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IMPACT OF SITING CHANGES ON TEMPERATURE OBSERVATIONS AT CYRIL E. KING AIRPORT, SAINT THOMAS, U.S. VIRGIN ISLANDS AND LUIS MUÑOZ MARIN INTERNATIONAL AIRPORT, SAN JUAN, PR

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I. Introduction

The proper siting of meteorological instrumentation has long been recognized as a key component to preserving the integrity of climate records. William Heberden (1769) wrote a famous paper detailing the difference in precipitation values collected in the garden of Westminster Abby and on its towers. In this paper, Heberden demonstrated a 50% difference in the amount of precipitation collected solely based on the height of the rain gage above the ground. In the early 1800's, Luke Howard, known as a pioneer in studying the urban heat island effect, published *The Climate of London, Deduced from Meteorological Observations made at Different Places in the Neighborhood of the Metropolis (Howard, 1883)*. In this publication, Howard noted the temperature difference between urbanized areas and the surrounding countryside. This temperature difference, due to the changes in physical and thermal properties associated with urbanization, showed that the temperature in the center of London was 3.7^{o} F greater at night than the surrounding rural areas. More recently, siting has been used to raise questions regarding the reliability of surface temperature trends in the U.S. as a whole (Watts 2009).

In order to preserve the integrity of its network of observers and to avoid unnecessary shifts in data, the National Weather Service established a standard for equipment, siting and exposure for all of its cooperative weather instrumentation in the late 1800's (National Weather Service 2008). In addition, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (1994) proscribed federal standards for the siting of automated meteorological sensors at airports.

In this paper, the siting of two Automated Surface Observing Systems (ASOS), one at the Cyril E. King Airport on Saint Thomas, U.S. Virgin Islands and the other at the Luis Muñoz Marin International Airport in San Juan, PR, are closely examined. Specifically, there was an investigation into the temperature trends at the Cyril E. King Airport on Saint Thomas since the commissioning of the ASOS in August 1998 (Case 1), and there was also an investigation into temperature trends at the Luis Muñoz Marin International Airport in San Juan since the completion of taxiway Juliet in 2008 (Case 2).

In Case 1, it will be shown that the relocation of the observation site at the Cyril E. King Airport on Saint Thomas contributed to a significant *decrease* in the maximum temperatures and a significant *increase* in the minimum temperatures, accounting for a 20% reduction in the daily diurnal temperature cycle. In Case 2, it will be shown that the addition of taxiway Juliet at the Luis Muñoz Marin International Airport in San Juan (more than 10 years after the commissioning of the ASOS), led to a significant increase in the minimum temperatures at the site.

II. Background: The Importance of Siting at Tropical Coastal Locations

Diurnal temperature ranges are dependent on several factors. The proximity to large bodies of water, regular moderate wind speeds and high relative humidities have all been previously identified as having a strong influence on the diurnal temperature range of a given site. These are all characteristics common at tropical coastal locations.

The fact that tropical coastal locations are particularly sensitive to siting is nothing new. In 1958, a report in the Miami News (Colbert, 1958) noted the relocation of the official temperature sensor for the city of Miami (maintained by the U.S. Weather Bureau) could significantly affect the local climate record. The article quoted meteorologist Leonard Pardue of the U.S. Weather Bureau, who stated "There is a considerable variation between the temperature at the shoreline and a couple of miles inland." Pardue went on to explain that this difference was likely the cause of an estimated two degree increase in temperature from the previous location, which was just a few blocks from Biscayne Bay.

The entire Lesser Antilles, which includes both the U.S. Virgin Islands and Puerto Rico, falls into this same category of tropical coastal locations, *i.e.*, locations highly sensitive to siting. Across Puerto Rico and the U.S. Virgin Islands, the average diurnal temperature range varies from only 10 to 20 degrees, depending on the month of the year and proximity to the coastline. As a result, even a small shift in the location of a station can have a large impact on both the range of temperatures as well as the actual temperature values recorded at a given site.

III. Case 1: The Cyril E. King Airport, U.S. Virgin Islands

1. Background

On 10 August 1998 the ASOS at the Cyril E. King Airport on Saint Thomas was commissioned, located on a strip of grass between runway 10/28 and the taxiway (Figure 1). Although the new location of the automated weather sensor adhered to the guidelines established by the Office of Federal Coordinator for Meteorology (2005), over the following years, large temperature discrepancies from long term averages, not seen at the surrounding Caribbean Islands, began to be noted at the Cyril E. King Airport (Figure 2).

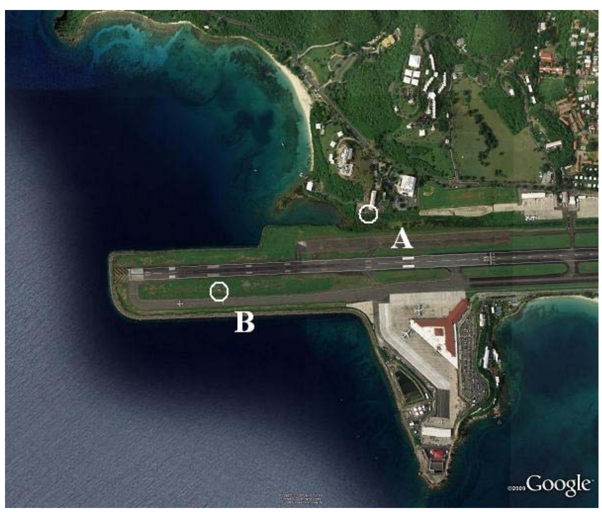

Figure 1 – Areal view of the Cyril E. King Airport on Saint Thomas, U.S. Virgin Islands.
(A) Location of the Limited Aviation Weather Reporting Station, official weather sensor for the airport, before the commissioning of the Automated Surface Observing System. (B) Location of the Automated Surface Observing System, commissioned on 10 August, 1998.

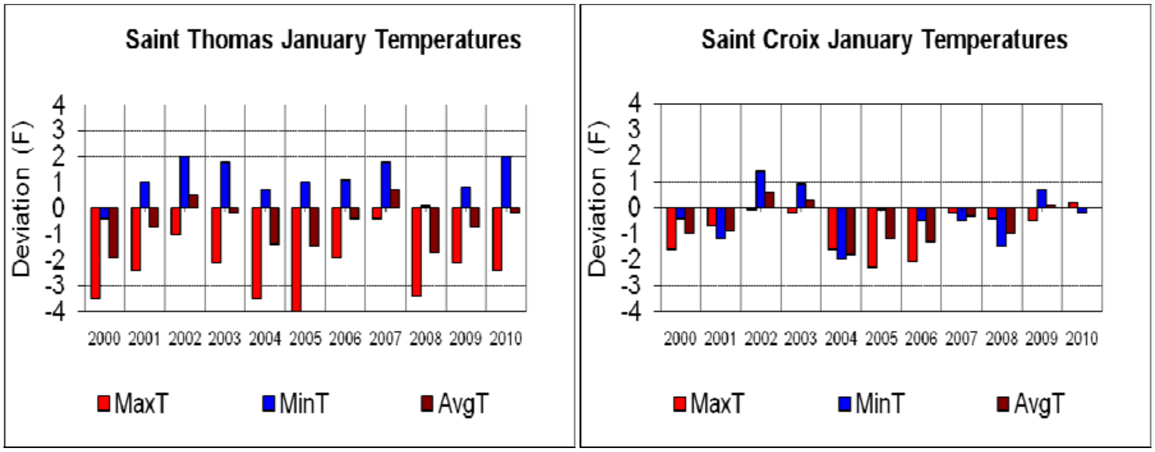

Figure 2 – Secular temperature trends (departures from 1971-2000 normals) for the months of January 2000-2010 at the Cyril E. King Airport on Saint Thomas and the Christiansted Airport on Saint Croix. Note: A similar pattern in both the maximum and minimum temperatures appears to be present, with the magnitude of the deviations substantially larger at the Saint Thomas.

After noting an apparent change in temperatures at the ASOS site at the Cyril E. King Airport on Saint Thomas, as compared to neighboring sites, it was recognized that the previous location of the LAWRS (see Figure 1, Point A) was on a bluff approximately 40 feet higher and approximately one half a mile east of the new site. While this changes fell within the first two compatibility table requirements for the relocation of meteorological instrumentation according to the NWS Instruction 10-1307 Table C-1 (NWSI 2008), it appears that the new location may have failed requirement #3, which states: "geographic setting of relocated and original stations are similar and environmental characteristics - ***including surrounding bodies of water*** – (emphasis added) are similar." While one might speculate that the new location, as seen from space (see Figure 1), might be much more affected by the surrounding Caribbean waters, this is not as obvious when viewed from the observation site (Figure 3).

Figure 3 – The ASOS at the Cyril E. King Airport on Saint Thomas as seen from ground level (photograph courtesy of National Climatic Data Center).

2. Data Analysis

Comparing the temperature trends at the Cyril E. King Airport on Saint Thomas with the nearest high quality observation station, which in this case was at the Christiansted Airport on Saint Croix (the same site used in Figure 2), the **average annual temperature** decreased similarly at both sites (see column 4 of Table 1).

However, after separating out the maximum and minimum temperatures at the two sites, it became strikingly clear that something had changed between the two stations since the year 2000 (the time period for which Table 1 was compiled). While the overall temperature trends were nearly identical at Saint Croix, which lies at a similar longitude just 40 miles to the south of Saint Thomas, the magnitude of these trends were significantly different (not only for the month of January, as seen in Figure 2, but similarly for all months of the year (Table 1). After the commissioning of the ASOS at the Cyril E. King Airport on Saint Thomas, it appeared that the averaged annual maximum temperature *decreased* 1.4^{o}F as compared to that for Saint Croix while the average annual minimum temperature *increased* 1.0^{o}F.

Table 1 – Averaged annual temperature departures from the 1971-2000 normals on Saint Thomas and Saint Croix

	Maximum Temperature	**Minimum Temperature**	**Average Temperature**
Saint Thomas	**-2.2 F**	**+1.1 F**	**-0.6 F**
Saint Croix	**-0.8 F**	**+0.1 F**	**-0.4 F**
Difference	**-1.4 F**	**+1.0 F**	**-0.2 F**

The frequency of daily maximum and minimum temperature departures from normal since 200- for both sites can be seen in Figure 4. While both plots indicate a trend of higher minimum and lower maximum temperatures, the magnitude of this trend at the Cyril E. King Airport is more apparent (Figure 4). This shift has likely contributed to the large number of record warm low and cool high temperatures recorded on Saint Thomas since 2000 (Tables 4 and 5).

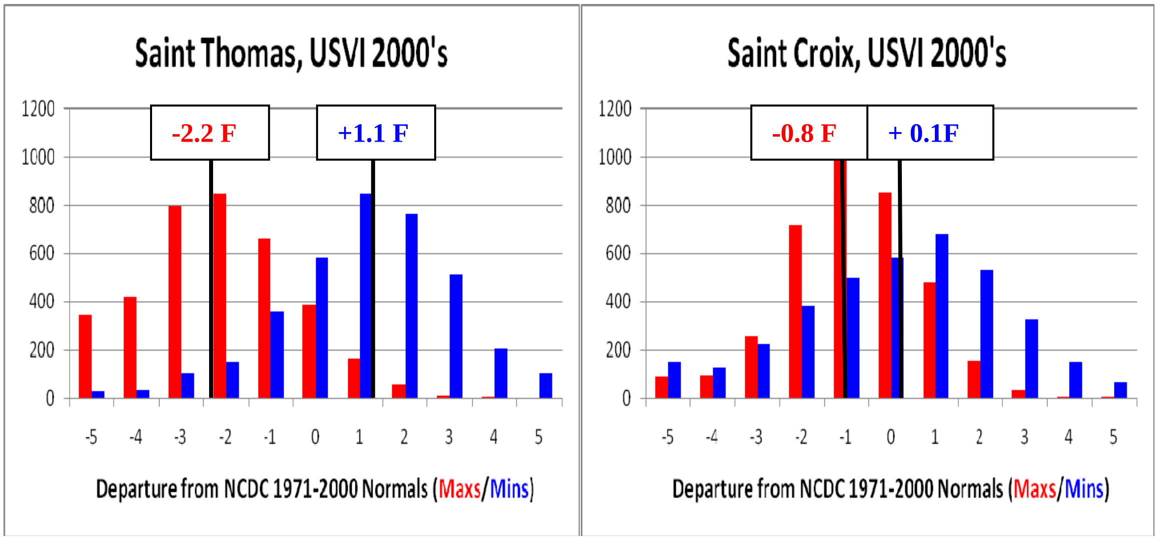

Figure 4 – Frequency of daily temperature departures from 1971-2000 normals for maximum (red) and minimum (blue) temperatures on Saint Thomas and Saint Croix for the years 2000-2009.

3. Case 1: Conclusions

Considering the location of the ASOS at the Cyril E. King Airport, it is likely that the proximity to the water has contributed to the noticeable difference in temperatures recorded at the new observation site. Specifically, during the heat of the day, the water acts as a buffer (due to its high heat capacity) to the solar radiation, resulting in a less heating of the air relative to the surrounding land mass. This reduced heat transfer into the atmosphere has effectively reduced the daily maximum temperatures at the new site by 1.4^{o}F. The reverse is true at night. Once the sun goes down, the island cools more rapidly than the surrounding water. As the typical light southeasterly trade winds observed at this site during the overnight hours carry the warmer air over the water across the peninsula where the ASOS is located, observed minimum temperatures have increased by an apparent 1.0^{o}F. While these changes might seem minimal at a mid-latitude station, this modification, magnified by the higher relative humidities, regular trade winds and smaller diurnal temperature ranges (all typical of coastal tropical locations), has led to nearly a 20% reduction in the diurnal temperature cycle being recorded at the Cyril E. King Airport since 1998.

IV. Case 2: Luis Muñoz Marin International Airport, PR

While sometimes the physical location of a meteorological sensor does not change, the actual siting of the instrument can be significantly affected by changes that occur within its vicinity. This appears to be the case with the ASOS at the Luis Muñoz Marin International Airport in San Juan, which has recorded some interesting temperature trends since the completion of taxiway Juliet in 2008.

1. Background

The Luis Muñoz Marin International Airport in San Juan became operational in 1955 and serves as the island of Puerto Rico's main international gateway. It is the busiest airport in the Caribbean and handles approximately 10 million passengers a year and over nine million tons of containerized cargo (Puerto Rico Ports Authority, 2006). Planning for an expansion of the airport to accommodate future air traffic and passenger loads, which included the construction of a new concourse and the addition of taxiway Juliet began in 2001. While the permits for the taxiway were issued in December 2004, construction did not begin until early 2006, and was not completed until early 2008. A picture taken prior to the construction of this taxiway can be seen in Figure 5 (the ASOS is circled and labeled A). Figures 6 and 7 are larger scale views of the area where the ASOS is located before and after the construction of taxiway Juliet, respectively.

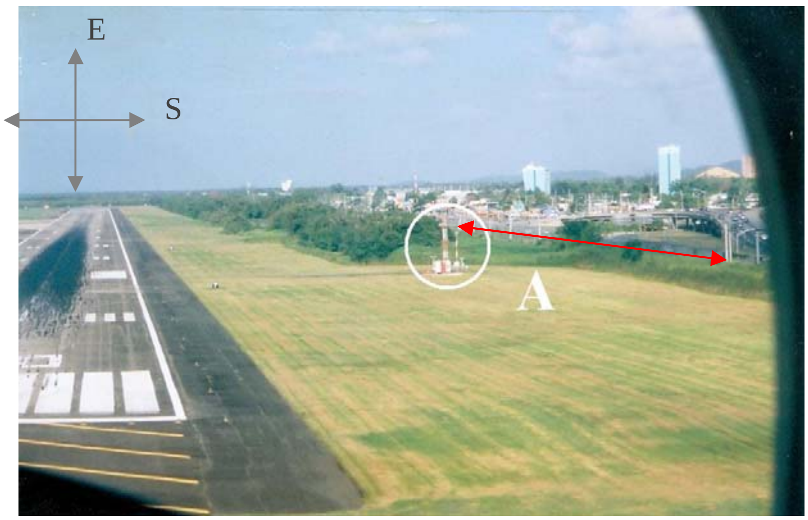

Figure 5 - The Luis Muñoz International Airport in San Juan, PR. The ASOS equipment is circled and labeled A. Note the lush vegetation just to the east and south of the site, separating the observation equipment from the westbound lanes of the highway (marked with the red line) and the overpass for the eastbound traffic on the far right.

Construction of taxiway Juliet between 2006 and 2008 brought the asphalt taxiway within 37 feet of the ASOS equipment and approximately 61 feet from the temperature sensor. Although the Office of the Federal Coordinator for Meteorology specifies that temperature and dew point sensors be mounted in such a way "to ensure that measurements are representative of the free air circulating in the locality and not influenced by artificial conditions, such as large buildings, cooling towers, and expanses of concrete and tarmac," there is no official minimum distance specified that the temperature or dew point sensors must be from either concrete or tarmac. However, according to NWS Cooperative Observer siting instructions (NWS 2010), "the sensor should be at least 100 feet from any paved or concrete surface." In the case of the San Juan ASOS, the siting was done over 10 years before the addition of taxiway Juliet, at which time it was in full compliance with NWS Instruction 10-1307, and a relocation northward at this point would position the ASOS within 100 feet of runway 10/28. (It should also be noted that the primary purpose of ASOS equipment is to serve the aviation community and is not solely for climatological purposes).

Figure 6 – Pre-Construction: An aerial view of the ASOS (white circle) at the Luis Muñoz Marin International Airport in San Juan with the **future** location of taxiway Juliet highlighted by the thin white line (photo courtesy of the Puerto Rico Ports Authority).

In order to investigate the impact that the addition of taxiway Juliet had on the temperature observation at the Luis Muñoz Marin International Airport, two high quality sites were chosen for comparison. Using the ASOS at the Christiansted Airport on Saint Croix and the ASOS at the Cyril E. King Airport on Saint Thomas (and recognizing the shift in data on Saint Thomas began in August 1998 as noted in Case 1 above), it was decided to compare the temperatures from 2000-2005 to those from 2008-2010. By computing the difference between 2000-2005 and 2008-2010, and leaving out the two years (2006-2007) during which taxiway Juliet was under construction, a standardized comparison of the sites could be performed. To further simplify the comparison, the differences for the stations on Saint Thomas and Saint Croix were combined (and hereafter are referred to as the U.S. Virgin Islands). It should be noted that the analysis was performed for Saint Croix and Saint Thomas individually, and the results were nearly identical and used as justification for their combination.

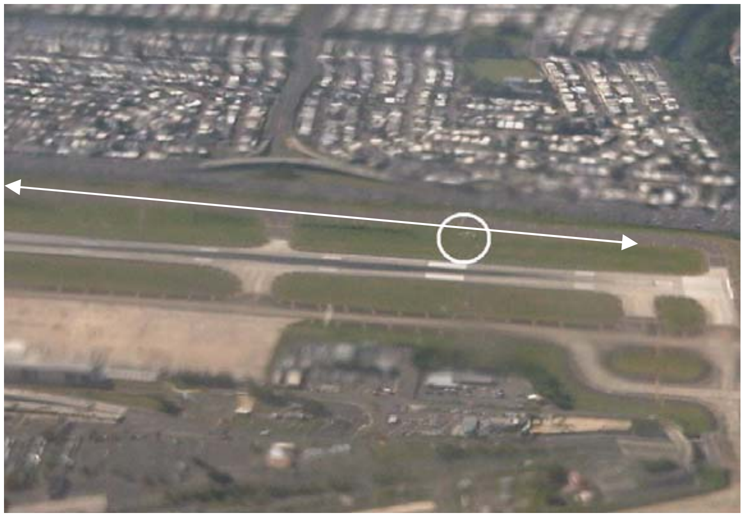

Figure 7 – Post Construction: An aerial view of the ASOS (white circle) at the Luis Muñoz Marin International Airport in San Juan with the location of **completed** taxiway Juliet highlighted by the thin white line.

2. Data Analysis

Figure 8 is a frequency plot of the deviations in average temperatures since the completion of taxiway Juliet. Compared the temperatures at the Luis Muñoz Marin International Airport with those at the U.S. Virgin Islands, it is apparent that the average temperature since 2008 has been greater in San Juan than at the U.S. Virgin Islands. While the raw data shows an overall increase in average temperature of 0.8^{o}F (Table 3), a clear shift in the frequency of days with higher temperatures can be noted by simply subtracting the two data sets used in Figure 8. These differences (Figure 9) show a clear tendency towards fewer cool days and more warm days in San Juan.

The addition of taxiway Juliet has affected the minimum temperatures significantly more than the maximum temperatures (Table 3). The minimum temperatures have increased approximately 1.4^{o}F since the completion of the taxiway, while the maximum temperatures have experienced a much more modest increase of 0.3^{o}F.

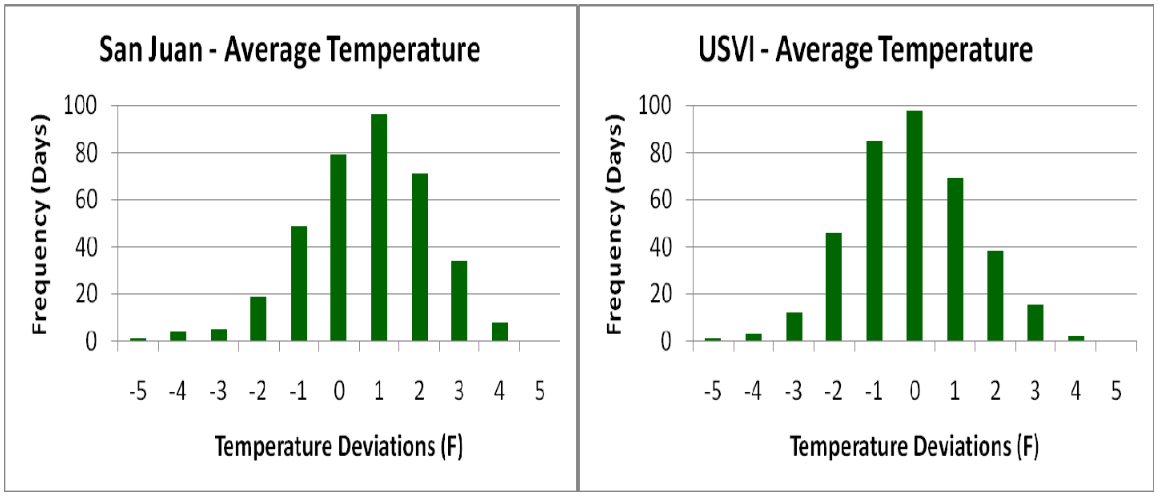

Figure 8 – The annual distribution of deviations in average daily temperatures in San Juan and the U.S. Virgin Islands from their 2000-2005 average.

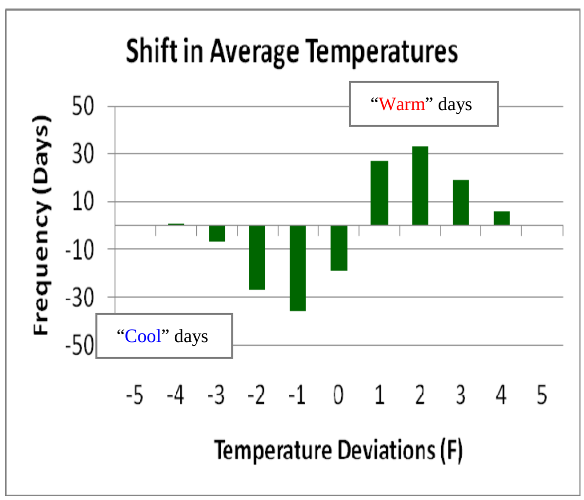

Figure 9 – The annual shift in temperatures in San Juan since the addition of taxiway Juliet.

Table 3 – Averaged temperature trends between 2000-2005 and 2008-2010 at the Luis Muñoz Marin International Airport in San Juan compared to that at the two U.S. Virgin Islands sites.

	Maximum Temp	**Minimum Temp**	**Average Temp**
U.S. Virgin Islands	**-0.1 F**	**-0.3 F**	**-0.2 F**
San Juan	**+0.2 F**	**+1.1 F**	**+0.6 F**
Difference	**+0.3 F**	**+1.4 F**	**+0.8 F**

Using the noted difference that the addition of taxiway Juliet had on both the maximum and minimum temperatures at the Luis Muñoz Marin International Airport as justification, an examination of individual frequencies of the maximum and minimum temperatures was performed. Those results (Figures 10-12) indicate how the maximum and minimum temperatures have shifted at the ASOS in San Juan since the taxiway's completion.

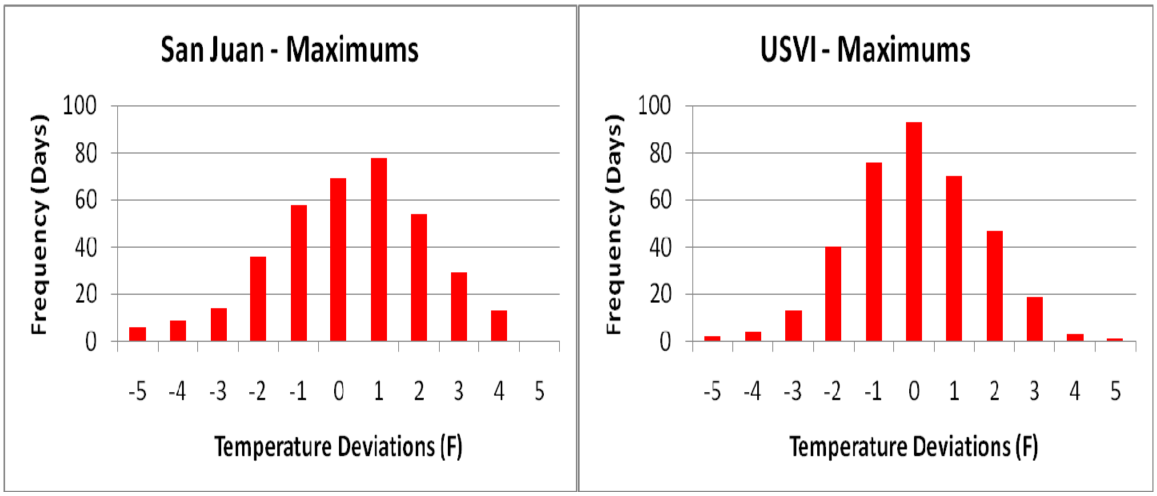

Figure 10 – The annual distribution of deviations in maximum daily temperatures in San Juan and the U.S. Virgin Islands (from their 2000-2005 average).

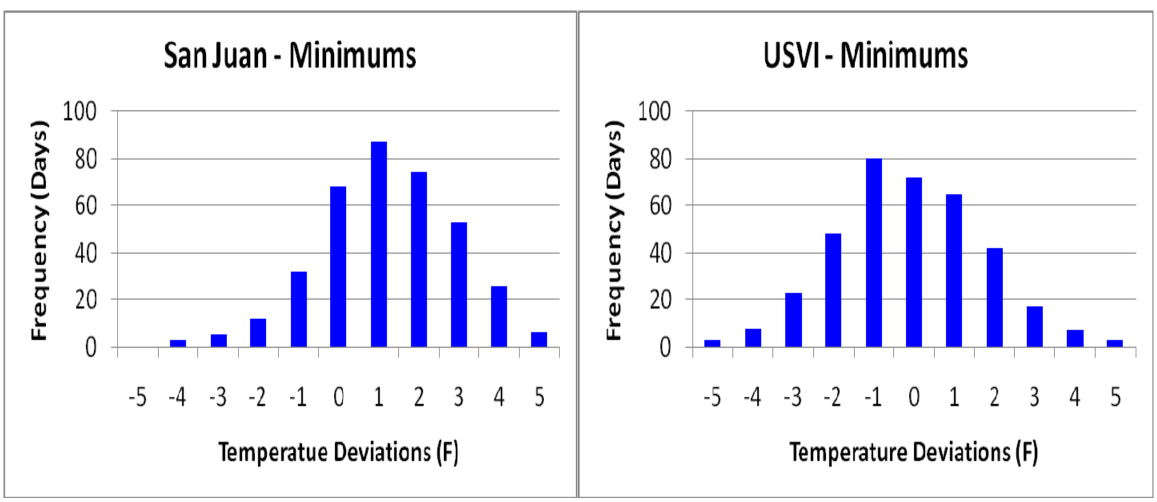

Figure 11. The annual distribution of deviations in minimum daily temperatures in San Juan and the U.S. Virgin Islands (from their 2000-2005 average).

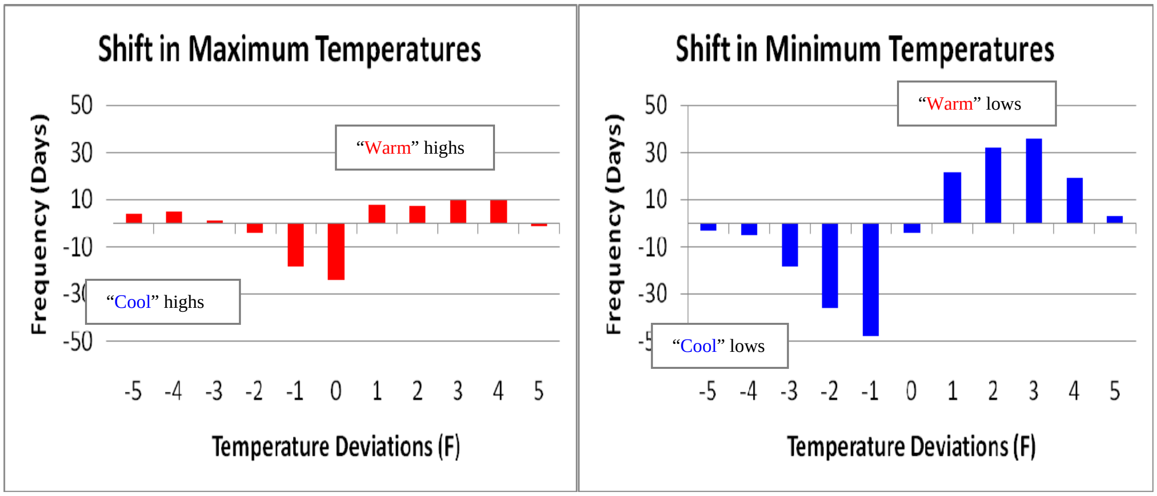

Figure 12 – The annual shift in both maximum and minimum temperatures in San Juan since the addition of taxiway Juliet.

Careful examination of Figures 10 and 11 reveal an increase in the frequency of days in San Juan where maximum and minimum temperatures were either near or above their 2000-2005 averages. However, in the case of the U.S. Virgin Islands, maximum temperatures have displayed a near normal distribution since 2008, while the minimum temperatures have exhibited a slight bias towards more days with near or below normal temperatures.

The annual shift in temperature frequencies (Figure 12) shows both the maximum and minimum temperatures exhibit a clear bias towards less frequent cool days and more frequent warm days. However, this signal appears stronger in the minimum temperatures (plotted in blue) than in the maximum temperatures (plotted in red), consistent with the data presented in Table 3.

This amplified effect on minimum temperatures is consistent with previous studies on the urban heat island effect which have demonstrated that temperature changes are greatest at night (Howard 1833). In this case, the addition of taxiway Juliet added a slab of asphalt where previously generally lush tropical vegetation was present, a modification typical to those associated with urbanization. Thus, it is thought that the resultant change in thermal properties associated with the addition of the taxiway (which retains heat more effectively than the natural vegetation) is likely why the minimum temperatures have shifted more significantly than the maximum temperatures at the site.

3. Case 2: Conclusions

Noting the proximity of taxiway Juliet to the ASOS observation equipment at the Luis Muñoz International Airport, it is apparent that the proximity of the new taxiway to the temperature sensor (61 feet) had an effect on the temperature record at the site. In fact, the NWS Instruction 10-1307, which describes the standard siting criteria for meteorological instrumentation, recognizes that **ideally** a temperature sensor should not be sited within 100 feet of a paved or concrete surface. While the ASOS at the Luis Muñoz Marin International Airport was originally sited more than 100 feet from the nearest paved surface, the addition of taxiway Juliet has had a substantial effect on temperatures recorded at the site. Once again, it should be noted that the primary purpose of ASOS equipment is to serve the aviation community and not solely for climatology purposes.

Since the completion of the taxiway there has been a noticeable shift if temperatures at the Luis Muñoz Marin International Airport when compared to other high quality surrounding meteorological stations. Compared with two other sites in the northeastern Caribbean an overall increase in the average temperature at the Luis Muñoz Marin Airport of 0.8 F was noted since the addition of the taxiway, with daily maximum (minimum) temperatures increasing approximately 0.3°F (1.4 F). The greater impact on minimum temperatures is attributed to the change in thermal properties of the ground near the observation site, similar to those that have been documented with urbanization.

As was the case with the relocation of the observation site at the Cyril E. King Airport on Saint Thomas, the temperature trends observed since the change in siting were likely amplified due to the tropical coastal location. Regular light southeasterly winds at night (coming from the direction of the added taxiway), along with high relative humidities and a small diurnal temperature range, all likely contributed to the impact on the temperatures than may not have otherwise been expected from a slab of asphalt 61 feet away.

V. Implications on Temperature Extremes at Both Airports

Since 1 January 2008, 143 record temperatures have been tied or broken at the Luis Muñoz Marin International Airport in San Juan (through 31May 2010). Of those, 124 (87%) have been record warm temperatures, while only 19 (13%) were record cool temperatures. These should be compared to the temperatures Christiansted Airport on Saint Croix and Cyril E. King Airport on Saint Thomas were the number of temperature records were much smaller (129 and 51, respectively) and were more evenly distributed between warm (47% and 53%, respectively) and cool (53% and 47%, respectively) records.

Recognizing that all three stations have roughly a similar period of record (varying from 47 years to 54 years) and that all three stations experience very similar synoptic scale weather conditions, it should be expected that a similar number of records would be broken at each of the three stations over the same time period.

In an attempt to create an impartial comparison between the two sites, it was decided to tabulate the number of records prior to the construction of taxiway Juliet at the Luis Muñoz Marin International Airport in San Juan, once again using the years 2000-2005as a comparison (see Table 5).

Table 4 – New record temperatures recorded at San Juan, Saint Croix, and Saint Thomas between 1 January 2008 and 25 March 2010.

	Record High Temperatures	Record Low Temperatures	Record Warm Low Temperatures	Record Cool High Temperature	Total Records
San Juan	21	0	103 ←	19	143
Saint Croix	13	9	11 ←	27	51
Saint Thomas	0	9	68 ←	68 ←	129

The bias towards an increasing number record warm low temperatures and record cool high temperatures at the Cyril E. King Airport on Saint Thomas remained similar for both time periods, and noticeably different from the distribution of record temperatures in San Juan and on Saint Croix (note the red and blue arrows highlighting the significantly higher number of record warm low temperatures and record cool temperatures recorded on Saint Thomas in Tables 4 and 5). The second point to note is the distribution of record temperatures in San Juan and on Saint Croix were similar prior to the construction of taxiway Juliet, with a marked increase in record warm low temperatures observed in San Juan since the construction of the taxiway (black arrows in Tables 4 and 5).

Table 5 – Same as Table 4, but for the period 1 January 2000 through 31 December 2005.

	Record High Temperatures	Record Low Temperatures	Record Warm Low Temperatures	Record Cool High Temperature	Total Records
San Juan	29	17	75 ←	58	179
Saint Croix	15	36	48 ←	66	165
Saint Thomas	0	16	120 ←	167 ←	303

As noted in previous studies of climate change (*e.g.*, Karl, *et al.* 2008), a small change in the average of a parameter can result in much larger changes in its extreme values (Figure 13). After a shift in temperatures at a given station, what was once considered to be an extreme event becomes just an above average event, with the corresponding number of new records occurring at a much higher frequency than in the recent past.

This is exactly what we have observed at both the Luis Muñoz Marin International Airport in San Juan and the Cyril E. King Airport on Saint Thomas. The number of temperature records broken on San Juan and Saint Thomas since 1 January 2008 were nearly double those broken on

Saint Croix, with a significant bias in the new temperature records towards their respective shifts in the temperature means.

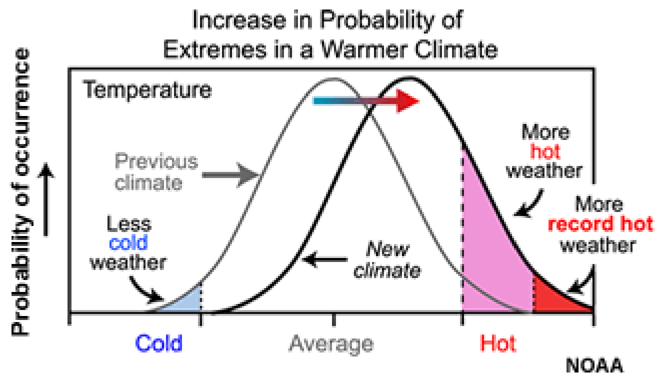

Figure 13. Effects that a shift in the average of a parameter, such as caused by a change in instrument siting, can have on the probability of occurrence of extreme values (taken from Karl, *et al*,. 2008).

In Case 1, the Cyril E. King Airport on Saint Thomas, due to the relocation of the observation site closer to the water, observed maximum (minimum) temperatures had become approximately 1.4°F cooler (1.0°F warmer) since the siting of the ASOS. Because this change occurred towards the end of 1998, it is not surprising to see a higher proportion of record cool maximum and record warm minimum temperatures since then (Tables 4 and 5) when compared to the entire period of record.

In Case 2, the addition of taxiway Juliet at the Luis Muñoz Marin International Airport in San Juan, an observed increase in the minimum temperatures of 1.4°F has been recorded, with a sharp increase in the record number of warm low temperatures recorded at the airport since 1 January 2008. Using the years 2000-2005 for a comparison, there has been nearly a three fold increase in the number of new record warm low temperatures in San Juan compared to those recorded on Saint Thomas and Saint Croix combined.

These changes in the number of record temperature at the Luis Muñoz Marin International Airport and Cyril E. King Airport are exactly what one would expect with a shift in climate or, in the case of the two ASOSs, a shift in temperatures due to changes in siting (Karl 2008).

While the shear number of records broken in San Juan and on Saint Thomas alone is notable, there have also been some other extraordinary records broken as a consequence. In 2009, the number of days in which the low temperature did not drop below 80 degrees in San Juan was 59, shattering the previous record of 32 set back in 1981. In addition, the two longest strings of days where the temperature did not drop below 80 were also observed in 2010, with strings of eight days in October 2009 and seven in August 2009 observed. The previous record was six days (June 1981). Not surprisingly, these record low temperatures also helped contribute to an average annual low temperature of 75.9°F recorded in 2009, the warmest annual minimum temperature recorded in San Juan since record keeping began on 1 January 1956.

VI. Summary

The importance of siting has long been recognized as a key component in the collection of accurate meteorological data. As far back as 1769 siting was recognized to have a significant impact on record keeping (Herberden 1769). This paper demonstrated how critical good siting can be, especially in coastal tropical locations where diurnal temperature ranges are small and temperature is strongly dependent on distance from water.

In Case 1, the relocation of the observation site at the Cyril E. King Airport on Saint Thomas, U.S. Virgin Islands, resulted in nearly a 20% reduction in the diurnal temperature range due to the new location slightly closer to the warm Caribbean waters. In Case 2, it was shown that a change in landscape 60 feet from the sensor at the Luis Muñoz Marin International Airport in San Juan had a profound impact on the temperatures at that site. Due to the change in thermal properties associated with the addition of taxiway Juliet, there has been a significant increase in the nighttime temperatures recorded there. Additionally, in both cases, these changes also likely contributed to a significant increase in the number of new record temperatures being recorded at their respective locations.

While focusing attention on the siting of meteorological instrumentation is not new, it is something that needs to be considered when investigating temperature trends at a particular site. In the end, what may seem like a small change in location can have a critical impact on the climatological record for that site, especially in the tropics where diurnal cycles are small and temperature extremes correspondingly vary only a few degrees from averages. With this in mind, it becomes extremely important to document not only changes in the location of observing sites, but also any changes in the vicinity of the site.

VII. Acknowledgements

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