Urban heat islands developing in coastal tropical cities

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Urban Heat Islands Developing in Coastal Tropical Cities

PAGES 397, 403

Beautiful and breezy cities on small tropical islands, it turns out, may not be exempt from the same local climate change effects and urban heat island effects seen in large continental cities such as Los Angeles or Mexico City. A surprising, recent discovery indicates that this is the case for San Juan, Puerto Rico, a relatively affluent coastal tropical city of about two million inhabitants that is spreading rapidly into the once-rural areas around it.

A recent climatological analysis of the surface temperature of the city has revealed that the local temperature has been increasing over the neighboring vegetated areas at a rate of 0.06°C per year for the past 30 years. This is a trend that may be comparable to climate changes induced by global warming.

These results encouraged the planning and execution of an intense field campaign in February 2004, referred to as the San Juan Atlas Mission, to verify the spatial and temporal extent of this urban heat index. Results of this field campaign recently have been analyzed and are the main topic of this article.

These results reveal the warming of a tropical coastal city that is significantly higher than typical temperatures in vegetated areas. This may be the first set of high-resolution thermal images taken in a tropical coastal city. Figure 1 shows that the daytime surface temperatures of a portion of San Juan at five-meter resolution are as high as 60°C, and that differences between urbanized and limited vegetation areas are in excess of 30°C.

Urbanization and the Urban Heat Island

Urbanization is an extreme case of land use change. It is estimated that by the year 2025, 60 percent of the world's population will live in cities, according to the United Nations Population Fund [*UNPF*, 1999]. Human activity in urban environments has impact at the local scale by changing atmospheric composition, affecting components of the water cycle (i.e., cloud cover and height, and convective activity), modifying ecosystems, and increasing energy demands.

In urban settings, global climate trends—particularly heat waves—are highly intensified. Recent reported cases of heat waves in urban areas include Europe in 2003 and Chicago, Ill., in 1995.

The clearest local indicator of climate changes due to urbanization is an urban/rural convective circulation known as urban heat islands (UHIs). This convective circulation is larger in clear and calm conditions and tends to disappear in cloudy and windy weather.

UHI effects of different magnitudes have been reported for a number of cities [*Tso,* 1995; *Lo et al.*, 1997]. Several observational and climatological studies have concluded that UHIs can have a significant influence on mesoscale circulation and the resulting convection. Early investigations have found evidence of warm seasonal rainfall increases over and downwind of major cities including Houston, Texas. [*Shepherd and Burian,* 2003]; Mexico City [*Jauregui and Romales,* 1996]; and Atlanta, Ga., and New York, N.Y. [*Bornstein and Lin,* 2000].

Investigations of the impact of urbanization on tropical coastal regions, where climate is usually dominated by the sea breeze, have been very limited. This article reports on a UHI for San Juan, Puerto Rico.

Description and Results of the San Juan ATLAS Mission

The Airborne Thermal and Land Applications Sensor (ATLAS) is a sensor, onboard a Learjet aircraft, from the NASA Stennis Space Center, Louisiana, that operates in the visual and infrared bands. ATLAS can sense 15 multispectral radiation channels across the thermal/near-infrared/visible spectrums. The data are radiometrically calibrated using onboard blackbodies for the thermal wavelengths and an integrating radiance sphere for the visible wavelenghts, corrected for atmospheric radiance, and georectified to map the coordinates system before data analysis. This ATLAS sensor has been used in other field campaigns to investigate UHIs in Atlanta, Salt Lake City, Baton Rouge, and Sacramento [*Luvall et al.*, 2005].

The mission was conducted during 11–16 February 2004 and analysis of the data has been recently completed. The flight plan for the mission covered the San Juan metropolitan area; El Yunque National Forest, east of San Juan; Mayagüez, a city west of San Juan; and the Arecibo Observatory, on Puerto Rico's central north coast; for a total of 25 flight lines. Each flight line covered an approximately 6.4 km swath width. The central area of San Juan was covered at five-meter resolution in day

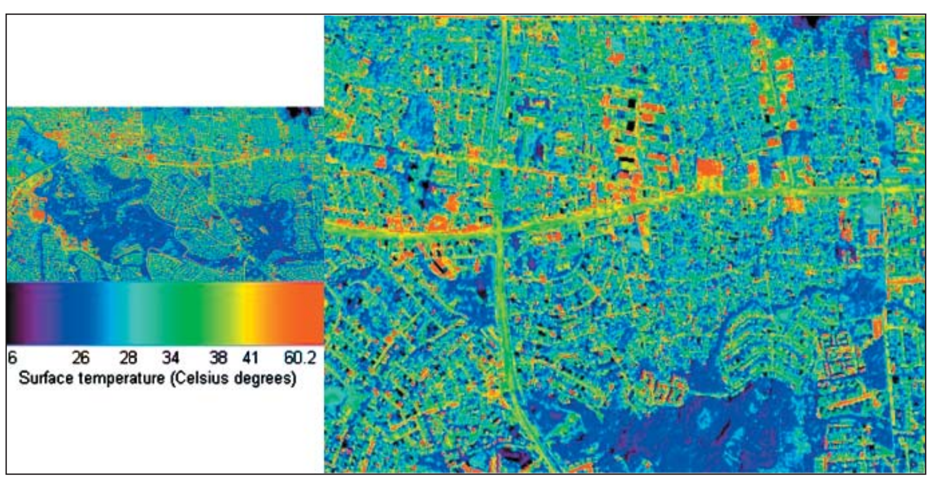

Fig. 1. Daytime ATLAS five-meter-resolution thermal image for downtown San Juan, Puerto Rico, 11 February 2004, 1420–1430 UTZ. Image at right is closer detail.

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and night flights. The remaining areas were covered at 10-meter resolution. The recently-completed imaging processing for the mission showed the presence of a constant UHI during the days of the mission in San Juan. More information about the mission can be found at www.cmg.uprm.edu/atlas.

Several additional upper air and ground instruments were used to support the ATLAS sensor data. Information from upper air soundings shows that during the days of the mission, the middle and high atmosphere in the Caribbean was relatively dry and highly stable. These conditions led to clear and dry skies which are necessary to use the ATLAS sensor.

Weather stations and temperature sensors were placed at strategic locations along the trade winds. Figure 2 shows the interpolated noon average ground station data results recorded at selected locations throughout greater San Juan and neighboring rural municipalities.

The average noon temperatures during the time period of the mission clearly show the existence of a pronounced UHI, with the peak of the high temperature dome exactly over the commercial area of downtown San Juan. That peak is represented by the stations within the red color areas. Most suburban areas are located west of downtown San Juan, represented by the light green and yellow areas. The El Yunque rain forest, east of San Juan, as well as the Central Mountains, south of San Juan, remained fairly cool as represented by the blue colors.

It is unclear why the San Juan UHI peaks in the late morning hours rather than in the early evening, which is a pattern shown in previous UHI experiments conducted in continental cities (http://www.ghcc.msfc.nasa.gov/atlanta/). A possible reason for this discrepancy is the low thermal storage of the shallow urban canopy of San Juan when compared to other cities with a high density of high-rise buildings. Also evident from the current study is that the UHI dominates the sea breeze effects in downtown areas. The winter tropical sea breeze tends to bring in cool air that refreshes the coasts.

Figures 1 and 3 show images of the ATLAS sensor at five-meter resolution for downtown San Juan at midday and nighttime, respectively. The density of the urban landscape can be easily observed from these images. Temperature differences between urbanized areas (red spots) and limited vegetated areas (blue spots) are higher than 30°C during daytime (Figure 1).

The roofs' temperatures drop rapidly from a maximum of 60°C during daytime to about 35°C in the nighttime, an indication of low thermal storage and shallow urban canopy for this tropical coastal city. During nighttime (Figure 3), the roads become the hottest surfaces (yellow spots), except for a few scattered warmer roofs. While temperatures for the roofs and the roads fluctuate between 35 and 60°C, the vegetation experiences temperature fluctuations lower than 10°C. At nighttime, the temperature differences between the immediate vegetated areas and the urban land, commonly referred to as the cool island, drops to about 10°C. This is an indication of low urban thermal storage.

Trends similar to those reported in this article may be expected in the future as coastal cities become more populated.

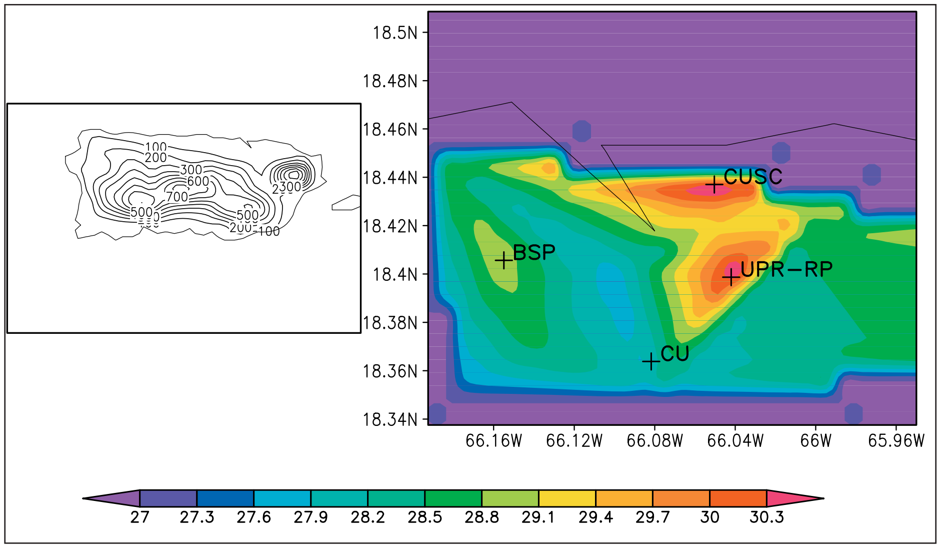

Fig. 2. East-west cross section of the average observed noon air temperatures during the mission at selected suburban and rural locations (UPR-RP, University of Puerto Rico-Río Piedras; CUSC, Sagrado Corazón University; BSP, Bayamón Science Park; CU, Cupey). Contours in the left panel represent elevations.

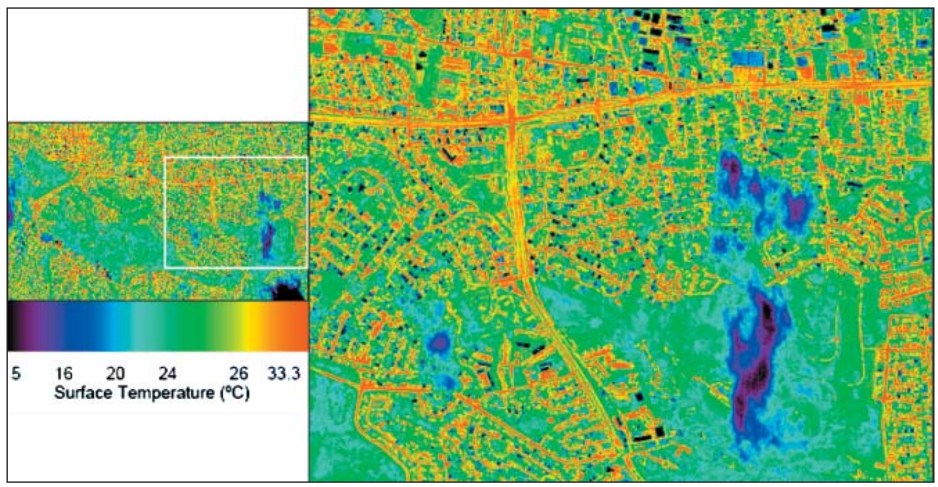

Fig. 3. Nighttime ATLAS five-meter-resolution thermal image for downtown San Juan, Puerto Rico, 13 February 2004, 2300 UTZ. Image at right is closer detail.

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References

Bornstein, R., and Q. Lin (2000), Urban heat islands and summertime convective thunderstorm in Atlanta: Three cases studies, *Atmos. Environ., 34,* 507–516.

Jauregui, E., and E. Romales (1996), Urban effects of convective precipitation in Mexico City, *Atmos. Environ., 30,* 3383–3389.

Lo, C. P., D. A. Quattrochi, and J. C. Luvall (1997), Applications of high-resolution thermal infrared remote sensing and GIS to assess the urban heat island effect, *Int. J. Remote Sens., 18*(2), 287–204.

Luvall, J. C., D. Rickman, D. Quattrochi, and M. Estes (2005), *Aircraft based remotely sensed albedo and surface temperatures for three US cities,* paper presented at Cool Roofing: Cutting Through the Glare Roofing Symposium, Roof Consult. Inst. Found., Atlanta, Ga., 12–13 May.

Shepherd, J. M., and S. J. Burian (2003), Detection of urban-induced rainfall anomalies in a major coastal city, *Earth Interact., 7*(4), doi:10.1175/1087-3562(2003)007<0001:DOUIRA>2.0.CO;2.

Tso, C. P. (1995), A survey of urban heat island studies in two tropical cities, *Atmos. Environ., 30,* 507–519.

United Nations Population Fund (1999), *The state of world population 1999*, 76 pp., New York. (Available at http://www.unfpa.org/swp/1999/index.htm)

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Chapopote Asphalt Volcano May Have Been Generated by Supercritical Water

PAGES 397, 402

Asphalt volcanoes and lava-like flows of solidified asphalt on the seafloor (Figure 1) were first discovered and described by *MacDonald et al.* [2004]. The flows covered more than one square kilometer of a dissected salt dome at abyssal depths (~3000 m) in the southern Gulf of Mexico. "Chapopote" (93°26'W, 21°54'N) was one of two asphalt volcanoes they discovered. MacDonald et al. determined that the apparently fresh asphalt must initially have flowed in a hot state, and subsequently chilled, contracted, and solidified, much in the same way as normal lava does on the surface of the Earth.

The two asphalt-volcanoes discovered occur at the apex of salt domes that pierce through the seafloor. These "piercement salt domes," known as the Campeche Knolls, are pertinent features of the deep Campeche Sedimentary Basin, which has a sediment thickness of about 10 km. According to conventional theory [*Vendeville and Jackson*, 1992], piercement salt domes represent "salt diapirs" that have risen up, due partly to density contrasts between salt and clay/sand from the "mother salt" located between 7 and 10 km below seafloor. A salt diapir is a vertical body of sub-surface salt, which is most often circular in cross section, is one to several kilometers in diameter, and can be 8–10 km high.

A close examination of the asphalt material by scanning electron microscopy and energy dispersive spectroscopy indicates that the material contains a myriad of varying sized, non-connected, isolated pores (0.1–0.5 mm). The largest pores contain pore-lining coats of chloride, sulfate, alumosilicate, and possibly carbonate minerals.

The earth-like, amorphous, and fine-crystalline structure of these pore-lining minerals suggests that they are authigenic precipitates, most likely deposited during cooling and solidification of the asphalt. Carbonate minerals also form macroscopic cement intermixed with the asphalt matrix [*MacDonald et al.*, 2004].

The observation of the precipitates raises questions concerning their mineralogical composition and crystalline structure, the temperature and origin of the source fluids (brines), and the role, if any, of microbes.

Supercritical Water – A 'Magic' Substance

Natural seepage of liquid oil also occurs from the Chapopote salt dome/asphalt volcano and from several of the other Campeche Knolls [*MacDonald et al.*, 2004]. Because "asphalt volcanism" was previously unknown and because there is no apparent strong heat source near the seafloor (the ambient water temperature is 4°C), *MacDonald et al.* [2004] were tentatively unable to provide a geologically sound formation model for the asphalt volcanoes.

A possibility is that hot hydrothermal fluids originating at the crust/sediment interface at about 13 km depth below sea level are able to transport molten asphalt inside the piercement salt structures, which may act as vertical "thermally insulated" conduits.

A recent model designed to explain how terrestrial mud volcanoes erupt similarly suggests that hot water may form near the base of very deep sedimentary columns [*Hovland*, 2005]. Thus, in the Caspian Basin of Azerbaijan the sediments are about 20 km deep [*Feyzullayev et al.*, 2001]. If the pore water temperature at this depth rises above 400°C, the water can no longer boil because of the high ambient pressure. Instead, it attains another phase; it becomes "supercritical water" [*Bellissent-Funel*, 2001]. This water phase is neither vapor nor liquid, but something in between.

Considering that supercritical water has a density of only one-third of liquid water (i.e., 0.3 g/cm^3: grams per cubic centimeter), it may represent the driving mechanism for some, if not all, mud volcanoes [*Hovland*, 2005]. Supercritical water forms at temperature and pressure conditions above 374°C (405°C for seawater) and 221 bars (300 bars for seawater) [*Tester et al.*, 1993; *Bellissent-Funel*, 2001]. This means that seawater will become supercritical when heated to beyond 405°C at water depths beyond 2800 m (equivalent to a pressure of 300 bars). The depth of 2800 m may therefore be called "the potential critical point" depth of the ocean.

Supercritical water also has other important properties, which include being very highly compressible, being highly corrosive, and having a very low viscosity. The water behaves as a non-polar rather than a polar fluid [*Bellissent-Funel*, 2001; *Tester et al.*, 1993; *M. Hovland et al.*, Salt formation by supercritical seawater and submerged boiling, submitted to Marine and Petroleum Geology, 2005, hereinafter referred to as submitted manuscript, 2005]. This means that when seawater or saline pore waters become supercritical, their salts precipitate as solid, small amorphous particles, by a process

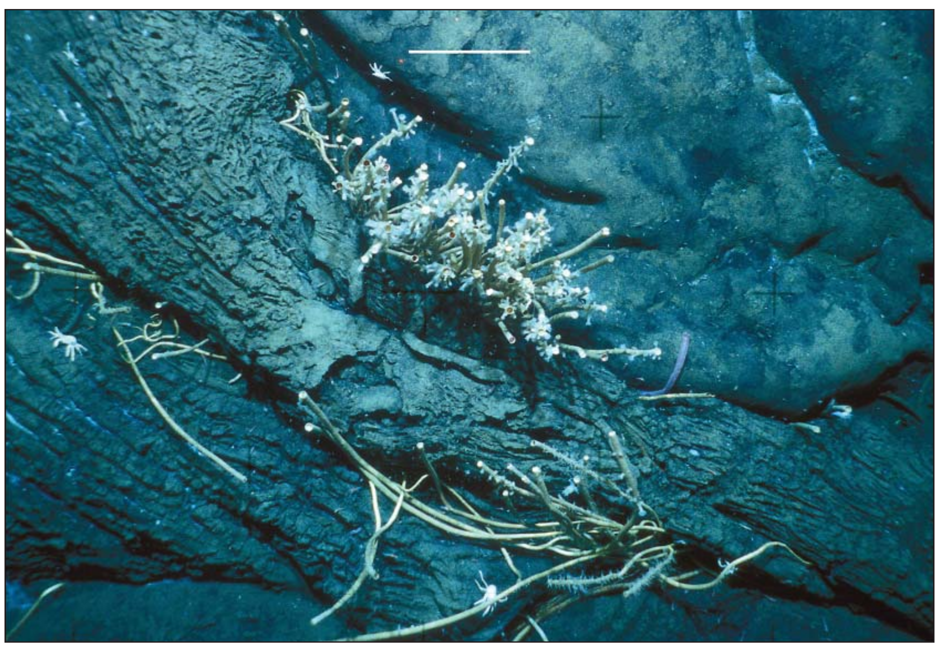

Fig. 1. Folds in the freshest Chapopote asphalt material, lined with tubeworms and white films (probably bacterial mats). Note the similarity to flow structures in terrestrial lava flows.

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