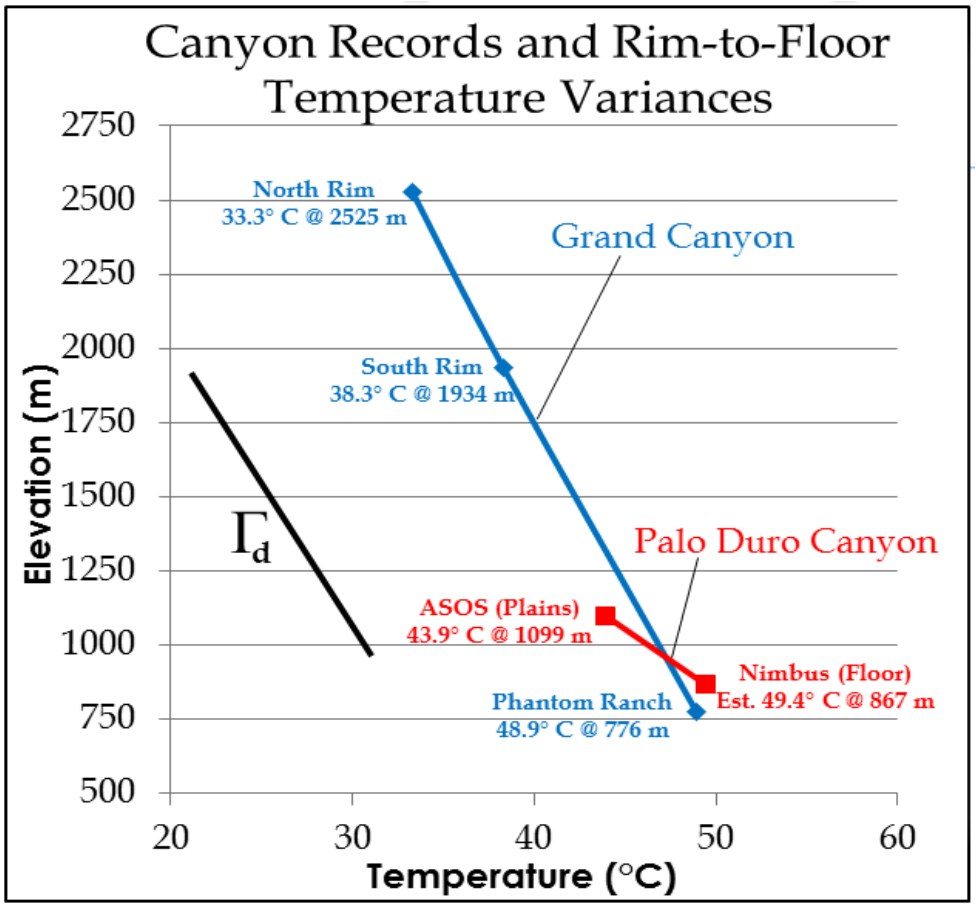

Figure 16: A profile of record temperatures at various Grand Canyon sites and estimated floor temperature based on the ASOS (plains) record temperature shown relative to elevation. The dry adiabatic lapse rate is shown in comparison.

5. CONCLUSION

This study provided preliminary analyses of temperatures recorded by two meteorological instruments deployed on the floor of Palo Duro Canyon, Texas, during the summer of 2014. These thermometers documented temperatures ≥38° (100° F) near trailheads in Palo Duro Canyon State Park on 46% of the sampled days. The relationship between daytime maximum temperatures on the canyon floor and those observed at established sites on the adjacent High Plains, where temperatures only exceeded 38° C (100° F) for 5% of the study period, was shown to be linear (R^2=0.92) with differentials frequently reaching more than 5° to 6° C. Rim-to-floor temperature lapse rates within the canyon were measured to be as much as 1.8 to 2.6 times those attributable to elevation change via adiabatic processes. Correlations in these data were used to determine approximate temperatures associated with past heat-related health incidents using linear regression which supported temperatures of 49° C during a record setting heat wave in June 2011. Such temperatures, estimated to occur at 867 m ASL in Palo Duro Canyon, are comparable to record high temperatures of 49° C observed at the 776 m Phantom Ranch in Grand Canyon National Park.

Given the frequency of heat-related health incidents in Palo Duro Canyon, it is hoped that this preliminary study illustrates the need for continued expansion of meteorological remote sensing within the canyon and improved safety protocols for dangerous heat. Deployment of automated research-grade instrumentation capable of measuring heat index and black globe temperature, as well as the means to disseminate real-time data to park administrators and the visiting public, would provide a basis for informed decision making and activity planning in this wilderness canyon environment. It is recommended that TP&WD and NWS officials collaborate to refine heat advisory criteria and outdoor safety messaging. Pursuit of a comprehensive awareness and safety campaign meeting these objectives has the potential to reduce heat-related illnesses and deaths in Palo Duro Canyon State Park.

Acknowledgements: Thanks are extended to those that have provided technical, logistical, or editorial assistance. This includes: Gary Skwira and Steve Cobb at NWS Lubbock, Texas, Jose Garcia, John Cockrell, Edward Andrade, David Wilburn, and Oferal Wise at NWS Amarillo, Texas, Wes Burgett at Texas Tech University West Texas Mesonet, as well as Cory Evans, Bernice Blasingame, Nathan Londenberg, and Shannon Blalock at Texas Parks and Wildlife Department.

REFERENCES

American Meteorological Society, cited 2014: "Heat island". Glossary of meteorology. [Available online at: http://glossary.ametsoc.org/wiki/Heat_island]

Bomar, W. G., 1983: *Texas Weather*. Austin, Texas: University of Texas Press, p. 207

Flores, L. D., 2010: *Caprock Canyonlands*. 20th Anniversary Ed. College Station, Texas: Texas A&M University Press.

Fodor's Travel, cited 2014: America's 10 best state parks. [Available online at: http://www.fodors.com/news/photos/americas-10-best-state-parks#!1-intro]

Londenberg, N., (2014, September 3). Personal communication, Preliminary results: Palo Duro Canyon heat study. Palo Duro Canyon State Park, Texas.

MacLeod, W., 2007: *Palo Duro Vistas: A Journey Through Palo Duro Canyon*. Alpine, Texas: Texas Geological Press.

National Park Service, cited 2014: Weather. [Available online at: http://www.nps.gov/grca/naturescience/weather.htm]

National Weather Service, cited 2015: Amarillo climate notes. [Available online at: http://www.srh.noaa.gov/ama/?n=rec_norm_ama]

Schroeder, J. L., W. S. Burgett, K. B. Haynie, I. Sonmez, G. D. Skwira, A. L. Doggett, and J. W. Lipe, 2005: The West Texas Mesonet: A technical overview. *J. Atmos. Oceanic Technol.*, **22**, 211-222.

Texas Office of the State Climatologist, cited 2015: Texas Extremes. [Available online at: http://climatexas.tamu.edu/index.php/data/texas-extremes]