A validation study of the urban heat island in the tropical coastal city of San Juan, Puerto Rico

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2.2 A VALIDATION STUDY OF THE URBAN HEAT ISLAND IN THE TROPICAL COASTAL CITY OF SAN JUAN, PUERTO RICO

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1. INTRODUCTION

The Urbanization is an extreme case of land cover/land use (LCLU) change. Human activity in urban environments has impacts in the local scale including changed in the atmospheric composition, impact in the water cycle, and modifying ecosystems. Nevertheless, our understanding of the role of urbanization in the Earth-climate system is incomplete, yet it is critical to determine how the Earth components atmosphere-ocean-land-biosphere act reciprocally in a connected system. The most clear local indicator of climate changes due to urbanization is a well-known urban/rural convective circulation known as urban heat islands (UHI). The urban heat island is defined as a dome of high temperatures observed over urban centers as compared to the relatively low temperatures of the rural surroundings (see Figure 1). These temperature contrasts are greater in clear and calm conditions, and tend to disappear in cloudy and windy weather by effects of thermal and mechanical mixture. Some of the factors that might cause the formation of a heat island is the intensive use of asphalt and diverse construction materials, mainly concrete, although they also include metals, crystals, among others.

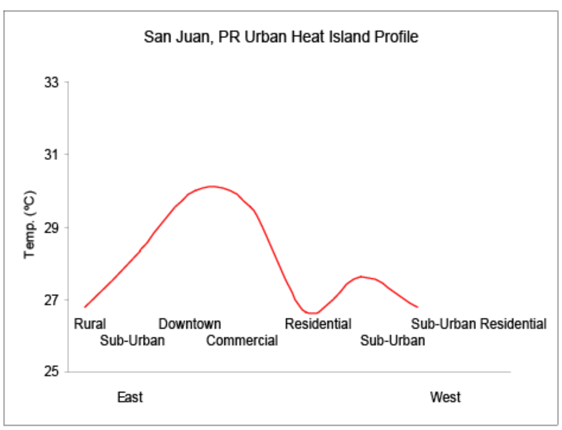

Figure 1 Schematic of the profile of temperatures typically observed in the San Juan Metropolitan Area.

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UHI effects of diverse magnitude have been reported for a number of cities (Landsberg, 1981; Tso, 1995; Jáuregui, 1997; Noto, 1996; Poreh, 1996). Although each city is exposed to diverse local and synoptic factors, a motive for why each UHI study is complex and specific to the locality, the general pattern is very similar. Several climatologic and observation studies have concluded that the UHI can have a significant influence in circulations of meso-scale and the resulting convection. An interesting topic that hav been recently address for large cities around the world in humid environments is the impact of land use for urbanization in the local and regional enhanced convection which may lead to enhances in precipitation.

A case study of the UHI in a coastal tropical city was conducted in San Juan, Puerto Rico. An earlier 50-years climatologic analysis of air temperatures at 2 meters above ground level was conducted calculating the difference between the daily averages of minimum, maximum, and average values from urban and rural cooperative stations (Velazquez et al 2005). The consistent presence of positive values was a clear indication that the temperatures in the city are greater than the temperatures in the countryside, and the positive slope of a linear regression indicates that this difference could be intensified if the present and past conditions persist without mitigation and suitable public policies for urban sprawl. The annual pattern of the urban-rural temperature differences showed that the greater differences occur during the first months of the year, which are the less humid in what is known in the Caribbean as the Dry and Early Rainfall Seasons when the convective activity is much smaller than during the Late Rainfall Season.

The results of the climatological analysis are surprising for a topical island where the climate is controlled mostly by the sea breeze and motivated the planning and execution of extensive and wide-ranging experimental campaigns aimed to understand the overall impact of land use for urbanization in the local climate of a topical coastal city. The studies are aimed to find responses to the following fundamental questions; how the land use for urbanization impacts the sea breeze circulation patterns? What is the relationship of the relative signals of land cover and land use (LCLU) and global climate change? What is the impact of local LCLU in tropical coastal cities in the hydrologic cycle? A first step to fin responses to these questions is to fully understand the horizontal spread of the urbanization and develop proper predictive tools able to replicate the UHI.

The first of the programmed field studies was designated as the San Juan Atlas Mission conducted in February 2004 (González et al., 2005). This extended abstract focuses on the validation of a regional atmospheric model for UHI studies in San Juan during this field campaign, and its subsequent use to analyze the effects of such LCLU changes.

2. OBSERVATIONS

The Atlas Mission of San Juan, Puerto Rico was conducted during February of 2004 to investigate the impact of the urban growth and landscape in the climate of this tropical city. The main sensor used was the Airborne Thermal and Land Applications Sensor (ATLAS) of NASA/Stennis operates in the visual and infrared bands. The ATLAS can detect 15 multispectral channels of the radiation through the thermal, near infrared and visible spectrums. The sensor also incorporates the active sources of calibration needed for all bands. The flight plan of the mission covered the metropolitan area within San Juan, the national forest of El Yunque to the east of San Juan, the city of Mayagüez in the west coats of Puerto Rico, and the Arecibo Observatory located in the north-central coast, for a total of 25 flight lines. The downtown area of San Juan was covered in a horizontal resolution of 5 meters in flights during the day and during the night. The remaining areas of the city were covered in 10 meters of resolution. The flights were executed between the 11 and the 16 of February of 2004. In order to validate and analyze the existence of an urban heat island in San Juan, and to support the data of the ATLAS sensor, several experimental campaigns for data collection were designed and conducted by different teams, in addition diverse numerical experiments were performed that helped to understand the phenomenon and its characteristics.

The information provided by the weather balloons launchings and the synoptic information provided by the National Center for Environmental Prediction (NCEP) demonstrated that during the days of the mission the mid and upper atmosphere in the Caribbean were relatively dry and highly stable (not shown), an ideal condition to conduct urban heat island studies.

The model results were validated with the observations obtained during the Atlas Mission experimental campaign. These observational data consist of weather stations and temperature sensors placed in strategic locations along the lines that follow the climatological pattern of the northeastern trade winds, and the weather balloons launchings performed regularly by the San Juan National Weather Service office. More details of the San Juan Atlas Mission and some of the data collected can be found in Gonzalez et al (2005) and in www.cmg.uprm.edu/atlas.

3. NUMERICAL EXPERIMENTS

The main objective of the numerical simulations presented here is to investigate the impact of land usage for urbanization on different environmental variables at local and regional scales. The approach used includes the configuration of a mesoscale atmospheric model, validation of the control simulations with the Atlas Mission observations, and quantify the impact of the land cover/land use (LCLU) by the cities. The regional model used for the study presented in this document is the Regional Atmospheric Modeling System (RAMS), developed at Colorado State University (Pielke et al. 1992, Cotton et al. 2003).

3.1 *Brief Model Overview*

RAMS is a highly versatile numerical code developed to simulate and forecast meteorological phenomena. The atmospheric model is constructed around the complete system of non-hydrostatic dynamic equations that govern atmospheric dynamics and thermodynamics, and the conservation equations for scalar quantities such as mass and humidity. These equations are complemented by a wide selection of parameterizations available in the model. The version of RAMS used in this investigation contains an upgraded cloud microphysics module described by Saleeby and Cotton (2004), an advance of the original package available in the current model release (Meyers et al. 1997, Walko et al. 1995).

3.2 *Model Configuration*

The simulations were conducted with three grids making use of the grid nesting capabilities of the model used. Grid 1 covers great part of the Caribbean basin with a horizontal resolution of 25 kilometers. Grid 2, which is nested within grid 1, covers the island of Puerto Rico in 5 kilometers of horizontal resolution. Grid three is nested within grid 2 and centered in the city of San Juan with a resolution of 1km (see Figure 2). For the vertical coordinate, all the grids have the same specification. A vertical grid spacing of 100 meters was used near the surface and stretched at a constant ratio of 1.1 until a Δz of 1000m is reached. The depth of the model is approximately 22.83 kilometers with 40 vertical levels.

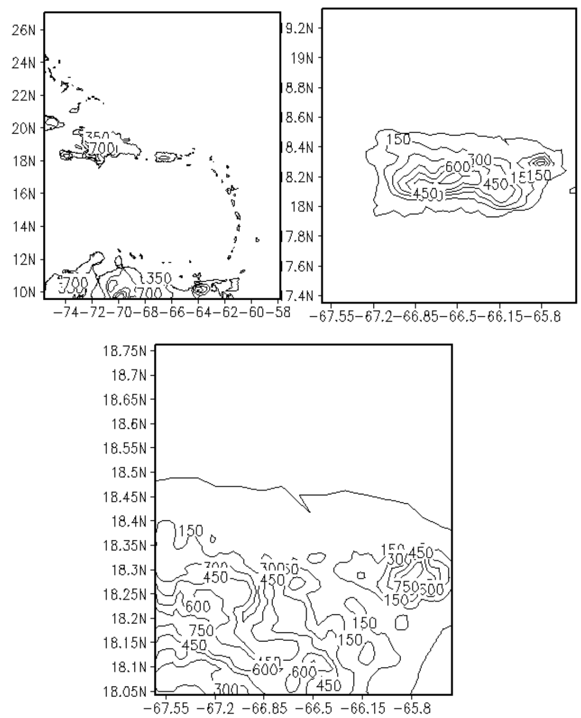

Figure 2 Model grids used in the numerical simulations to investigate the impact of the urban LCLU in the local climate. The topography contours have an interval of 150 meters in the three panels.

The cloud microphysics humidity complexity was set at the highest level. This level incorporates all the categories of water in the atmosphere (cloud water, rainwater, pristine ice crystals, snow, aggregates, graupel and hail) and includes the precipitation process. All simulations were forced with the same initial conditions and variable lateral conditions for the period of February 10 to the 20 of the year 2004, as given by the NCEP-Reanalysis atmospheric fields. The use of this regional atmospheric model already has demonstrated to produce satisfactory results in the Caribbean basin, simulating the precipitation pattern in the island of Puerto Rico in months of the early rainfall season (Comarazamy, 2001).

In order to quantify the impact of the LCLU change in the metropolitan area of San Juan, three different scenarios were configured. First the standard USGS specification of the surface characteristics used in regional atmospheric models was specified. Then one of the model sub-routines was modified to represent the urban extension and configuration of San Juan as it was observed from aerial photography. The third configuration was designed to represent the possible natural vegetation of the zone occupied by the city interpolating the surrounding vegetation covering all the areas. The runs were denominated Present, Urban, and Natural, respectively. The variable modified for these numerical simulations was the denominated Vegetation Index defined by the Biosphere-Atmosphere Transfer Scheme (Dickinson et al 1986), this index includes the physical parameters of albedo, emissivity, leaf area index, vegetation percentage, surface roughness, and root depth. The configuration of the LCLU index used in the three simulations is presented in Figure 3.

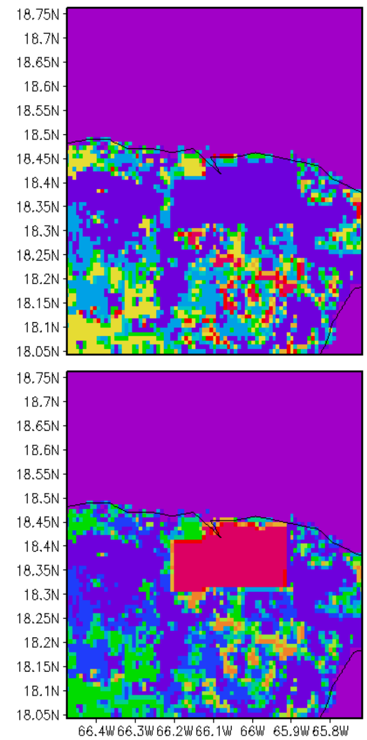

Figure 3 Specification of the surface characteristics used in the two runs of the atmospheric model used for the present analysis, the natural (top) and urban scenarios (bottom).

4. RESULTS

4.1 *Model Validation: Comparison with Observations*

The validation of the mesoscale model was performed by comparing the air temperatures at 2 meters above ground level produced by the simulation Urban with the values recorded by the stations, and by comparing the vertical profiles of temperature and wind speeds with the data from balloon launchings by the National Weather Service.

The daily temperature cycle presented in Figure 4 was obtained by averaging the temperature values predicted by the model over the entire area represented by the city at each hour for the duration of the Atlas Mission, and compared with the stations and sensors averaged over the same geographical area and time span (Feb. 11-16 2004). This comparison shows that the model performs satisfactorily even though it produced temperatures higher during the heating hours. This over prediction could be explained by the use of a homogenous urban LCLU in the model, and therefore it is not capturing the different microclimates present in the metropolitan area and producing a more uniform temperature distribution throughout the area.

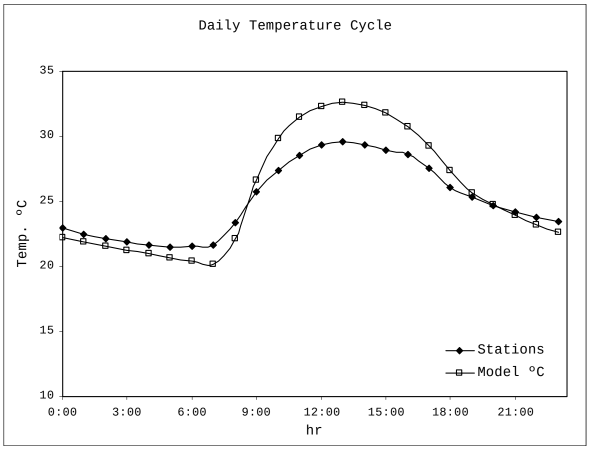

Figure 4 Comparison of the air temperatures between the regional model results and the stations and sensors deployed in the San Juan Metropolitan area.

The vertical profiles in Figures 5-7 show the comparison between the model results and the sounding data performed on the dates when the San Juan Atlas Mission flights took place, at the time of the closest NWS sounding launch. On every panel it is seen that the model follows the general pattern of the observations, especially in the case of the temperature vertical profiles. For the case of the wind speed variable, the model performs very well at mid to high altitudes, capturing the low level jet present at approximately 14.5 Km. Near the surface however (below 2 Km) the model, as noted before, follows the general trend of the sounding but is unable to capture fluctuations in wind speeds, this might be due to the relatively coarse resolution specified in the vertical coordinate (100 m for the lowest model layer), or the inability of RAMS to capture large eddies close to the urban boundary layer. Further studies should address this specific concern. However, it is clear that the thermal boundary responds to the LCLU parameterization specified here.

4.2 *Impact of LCLU changes on different climate variables*

To study the impact of the urban LCLU on the temperatures of the San Juan metropolitan area (SJMA), an analysis of the air temperatures at two meters above ground level (AGL) was performed with the results produced by the scenarios Urban and Natural. The analysis consists of calculating the difference of the values averaged during the period of greater heating, considered to be 3pm in this case, with the following operation: Urban-Natural. In order to visualize the effect of the slab of concrete that represents the city of San Juan on the wind pattern, a similar procedure was followed with the diurnal cycle of the marine/land breeze circulation.

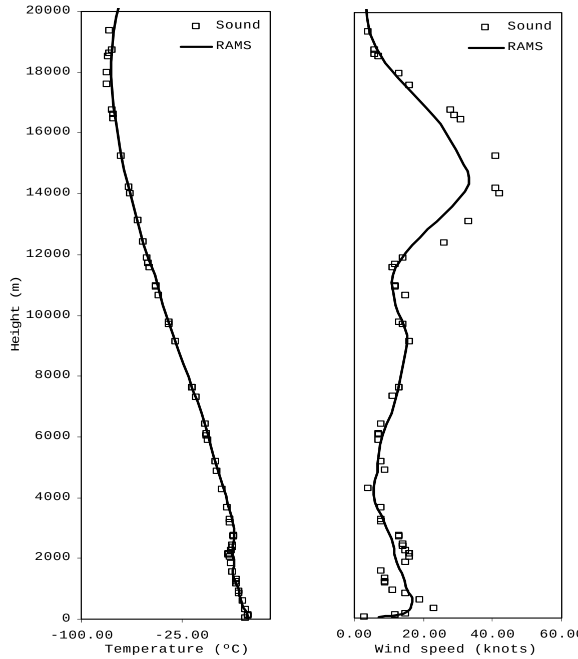

Figure 5 Simulated temperature (ºC) and wind (ms^{-1}) profiles (solid line) in comparison with the NWS balloon data (open squares) for Feb. 11 2004, 12 Z

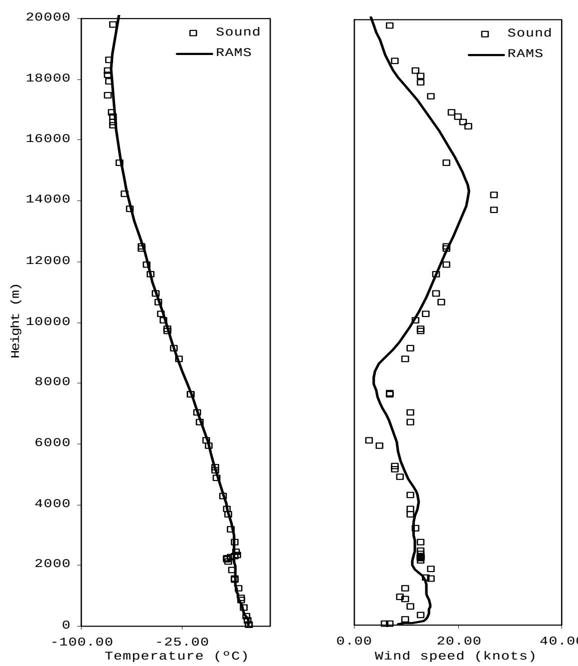

Figure 6 Same as Fig. 5, but for Feb. 14 2004, 00 Z

The results of the analysis of air temperatures averaged in mid afternoon through the complete period of simulation are shown in Figure 8 for the Urban-Natural case. Here it is shown that the atmospheric model predicts that the presence of San Juan has an impact in the low atmosphere of the area occupied by the city, this impact is reflected in higher temperatures for the simulations that have a specified urban LCLU in the bottom boundary. This temperature difference occurs, with positive values of up to 2.5ºC, mainly downwind of the city. The spatial pattern of the temperature differences on the zone represented by the SJMA can be explained by the presence of a sustained wind from the northeast direction during a great part of the afternoon (see Figure 9). The three simulations produced the same daily cycle for wind pattern, characterized by a strong influence of the northeasterly trade winds. Nevertheless, differential heating between the Atlantic Ocean and the north coast of Puerto Rico induced an inland circulation during the day, as can be observed in Figure 9, and a wind direction inversion at night. Both circulations showed a slanted pattern of approximately 45º due to the synoptic influence.

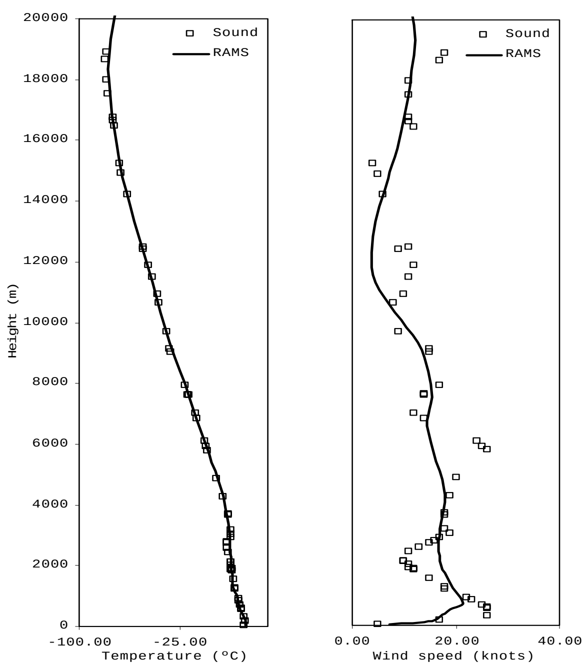

Figure 7 Same as Fig. 6, but for Feb. 16 2004, 12 Z

The impact of the presence of model grid cells that specify an urban LCLU is also significant. In Figure 10 it can be observed that the difference of the wind field between the two scenarios being analyzed lies essentially over the area covered by the city, and in the direction of the prevailing winds. The effect is that of accelerated wind reflected in an increment of the wind vectors, in the order of 3 ms^{-1}.

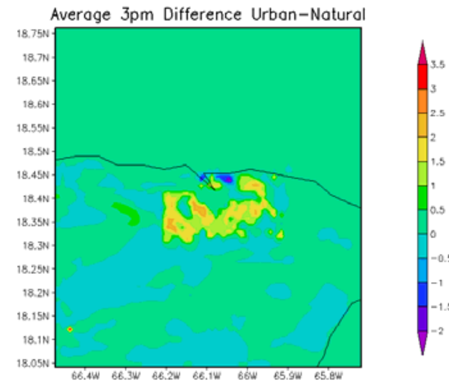

Figure 8 Spatial distribution of the air temperature difference (ºC) at 2m AGL between the Urban and Natural scenarios simulated for the analysis.

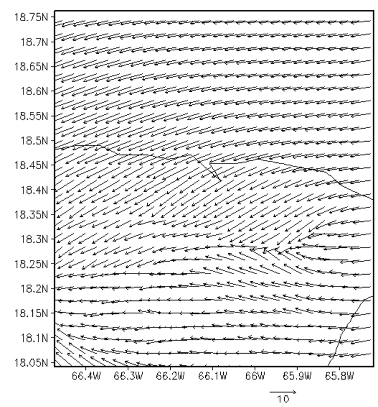

Figure 9 Wind field averaged at 3pm, local time, during the complete period of simulation of the Actual run

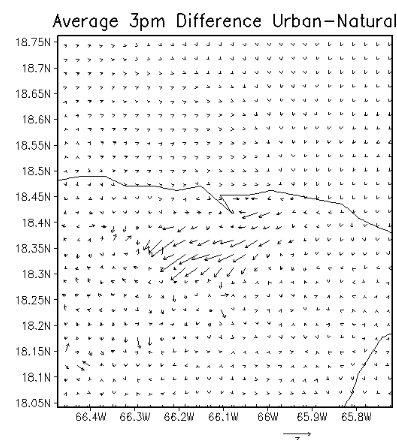

Figure 10 Average differences in the modeled wind fields calculated at 3pm.

Gonzalez et al (2005) reported that the SJMA UHI was affected by the occurrence of a short and weak precipitation event that station data showed to be localized in the city vicinities. In the present study it was interesting to find that the model was able to capture a small amount of accumulated precipitation just southwest of the city in the model run Urban (Figure 11, left panel). A comparison with the total accumulated precipitation produced with the simulation Natural showed that part of that precipitation was not present in this latter run (Figure 11, right panel). A simple qualitative comparison of the vertical wind fields simulated by the two runs presented in the analysis shows that the Urban run produced slightly more vigorous vertical motions just over the city than the Natural runs (Figure 12). The cross section are presented north to left (right to left in each panel) and covers roughly the area of the city to facilitate visualization, since further south there is a significant vertical activity due to orographic effects induced by the central mountains (see Figure 2). We believe that the vertical *w* velocity field is responding to the increased heating showed in Figure 8 and advection occurs due to the approaching northeasterly winds.

5. SUMMARY AND CONCLUSIONS

The work presented here is a comprehensive investigation of the impact of land use for urbanization in the environment for a city located in a small tropical island, in this case San Juan, Puerto Rico. The findings can be summarized as follows.

- The atmospheric numerical model RAMS was validated to capture the impact of the urban LCLU of San Juan on different atmospheric variables during the San Juan Atlas filed campaign (February 2004).
- The analysis of two simulated land use scenarios leads to the conclusion that the urban LCLU has an impact in the general atmospheric dynamics of the north coast of the island of Puerto Rico as shown by the changes in AGL temperature, sea breeze and vertical advection.
- Model results demonstrate that the influence of the city of San Juan in the local climate is to produce higher temperatures in the region where the urban area was represented. This influence could be quantified in air temperatures increases between 2.5 and 3ºC, and an acceleration of the winds in the area of study.
- A precipitation anomaly seems to arise from the presence of San Juan in the form of a small precipitation event, possibly advected by the approaching trades. It might be due to the combination of atmospheric warming and the enhanced vertical motion that the city generates.

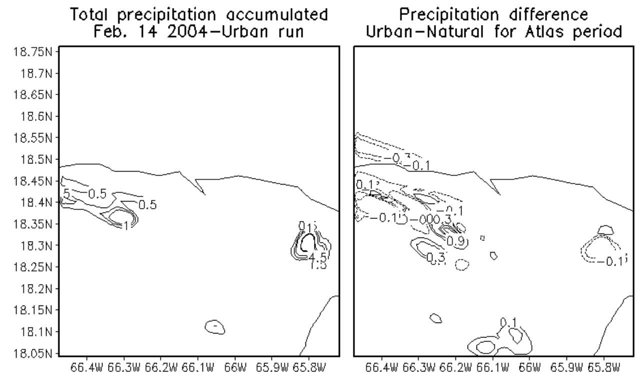

Figure 11 Total Accumulated precipitation for the Urban run for Feb. 14 (left panel, in mm) and precipitation difference between the model runs Urban-Natural.

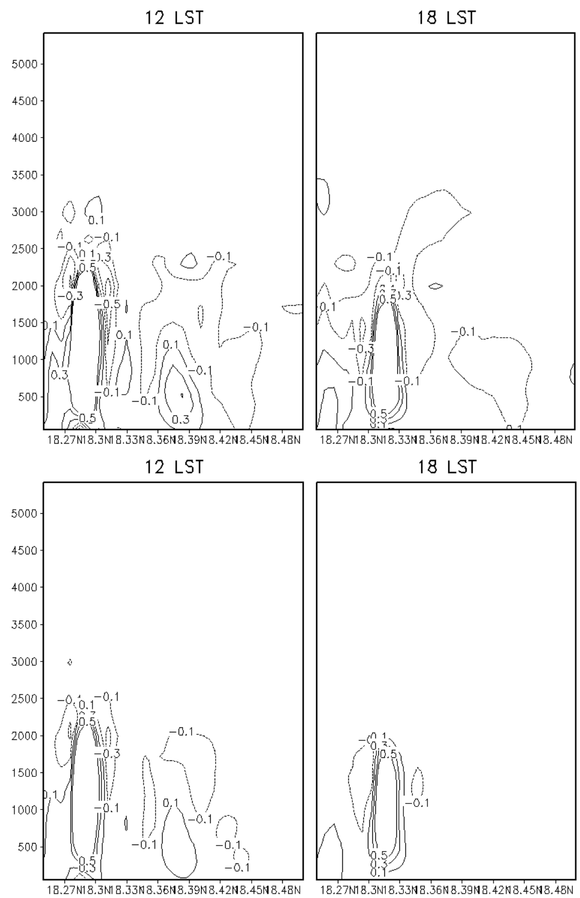

Figure 12 Simulated vertical motion fields (ms^{-1}) during Feb. 14 2004 at specified times, by the runs Urban (top panels) and Natural (bottom panels). Early morning hour panels were omitted because they provided much information since very little activity occurred.

6. ACKNOWLEDGEMENTS

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