2.4 A MODEL STUDY ON THE EFFECTS OF URBANIZATION ON THE THERMAL AND CONVECTIVE PROPERTIES OF SAN JUAN, PUERTO RICO

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1. INTRODUCTION

Urban heat islands (UHIs) are defined as the warmth produced by the cities, as compared to the heat released by rural areas surrounding them. Many studies have shown the impact of UHIs on local climates. For example, Baik et al. (2000) used a two-dimensional, non-hydrostatic model to show that an UHI is capable of producing dry and moist convection predominantly downwind of the city. Other important observational and modeling studies of urban-induced convective activity are documented in Bornstein and Lin (2000), Rozzoff (2002), Shepherd and Burian (2003), Shepherd et al. (2002).

A comprehensive look at the interaction of urban-induced heat with the sea breeze circulation is given by Yoshikado (1992) and Cenedesi and Monti (2003), who conducted numerical and laboratory studies, respectively. Hafner and Kidder (1998) employed a three-dimensional model to simulate the UHI effect. They retrieved surface parameters from AVHRR satellite data, such as albedo and soil thermal and moisture properties, to incorporate these into their modeling tasks. Martilli (2002) used a 2-D mesoscale model to study the effects of urban morphology (using different urban configurations with varying building heights), wind speed, and rural soil moisture, on the boundary layer structure.

Velazquez-Lozada et al. (2002) demonstrated the existence of the UHI effect over San Juan by performing a series of three numerical experiments, in which the thermal and mechanical characteristics of the soil were configured differently for each one. In this experiment, they constructed three scenarios: ‘primitive’, current, and future, each one with varying degrees of soil and land use characteristics. They concluded that the intensity of the San Juan UHI -measured by the temperature difference between the urban and rural areas- is bound to increase at a rate of 0.06° year^{-1} if we expand the urban landscape of San Juan at a linear rate in relation to the population growth expected for 2050 (i.e. the future case). A follow-up model study by Mulero et al. (2003) depicted a temperature increase over San Juan as the urbanized area was doubled (as compared to the current urban horizontal area), more prevalent over central parts of the city. However, this study showed that temperatures along the coastal San Juan area remained unaltered or even decreased under the same urban growth scenario.

The results from the modeling experiments over the San Juan area suggest that the San Juan UHI is indeed influencing the local climate of the area, and likely the atmospheric conditions of the rural regions around the city. More specifically, the San Juan UHI might be influencing local climate by enhancing convective activity over and downwind of the city as previous studies have indicated for other major urban areas. The objective of this study is to quantify the effects of the urban San Juan area on the local climate over the city and areas nearby. The horizontal distribution of surface temperatures and the convective development over these areas are the key elements to be studied herein. A primitive equation, non-hydrostatic mesoscale model is used for these purposes. Two different land cover-land use (LCLU) scenarios are tested, each with a different amount of horizontal urban mass. A control simulation (CTL) uses an urban area of 336km^2, which closely resembles the current urban extent of San Juan based on airborne and satellite images. The second experiment is the rural or RUR run, which is a sensitivity test in which the current urban scenario is removed with rural characteristics, namely the ones that round the city at the present (e.g. needleleaf trees, bog/marsh, etc). A ‘traditional’ approach is used when modeling the urban area. That is, special parameterizations that account for urban geometry (i.e. building heights, street canyons) and the thermal and/or dynamic effects induced by it are not used. Instead, the surface-air heat and momentum exchanges within the city are calculated with the use of empirical values that represent the radiative and thermal properties of the urban environment. We believe that by performing a high-resolution simulation using this approach, the goal of detecting climate changes induced by the San Juan urban area is accomplished.

The remaining of this paper is organized as follows. A description of the model grid configuration and parameters is given in Section 2 along with a description of experiments conducted in the study. Section 3 shows the results of the simulations and analyzes them. Finally, Section 4 summarizes the study and points at current work being conducted currently to further expand on the conclusions presented here.

2. NUMERICAL EXPERIMENTS

2.1 *Model configuration*

Numerical experiments in this study are conducted using the CSU/MRC-ASTeR Regional Atmospheric Modeling System (RAMS) (Tripoli and Cotton, 1982; Tremback, 1990; Mahrer and Pielke, 1977). A two-way interactive doubly nested-grid technique is employed to achieve the multiscale simulations. The outer mesh has (x,y) dimensions of 64 x 34 grid points with a horizontal grid spacing of 64km. The middle and innermost meshes have dimensions of 86 x 58 and 86 x 58 points, respectively, with the former having a grid spacing of 16km and the latter of 4km. All grids contain 50 vertical levels (non-dimensional sigma levels). The finest mesh is centered over the island of Puerto Rico (refer to Fig. 1 for the grid configuration). The 50 vertical levels are spaced so that higher resolution is provided in the planetary boundary layer (PBL) than at the upper levels with the model top at ~18km. Bottom boundary conditions are mostly provided by standard sea surface temperature (SST) datasets provided at 1 km resolution in space with a monthly temporal variation (give reference). The topography is given from land surface observations (give reference). The model also uses vegetation/land cover standard files, which we modified to suit our experimental design. Figure 2 shows the urban scenario used in the CTL run.

Data from the United States Department of Agriculture (USDA) was used to provide detailed soil type data for Puerto Rico. The same soil type is assigned homogenously to the entire soil column, which has a depth of 50cm and 10 vertical layers. Soil moisture was also initialized homogeneously for all layers at 25%.

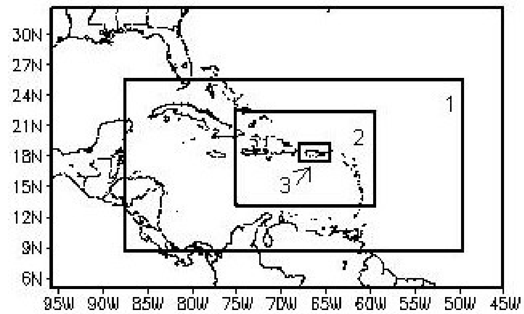

Figure 1: RAMS grid configuration.

A land surface model, LEAF-2 (Land Ecosystem-Atmosphere Feedback) (Walko et al., 2000), is coupled to the atmospheric model. The radiation scheme of Harrington (2000) and the convective parameterization of Kuo (1974) are used in the two experiments. The Mellor and Yamada scheme is used for the parameterization of vertical diffusion (Mellor and Yamada, 1982).

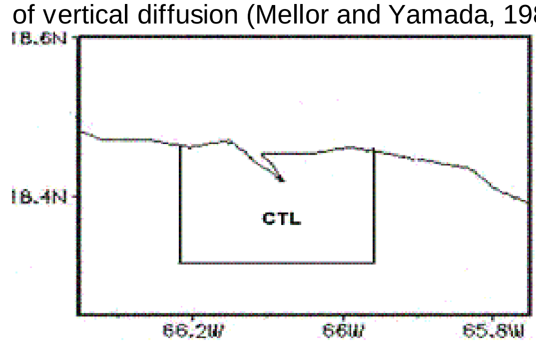

Figure 2: Urban configuration for the CTL experiment.

2.2 *Modeling exercises*

Velazquez-Lozada et al. (2002) showed that 2-m height temperature differences between the urban areas and its rural surroundings (i.e. intensity of the urban heat island) increase progressively from the 'primitive' state to the 'current' and then a 'future' case scenario. His 'future' scenario, as they referred to, employs a much larger urban landscape than the one used in this study for the CTL run.

In this work, the effects of urbanization on the surface atmospheric and convective properties over San Juan are more broadly discussed. A control (CTL) simulation is developed in which the San Juan area is represented by an aerial coverage of 336km^2, which is closely the horizontal extent of the current San Juan metro region. A RUR experiment is developed by removing all urban land use from the previous run. Experiments are initialized on 1200UTC 21 January 1998 and integrated over 10 days. Analysis is primarily done during the peak insolation hours on the last seven days of each simulation. NCEP Reanalysis data (Kalnay et al., 1996) provides the lateral boundary conditions at every 6h. Surface land observations enhance the NCEP reanalysis data at every 6h by further nudging the model solution to the actual data.

3. RESULTS

3.1 Urban Effects on Thermal Distribution

Figure 3 shows that removing the San Juan urban mass caused surface temperatures to decrease mainly in areas downtown of the city during the peak hours of afternoon solar insolation for the 24-31 January 1998 period. The cool spot seen at the lower-right part of the domain shows the location of the Sierra de Luquillo mountains, wherein El Yunque National Rainforest sits. Temperatures over the city, however, show little response to the removal of urban mass. This suggests heat is being advected to the west by the east-northeasterly flow present during the period at 1400LST (Fig. 4). Flow direction structure shows that when the urban mass is present, winds tend to tilt in a more northerly direction, probably due to the increased coastal-land pressure-gradient. This shows a pattern of flow modification induced by an urban area. The magnitude of the flow, however, changes little from one simulation to the other. One would expect that urban-related surface roughness cause a decrease in wind speed over the area. It still remains unknown the net effect of this warm and moist onshore flow on the temperature distribution over the San Juan region, which could be a topic for further study.

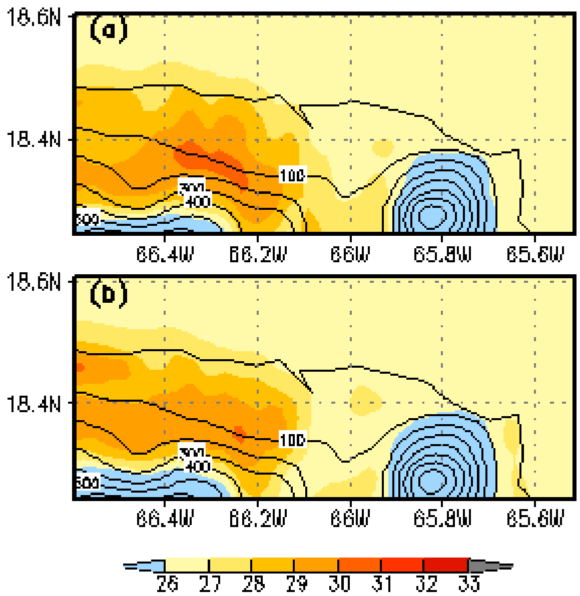

Figure 3: Horizontal distribution of averaged 1400LST surface temperatures (in °C) across San Juan and the northeastern part of Puerto Rico for the (a) CTL and (b) RUR simulations. Topography is contoured at 100m intervals.

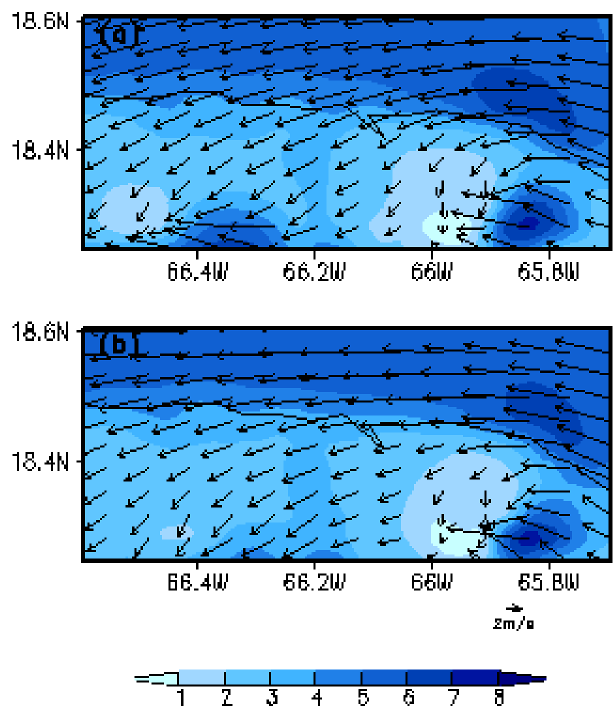

Figure 4: Wind vectors and magnitude for the 24-28 January 1998 period at 1400LST for the (a) CTL and (b) RUR run. Units are m s^{-1}.

3.2 Urban Effects on Moist Convection

As shown in previous studies concerning the enhancement of convection by big urban areas (Rozzoff 2002, Shepherd et al, 2002, Shepherd and Burian 2003), the San Juan presented herein is seen to influence the generation of an updraft right over the San Juan urban area within the lower 1km layer during the peak hours of solar insolation (Fig. 5). Updrafts are also seen downwind of the city

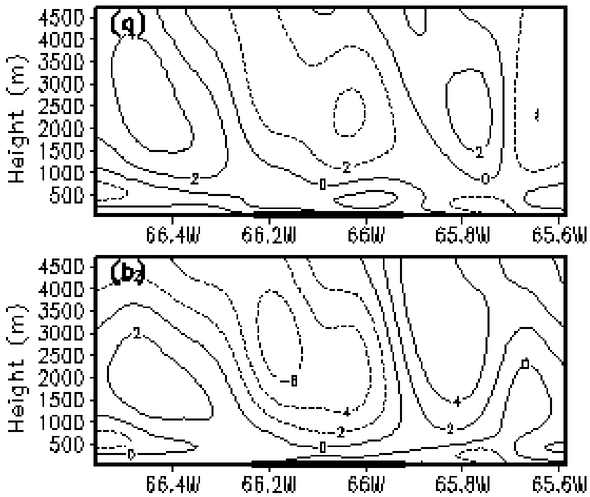

Figure 5: Vertical cross section depicting the vertical velocity perturbation (*w'*) averaged for the 24-31 January 1998 period at 1400LST; (a) shows *w'* for CTL and (b) shows *w'* for RUR at 2cm intervals. Thick solid line along the horizontal axis represents the area where San Juan is located.

on both experiments, although the one in (a) is slightly stronger, probably enhanced by the urban heating effects. Figure 6 shows the cross-sectional line, which passes over the central parts of the city.

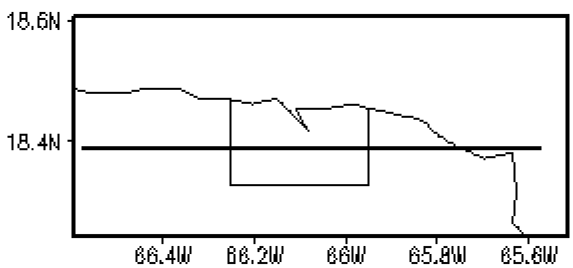

Figure 6: Line depicting the vertical cross-sections taken over San Juan and areas upwind and downwind of the city. The box represents the area extent of the city in the CTL run.

Vertical cross sections of cloud water mixing ratio averaged over the analysis period at 1400LST show that the favored areas for cloud formation are above the city, or just slightly east of the central San Juan, and over downwind areas of the city (Figure 8). Only values above $5*10^{-2}$ are color-shaded. The larger amounts of cloud water are exclusive to the 4500m-5500m layer. It is not clear whether rain water was associated to these clouds. We can clearly see an increase in cloud water as the afternoon progresses (Fig. 8) as more surface energy is available to enhance buoyancy of air parcels and hence release of latent heat until they reach a certain level.

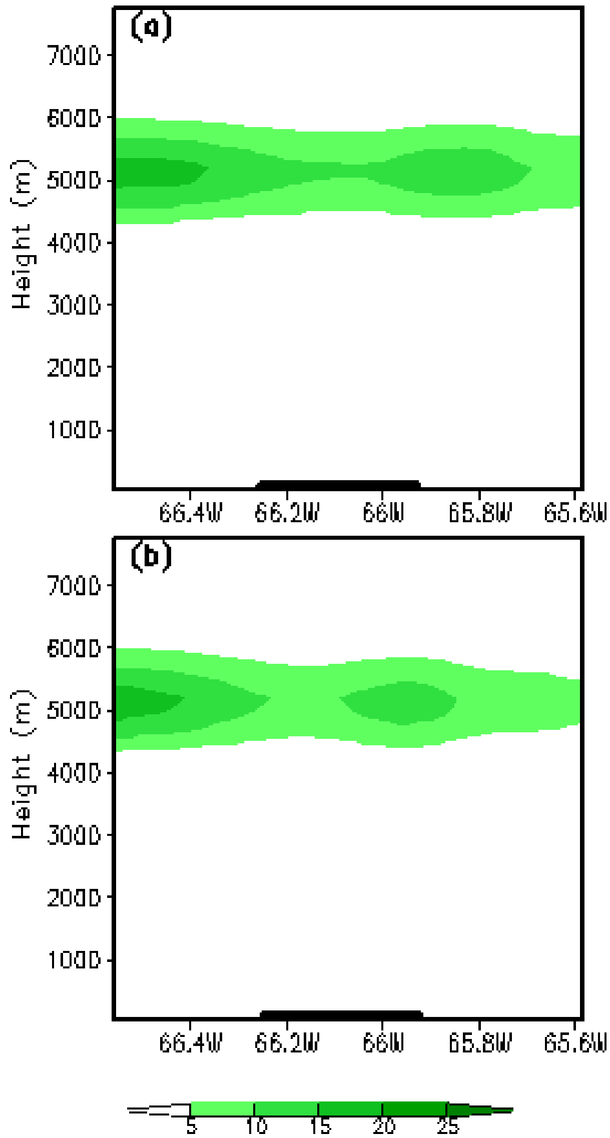

Figure 7: Cloud water mixing ratio (10^{-2} g kg^{-1}) averaged at 1400 LST (left) and 1500 LST (right) during the 24-31 January 1998 period; (a) depicts the CTL run and (b) shows the results for the RUR run. Thick bar at the bottom of each plot represents the San Juan area.

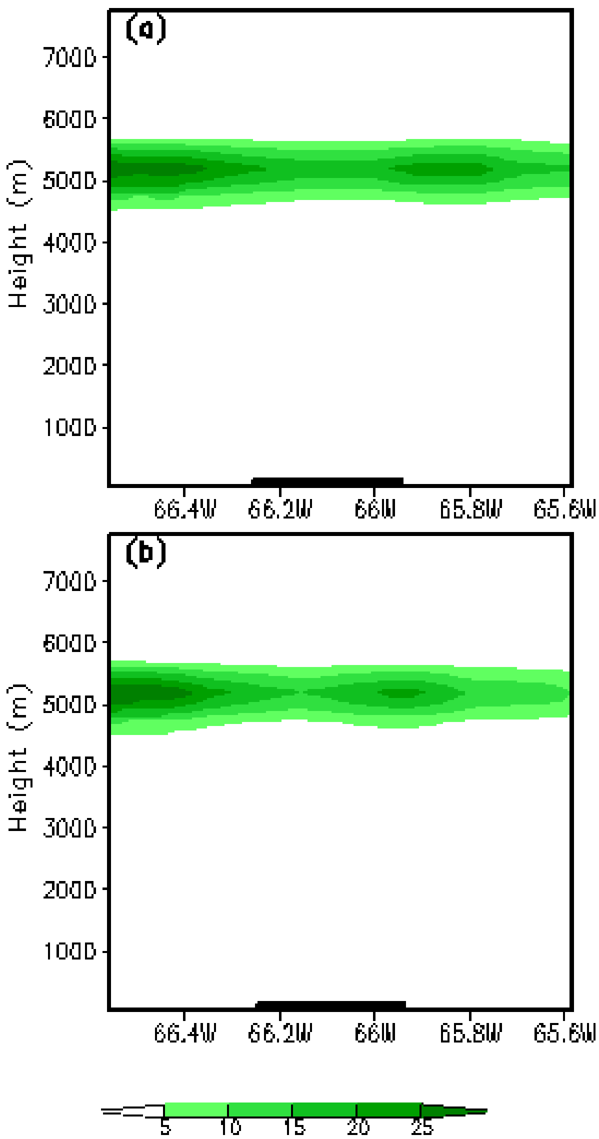

Figure 8: Cloud water mixing ratio (10^{-2} g kg^{-1}) averaged at 1500 LST during the 24-31 January 1998 period; (a) depicts the CTL run and (b) shows the results for the RUR run. Thick bar at the bottom of each plot represents the San Juan area.

Figure 9 clearly shows a tendency for more rainfall during this week period when the urban scenario is present. Although rainfall does not vary much in the higher elevations and waters away from the shores, rainfall over and downwind of the San Juan area is noticeably higher in the CTL experiment. This further proves that major urban areas provide a more favorable environment for the triggering of moist convection and rainfall, and this includes cities located in deep tropical regions such as San Juan.

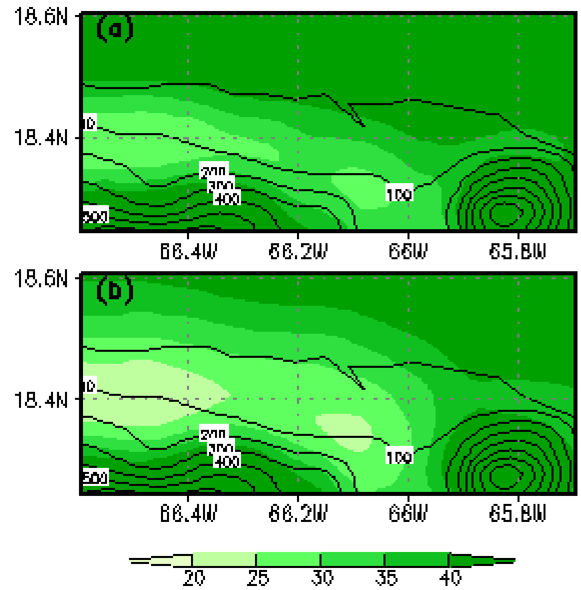

Figure 9: Total rainfall amounts (in mm) for the 24-31 January 1998 period for the (a) CTL and (b) RUR runs.

4. CONCLUSIONS AND WORK IN PROGRESS

A simple model study on the effects of the urban environment on the thermal and convective characteristics of areas in and around San Juan, Puerto Rico, has been performed with satisfying results. A conventional approach of parameterizing the thermo-mechanical properties of urban land use has been used. Two simulations were conducted to achieve our results: a control (CTL) run depicting the urban area of San Juan as it currently is and a rural (RUR) run, in which all urban mass was removed.

The week-averaged (24-31 January 1998) surface temperature distribution at the peak hours of surface heating showed a decreased in temperatures when the urban mass was removed, particularly over and downwind of the city. This suggests that areas to the west of San Juan are being directly affected by the effects of urbanization of San Juan as trade winds, generally from the east with sometimes a small northward or southward component, advect the heat generated over the city in their direction. Results also point at the modification of flow direction in and around San Juan, directly linked to the heating produced by the city. Urban-induced heat over and downwind of San Juan likely enhanced convective activity over these areas. This fact is evidenced by the vertical velocity perturbation *w'* field on the CTL simulation, which showed a bubble of rising air right above the city, as compared to the RUR experiment, which showed no significant updraft over the city. The CTL experiment generally showed greater areas of precipitation in and downwind of San Juan than the RUR run. Not surprisingly, it also showed larger amounts of cloud water, which was confined to the 4500m-5500m layer during the afternoon hours. These results confirm findings from previous studies that show increased amounts of moist convective activity and precipitation mainly in areas downwind of a major city owing to enhanced parcel instability resulting from excessive heating over the central city areas.

This work is currently being extended to include prolonged simulations that will address UHI effects for the months of July and August, when temperatures rise at their highest over the island and hence convective activity should be further enhanced. An analysis of the sea-breeze circulation and its interaction and effects on the San Juan-induced heat will be the outcome of these new efforts.

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