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ANALYSIS OF UPPER AIR, GROUND AND REMOTE SENSING DATA FOR THE ATLAS FIELD CAMPAIGN IN SAN JUAN, PUERTO RICO

Jorge E. González[1], Jeff Luvall[2], Douglas Rickman[2], Daniel Comarazamy[3] and Ana J. Picón[4]
[1]Department of Mechanical Engineering, Santa Clara University, [3]NASA Global Hydrology and Climate Center, Huntsville, AL, [3]Department of Mechanical Engineering, University of Puerto Rico-Mayagüez, [4]Department of Electrical Engineering, University of Puerto Rico-Mayagüez
E-mail: jgonzalezcruz@scu.edu

ABSTRACT

The Atlas San Juan Mission was conducted in February 2004 with the main objective of observing the Urban Heat Island of San Juan. To support the Airborne Thermal and Land Applications Sensor (ATLAS) data, remote sensing observations were conducted, upper air soundings were launched, and a number of ground-based weather stations and temperature sensors were deployed. This paper focuses in the analysis of this complementary data for the Atlas San Juan Mission. Upper air data show that during the days of the mission the mid and high atmosphere in the Caribbean was relatively dry and highly stable, reflecting positive surface lifted index, a necessary condition to conduct this suborbital campaign. In consequence, only 8.4 mm of precipitation were reported during the entire mission. The weather stations and temperature sensors data show that heavily urbanized commercial areas have higher air temperatures than suburban residential areas, and much higher temperatures than rural areas. The data also shows that the UHI peaks during the late morning to an average of 4.5ºC, a pattern not observed in similar studies of other cities. It is observed a high variability of the UHI with the precipitation pattern, even for short events. These results may be a reflection of a large land use by low rise buildings with an apparent absence of significant heat storage effects in the urban areas, and of the importance of the surrounding soil/vegetation moisture evapotranspiration in controlling the urban tropical climate. The ATLAS data was used to calibrate the spatial distribution of the surface temperature when using remote sensing images from MODIS (Moderate Resolution Imaging Spectroradiometer). The information retrieved from MODIS for land surface temperatures reflected similar temporal and spatial variations as the weather stations and ATLAS measurements, with a highest absolute offset of about 5ºC due to the differences between surface and air temperatures.

1. INTRODUCTION

The general climate of the island of Puerto Rico is dominated by the easterly trade winds from the Atlantic Ocean, and during synoptically calm days by the topographic and local land surface characteristics. The variety of microclimates present in the island may demonstrate the impact that the different land cover/land use (LCLU) classifications have on the climatology of the island. The urban canopy of the metropolitan area of San Juan may introduce a new microclimate that changes the characteristics of the low atmosphere and interacts with the other microclimates already present in the island. The primitive LCLU of the metropolitan area of San Juan was composed by broadleaf trees, moist soils, and very dense vegetation in general. The urban LCLU changes the balance of mass, momentum and energy between the bottom boundary and the lower atmosphere, creating different climate conditions over urban and rural regions, especially of temperature. These temperature differences are called the Urban Heat Island (UHI) effect.

Factors that contribute to the formation of the UHI are anthropogenic heat sources, aerosols from pollutants, fast water canalization due to the presence of buildings and streets, among others. Nevertheless, the thermal inertia of concrete and the absence of vegetation in the urban areas are considered to be the most significant causes of the UHI. These contrasts are larger in clear and calm conditions and tend to disappear in cloudy and windy weather. The UHI was recognized in the early 1950's as closed isotherms that separates the city from the general temperature field [1]. UHI effects of different magnitudes have been reported for several cities [1-9]. Each city is exposed to different local and synoptic factors, which makes the study of the UHI a complex one. Two works related to physical models provided good insights of how the atmosphere could react to sensible heat fluxes coming from hot urban surfaces [10, 11].

An analysis of the climatological data revealed that a UHI effect exists in the metropolitan area of San Juan, Puerto Rico (SJMA). The mean temperature of the urban canopy air at 2 meters above ground level (AGL) for the coastal and inland urban areas is over 1.84ºC higher than the surroundings north rural areas. This reveals a permanent urban heat island effect present in the SJMA during the year, which is increasing according to the linear regression for the last forty years at a rate of 0.41ºC/decade. These results encouraged the planning and execution of an intense field campaign in February 2004 referred as the ATLAS San Juan mission.

2. DESCRIPTION OF THE ATLAS MISSION

The Airborne Thermal and Land Applications Sensor (ATLAS) from NASA/Stennis operates in the visual and IR bands. ATLAS is able to sense 15 multispectral radiation channels across the thermal - near infrared - visible spectrums. The sensor also incorporates onboard, active calibration sources for all bands. The sensor is capable of approximately 2.0 meter resolution per pixel when flown in a Lear 23 jet plane and sees about a 30 degree swath width to each side of the aircraft. The data must be corrected for geometric abnormalities due to flight path variations, and must be radiometrically calibrated. These raw sensor scan lines are then reconstructed into a two dimensional image data set. The sensor also operates a 9 inch Zeiss camera for high resolution photographic work. This ATLAS sensor has been used in other field campaigns to investigate UHI in Atlanta [12], Salk Lake City [13], Baton Rouge [14], and Sacramento [15]. No major effort has been reported to investigate the UHI in a major tropical city.

The San Juan, Puerto Rico, ATLAS mission was conducted during February 2004 to investigate the impact of the urban landscape and growth on the climate of this tropical city. The flight plan for the mission covers the San Juan metropolitan area, el Yunque National Forest, Mayagüez, and the Arecibo Observatory, for a total of 25 flight lines (Figure 1). The central area of San Juan was covered at 5 meters resolution in day and night flights. The remaining areas were covered at 10 meters resolution. The flights were conducted between February 11th and February 16th, 2004.

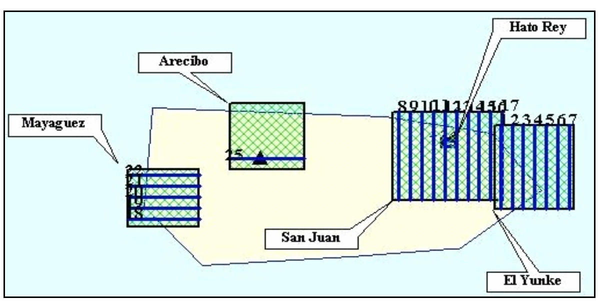


Figure 1 San Juan ATLAS Mission Flight Plan

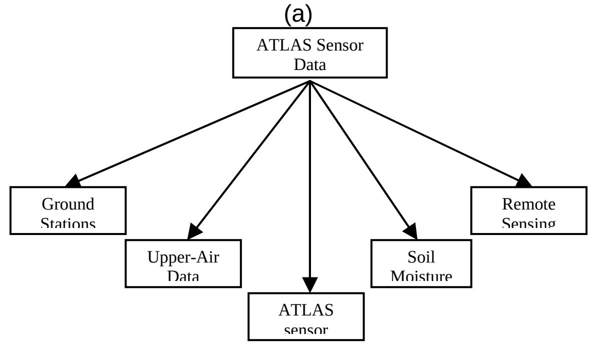
In order to analyze the existence of an urban heat island in San Juan, and to support the Atlas sensor data, several experimental campaigns for data collection were designed and conducted by different teams. The execution and different components of the San Juan Atlas Mission are presented in Figure 2. The focus of this paper, and of the next sections, is in the analysis of the supporting measurements during the San Juan ATLAS field campaign, specifically for upper air data, ground weather stations, and remote sensing.

3. UPPER-AIR DATA

The upper air information consisted of sounding launches and synoptic information provided by the NCAR Reanalysis data [16]. The San Juan office of the National Weather Service (NWS) increased the frequency of the standard soundings during the mission days, and launches were made from Mayagüez in the west coast, San Juan, and Dorado, about 25 miles east of San Juan.

Day	Lines	Flight	Time (UTZ)	Resolution
Feb 11	18-22	Mayaguez	13:27-14:03	10 meters
Feb 11	23-24	Hato Rey Day	14:22-14:36	5 meters
Feb 13	1-7	El Yunque	17:54-18:49	10 meters
Feb 13	23-25	Hato Rey & Arecibo Night	23:59-00:29	5 meters
Feb 16	8-17	San Juan	14:03-15:29	10 meters

(a)

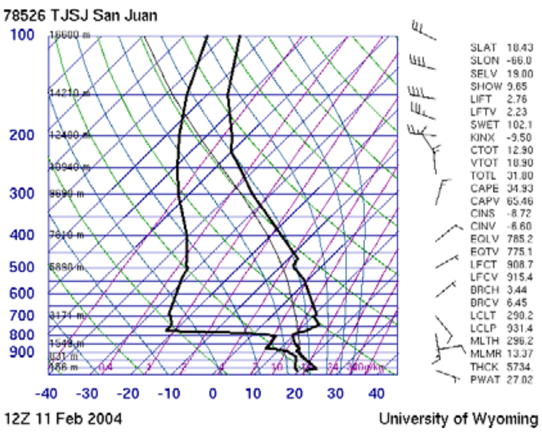


(b)

Figure 2. (a) Execution of flight plan and (b) Different components supporting the ATLAS Mission

The upper air data clearly shows that the atmosphere was unusually stable and dry during the days of the mission. February 11, 2004 for example, when lines 18-24 were flown, presented a highly stable and dry atmosphere as shown in Figure 3. The differences between the dew point and the temperature of the sound indicate a dry atmosphere under stable conditions. The stability was slightly affected by daytime solar heating. The NCAR reanalysis data was used to verify the upper air synoptic conditions. The surface pressure and the surface Lifted Index (LI) for 12UTZ February 11, 2004 (not shown) observe that a high surface pressure prevailed in the Caribbean region. The Lifted Index is found by comparing the temperature of a parcel of air raised from the surface to the 500mb level to the actual temperature at 500mb. Fortunately, a prevailing positive LI was present in the Caribbean region during the days of the mission. The exception for these conditions occurred in February 14th, 2004 when low clouds were present until late in the morning, leading to local instability and precipitation in the San Juan area (see Figure 4b).

Combined sounding data for San Juan (SJ) and Mayaguez (MZ) is presented in Figure 5. San Juan soundings were launched at 00, 12 and 18UTZ, while Mayaguez data was collected for 18UTZ. It can be noted that the atmosphere is relatively humid at 00UTZ and becomes dry as local heating pushes upward the moist clouds leaving a drier lower atmosphere. It can also be noted that differences in the local boundary layers are present for San Juan and Mayagüez at levels below 900mb only, maybe due to the topography of Puerto Rico which presents peaks as high as 1,300 meters between the two locations.



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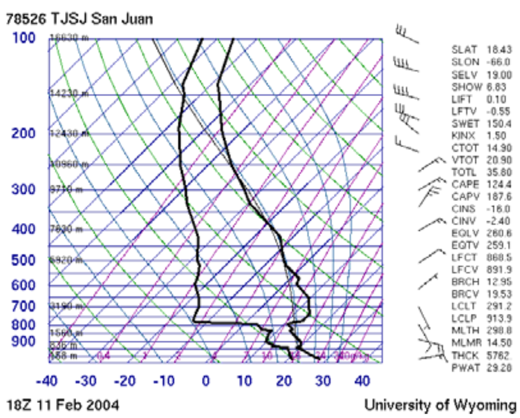

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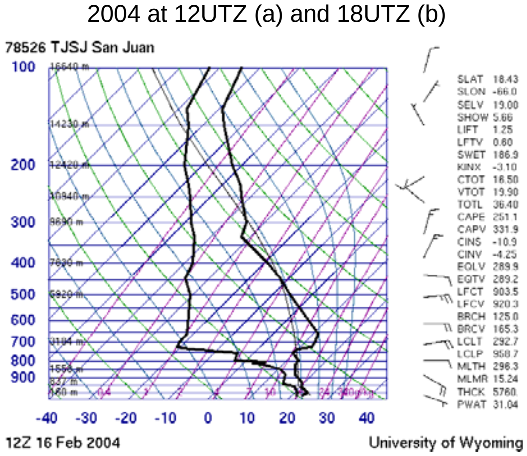
Figure 3 Upper air data from San Juan for February 11, 2004 at 12UTZ (a) and 18UTZ (b)



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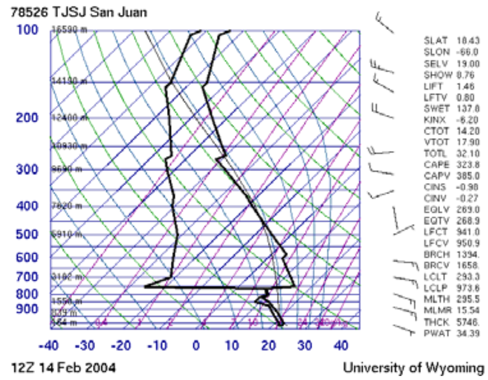


(b)

Figure 4 San Juan sounding for February 16 (a) and February 14 (b) at 12UTZ

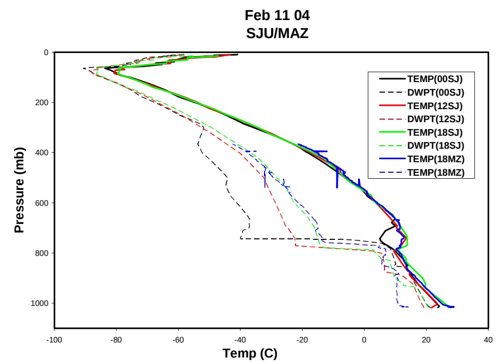
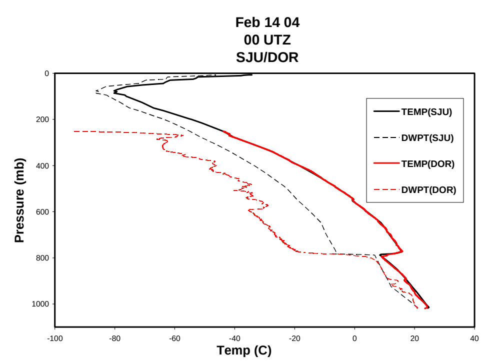


Figure 5 Combined upper air data for San Juan (SJ) and Mayagüez(MZ) for February 11, 2004

A comparison of the upper air data for San Juan (SJU) and Dorado (DOR) reflects minimum differences in the lower thermal boundary layer for 00UTZ in February 14, 2004 and increasing humidity by 06UTZ, as shown in Figure 6. These results are of particular interest since Dorado is about 25 miles east of San Juan and located in a coastal rural region. The differences in the thermal or mechanical boundary layers between these two points will be a direct effect of the urban canopy. When the atmosphere is dry and stable, minimum differences are observed, however, the humidity will increase faster in the rural area than in San Juan as the night progresses, due to the high percentage of surface vegetation in Dorado.



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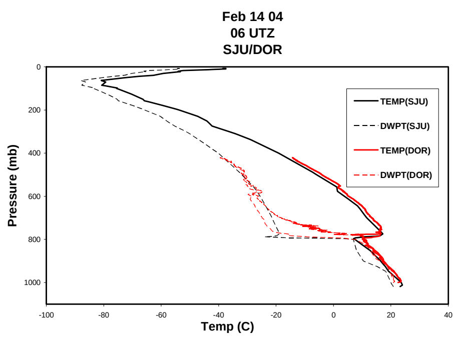


(b)

Figure 6 Combined upper air data for San Juan (SJU) and Dorado (DOR) for February 14, 2004 for 00UTZ (a) and 06UTZ (b)

4. GROUND STATIONS AND SENSORS DATA

Weather stations and temperature sensors were placed at strategic locations in order to analyze possible temperature differences between the commercial area (Hato Rey, Santurce, Old San Juan, San Juan International Airport, and North Bayamón), residential areas (Cupey, South and East Bayamón, Trujillo Alto, and Toa Baja), and rural areas (Dorado and Rio Grande). The storing frequency of all the data loggers, stations and sensors alike, was set to 5 minutes. Figure 7 shows a map depicting the different locations and the type of equipment. Tables 1 and 2 show the specification of each weather station and temperature sensor, with identification, location, coordinates, and variables measured.

Figure 7 Location of all the weather stations and temperature sensors deployed in the San Juan Metropolitan Area and surrounding areas. The solid black line represents the track of the cross-section presented in Figure 9

4.1 Observed results from ground stations

The Urban Heat Island effect is defined as the dome of elevated air temperatures that presides over cities in contrast to their cooler rural surroundings. The weather stations and temperature sensors data show strong indications of an Urban Heat Island in the SJMA. Figure 8 shows the station data results recorded at selected locations throughout the greater SJMA and neighboring rural municipalities. It is clearly seen that the average noon temperatures during the time period of the Atlas Mission evidence the existence of a pronounced Urban Heat Island, with the peak of the high temperature dome exactly over the commercial area of downtown San Juan, represented by the stations in the Sagrado Corazón University and the UPR Río Piedras Campus. It is also important to point out that Figure 8 was created with noon average temperatures. It is still not clear why the San Juan UHI peaks in the late morning hours and not in the early evening, a pattern shown in previous UHI experiments conducted in continental cities [12].

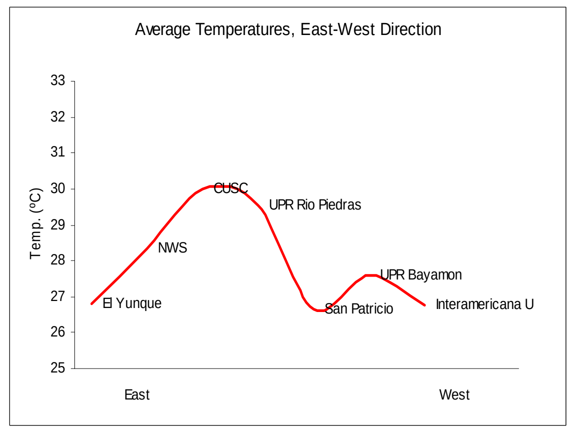


Figure 8 East-West cross-section of average noon temperature at selected locations in the San Juan Metropolitan Area and rural adjoining areas

Table 1 Ground Stations Covering the San Juan Urban Area and Rural Surroundings										
Station	Location	Coordinates		Variables						
		Latitude	Longitude	Temp	RH	Wind	Precip	Solar Rad	Press	Soil Mois
Polytechnic Station	Hato Rey	18º25’19”	66º03’19”	x	x	x	x	x	x	
Dorado Station	Eco House	18º27’55”	66º19’37”	x	x	x		x		
UPR Station	Rio Piedras	18º24’08”	66º03’04”	x			x			x
Rio Grande Station	Rio Mar Beach	18º22’44”	65º45’22”	x			x			

Table 2 HOBO Sensors		Latitude	Longitude	Temp.
Bayamón Sensor	Science Park – North Bayamón	18º24’41”	66º09’37”	x
Cupey Sensor	South Guaynabo	18º21’12”	66º05’13”	x
CUSC Station	Santurce – Central SJ	18º26’29”	66º03’31”	x
Guaynabo Sensor	North Guaynabo	18º24’23”	66º06’07”	x
Interamericana Sensor	South Bayamón	18º21’06”	66º11’00”	x
NWS Sensor	North Carolina	18º25’53”	65º59’29”	x
Toa Baja Sensor	Naval Base Sabana Seca	18º27’28”	66º11’47”	x
UPR Bayamón Sensor	East Bayamón	18º22’14”	66º08’36”	x

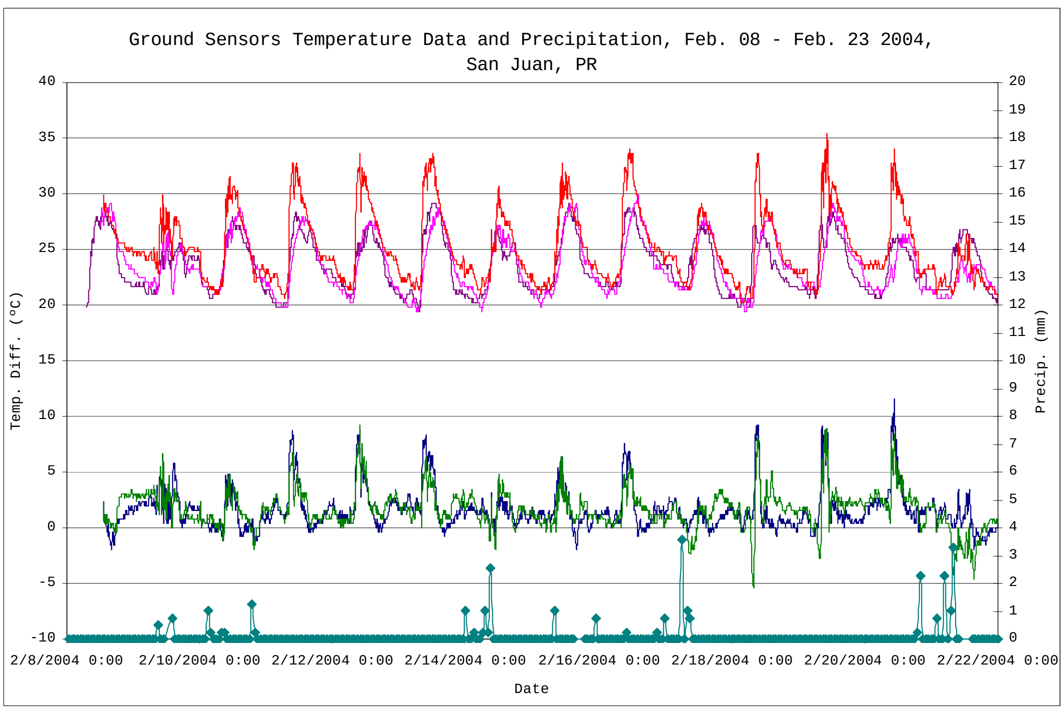


Figure 9 True temperature at a urban-commercial, urban-residential, and rural areas (top three series); temperature differences between the commercial area and the residential and rural areas (middle two series); total precipitation recorded every 5 minutes by the San Juan National Weather Service (bottom series)

An analysis of the data gathered shows that peak true temperatures occurred at mid afternoon, and ranged from 33 to 35ºC in urban areas, and between 26-28ºC in sub-urban and rural areas. Low temperatures consistently reached 20-22ºC in the late evening (around 10:00pm). Top temperatures in rural areas were substantially lower that those in urban areas in the mid to late morning hours, more specifically between 9:00am and noon with average temperature differences of 4.5ºC in such time frame, a temporal pattern not observed in previous UHI studies of large continental cities. It is also observed the nonappearance of a Cool Island, a dip of negative dT(U-R) opposite to the Heat Island caused by thermal heat storage. This might be due to the high percentage of low rising buildings in the metropolitan area of San Juan, despite having a large concrete density within the city.

The high concrete density, and the importance of the soil moisture content and vegetation transpiration in controlling the urban tropical climate, is evidenced by the variability of the UHI pattern with respect to rainfall. Even for relatively small and short precipitation events, in the order of only 8.4mm during the entire mission, the temperatures in the commercial core of San Juan and the surrounding residential and rural areas become very similar, showing a low dT(U-R). These results are summarized in Figure 9, which shows the true temperature, temperature difference, and accumulated surface precipitation for selected stations.

5. REMOTE SENSING DATA

Remote sensing measurements can provide land surface temperatures at the regional scale. A calibration exercise was conducted for the MODIS sensor using information gathered during the San Juan Atlas mission with the intention of verifying the ability of this sensor in observing surface temperatures in tropical regions. The land surface temperature(LST) product from MODIS (MOD11 from level 2) has been developed to get LSTs at a resolution of 1km and was used for this study. The theoretical basis of the LST algorithm is described in Wan [17] where the author presents two algorithms: the generalized split-window LST algorithm and the day/night algorithm. The generalized split-window LST algorithm uses the information from the spectral bands 31 and 32 (10.78 to 11.28µm and 11.77 to 12.77µm). Some of the constraints of the MODIS LST product are discussed in Wan [18]. One important concern about the day/night algorithm is to apply it to tropical regions because of the less clear-sky days.
Different images were collected during the ATLAS campaign period and will be analyzed to assess the accuracy of the MODIS sensor for tropical locations. Table 3 shows the date and time for every image collected from MODIS during the days of the mission. For every day, there are two periods in which MODIS captures Puerto Rico. For some days only half of the Island of Puerto Rico is captured. That means that the day image will include half of the Island, most likely western Puerto Rico, while the night image will include eastern Puerto Rico. During the ATLAS period this occurred once.

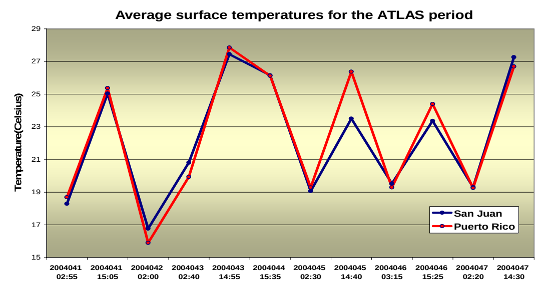
Table 4 Date and time for MODIS images

Date	Time
2004-02-11 (Day 042)	02:00 , 15:50
2004-02-12 (Day 043)	02:40 , 14:55
2004-02-13 (Day 044)	03:25 , 15:35
2004-02-14 (Day 045)	02:30 , 14:40
2004-02-15 (Day 046)	03:15 , 15:25
2004-02-16 (Day 047)	02:20 , 14:30

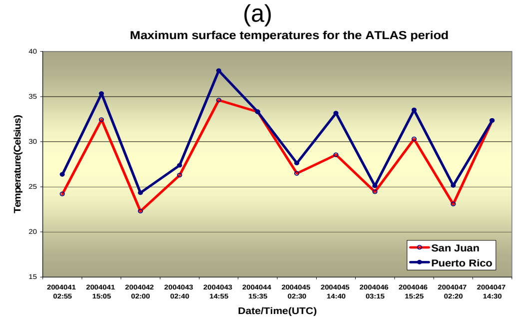
All the images from the ATLAS period were georeferenced. The San Juan region was extracted according to the coordinates defined by ATLAS. The hours during daytime may vary from one day to another. One note about the retrieval is the lack of identification of some pixels. The day when most pixels were recovered was February 16, 2004 which was the day that the ATLAS over passed San Juan at 10 meters resolution (see Figure 1). The worst retrieval was February 14, 2004 which also corresponds to the largest precipitation activity during the mission and when no flights took place. Two important time intervals were not captured: February 11, 2004 at daytime and February 13, 2004 at nighttime.

5.1 Results of Remote Sensing Analysis

Three different tasks were performed as part of the temporal analysis using MODIS. The first one was to calculate the average temperature (T_{avg}) for San Juan and Puerto Rico during the time intervals mentioned before. To conduct this calculation, pixels that do not show retrieval were not taken into account. Figure 10(a) shows the average temperatures for the specified time intervals. The lowest T_{avg}, 15.9ºC, occurred during February 11 at 2:00UTC. The highest T_{avg}, 27.85ºC, occurred during February 12 at 14:55UTC. Both extreme T_{avg} were retrieved outside of San Juan. The second task consisted in estimating the maximum temperature for San Juan and Puerto Rico. Maximum temperatures (T_{max}) were encountered at more than one location for the same time interval. In February 11, 2004 at 2:00UTC, for example, five different locations were identified with the highest temperature. Locations were near one to another which means that an area of approximately 4 by 4 km was observed with 22.29ºC at night during that particular day. Figure 10 (b) shows the maximum temperatures for San Juan and Puerto Rico. The highest T_{max} observed was 37.87ºC during February 12, 2004 at 14:55UTC and the lowest T_{max} was 22.29ºC during February 11, 2004 at 2:00UTC.



(a)



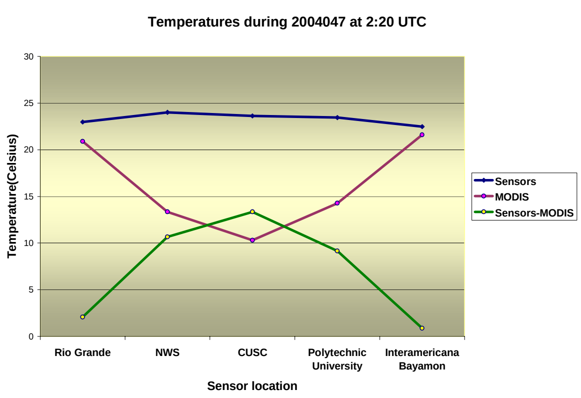
(b)

Figure 10 (a) Average and (b) Maximum land surface temperatures gathered from MODIS during the San Juan Atlas Field Campaign

The third task consisted in a comparison of the LSTs from MODIS with surface temperatures from sensors located around San Juan, and discussed in the previous sections. Figure 11 shows the MODIS temperatures and the temperature of the sensors in Table 4. Two different periods were studied for this purpose. The first period was at night, during February 16, 2004 at 2:20UTC. The pattern that can be observed is that MODIS responds contrary to the sensors for this period. The second period occurred at 14:30UTC in the same day of February 16, 2004. The MODIS pattern seems to be more synchronized with the ground sensors for this case. Differences in temperatures for this case are reasonable because the ground sensors were measuring air temperature and not land surface temperatures. At rural areas, surface temperatures tend to decrease while urban areas will experience higher temperatures. MODIS resembles these expected trends which relates well with the urban heat island effect.

Table 4 Locations near temperature sensors for nighttime and daytime observations

Temperature sensor	Geographic Location (Lat/Lon)	Geographic location(Lat/Lon)
Rio Grande	18° 22'43.94"N / 65°45'22.4"W	18° 22'44.01"N / 65°45'22.07"W
NWS	18° 25'52.99"N / 65°59'29.14"W	18° 25'53.28"N / 65°59'29.00"W
CUSC	18° 26'29.11"N / 66°3'31.2"W	18° 26'29.02"N / 66°3'31.19"W
Polytechnic University	18° 25'19.10"N / 66°3'19.07"W	18° 25'19.06"N / 66°3'19.06"W
Interamericana Bayamón	18° 21'6.15"N / 66°11'0.18"W	18° 21'5.81"N / 66°11'0.6"W



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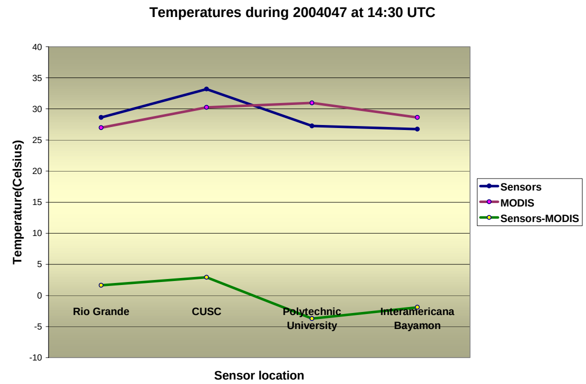

(b)

Figure 11 Comparison between weather stations and MODIS at nighttime (left panel) and daytime (right panel)

6. CONCLUSIONS

The upper air analysis for the days of the San Juan ATLAS Mission in San Juan, Puerto Rico, clearly shows that the lower and upper atmospheres of the Caribbean remained unusually dry and stable during the mission, conditions favorable for Urban Heat Islands (UHI). A comparison of upper air data for San Juan, Mayagüez, and Dorado for the mission days reflects that minimum differences in the thermal boundary layer are observed due to the topography of the Island of Puerto Rico and significant urban landscape.

The weather stations and temperature sensors data clearly show indications of the existence of an UHI in the metropolitan area of San Juan, PR. Temperature variations during the day had a range of ~20ºC in the early morning hours, and ~35ºC at mid afternoon. Temperatures were on average 4.5ºC higher in the urban areas when compared to the observation of rural areas during the time period of 10:00 am to noon. The precipitation pattern and cloud coverage significantly affected the UHI of San Juan, PR.

One important comparison between temperatures measurements by weather stations and those detected from MODIS satellite images is the one at night. There is a large difference: urban surface seem to cool down more rapidly than rural surfaces. Higher temperatures are detected on February 12, 2004 at 14:55UTC for San Juan when observed with the MODIS sensor. The lowest temperature detected by MODIS was on February 11, 2004 at 2:00UTC. Temperatures tend to rise from about 10:00 a.m. to 11:00 a.m. in Puerto Rico. MODIS shows good agreement with the expected UHI pattern in San Juan. One suggestion to improve the retrieval rate is to combine other satellite land surface data with MODIS LSTs.

These are preliminary results and further analysis needs to be conducted, nevertheless they are the most encouraging starting point on the road to objective evidence of the presence of an Urban Heat Island in San Juan.

ACKNOWLEDGEMENTS

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