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IMPACTS OF LOW LAND USE ON A TROPICAL MONTANE CLOUD FOREST UNDER A CHANGING COASTAL CLIMATE

Isaac Torres D.*
University of Puerto Rico. Mayagüez Campus. Department of Mechanical Engineering

Jorge E. Gonzalez
Santa Clara University. Departmet of Mechanical Engineering

Daniel Comarazamy
Santa Clara University. Departmet of Mechanical Engineering

Abstract

Tropical Montane Cloud Forest (TMCF) are a primary source of fresh water in tropical locations and are highly sensitive to climate changes. Climatological analysis for El Yunque Rain Forest, a TMCF, located in North Eastern of Puerto Rico, reflects changes in the regional meteorology reflected by increasing moisture content and surface air temperatures in certain regions. This TMCF is the main water resource of San Juan, surrounded by increasing urban sprawl in the lower elevations. These changes may have affected atmospheric and surface variables such as latent and sensible heat fluxes, surface albedo and surface roughness, and the overall energy budget within the forest. It is also hypothesized that increases in sea surface temperatures are also influencing the climate of the forest. The focus of the present research is to quantify the impacts of changes in land use close to coastal TMCFs, characterized by the case of El Yunque in the north-eastern coast of Puerto Rico during the dry season. A climatological and numerical analysis is presented. The research makes use of a high resolution visible imagery from the NASA ATLAS sensor to characterize the current land-use condition. Surface parameters such as albedo and land classes were introduced into a Mesoscale Model RAMS (Regional Atmospheric Modeling System). The atmospheric model was calibrated favorably against a high density network of surface temperature sensors located in and around the TMCF. The coupled and decoupled effects of land use and Green House Gases (GHG, represented by SSTs) is investigated in detail by organizing an ensemble of simulation runs that include reconstructed past land-use, present land use, reconstructed atmospheric variables and present climate. Results indicate significant impacts in surface temperatures due to increases of SSTs and cloud base, and reductions in cloud cover due to GHG effect.

Keywords: Dry Season, Land use, Puerto Rico, RAMS, Tropical Montane Cloud Forest

*Corresponding author address: Isaac Torres D., University of Puerto Rico. Mayagüez Campus, Department of Mechanical Ingeneering, P.O Box 9045 Mayagüez, P.R. 00681. 787-8324040 x3659; email:**itorres@me.uprm.edu**

1. INTRODUCTION

El Yunque Rains Forest, a Tropical Montane Cloud Forest (TMCF), located in North-eastern Puerto Rico, around 40 Km South-east of San Juan city (Puerto Rico), has a complex topography with a rapid elevation to around 1000 meters in less than 15 km. Because the physical models are limited to obtain accurate results in the mesoscale analysis (Pielke, 1984) for the complex topography and the variables immersed in the system such as the coriolis influence and the distribution of the water vapor in the atmosphere, without considering the presence of the CO_2 and another Green House Gases (GHG), so the computational modeling is the better choice to describe this complex system, which is highly influenced by the temporal and spatial boundary conditions of the system. The bottom boundary is very important in the atmospheric balance, because the most important terms of momentum, energy and mass from and to the atmosphere are transported in this interface; many specific variables such as: surface roughness, albedo, emissivity, etc, which are highly related with land-use are inmersed in this boundary. In the Intergovernmental Panel on Climate Change Four Assessment Report (IPCC, 2007), indicate that Global concentration of Carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities, and one of the causes that generate the increment of the carbon dioxide is due to land-use change, where the scale of influence of land-use is very low compared to GHG, but has an important effect in local areas. The global land-use produces a reduced effect than other influences in the global warming (IPCC, 2007); but in the tropics where the redistribution of heat to the poles start through the Hadlley Cell, land use has an important effect as part of the global climate change (VanderMolen, 2002) (VanderMolen et al., 2006), and on the local climate variables.

1.1 ***Puerto Rico and El Yunque***

Puerto Rico is located in the contour that limits the Atlantic Ocean and the Caribbean Sea, approximately between 18°- 18.5° N, and 65.30°- 67.25° W (around 177 Km long by 56 Km wide) (Briscoe, 1966). The island has a large area covered by mountains (figure 1) which have an influential role on the climate in both, mountains and surroundings areas, as the case of El Yunque Rain Forest (hereafter El Yunque), also known as Luquillo Experimental Forest (LEF), which is a protected area located in the north-eastern part of the Island with elevations from about 100 m to 1075 m above mean sea level (Briscoe, 1966). In this mountainous area four ecosystems can be clearly differentiated (Wu et al., 2006) Tabonuco Forest (<600m 70% LEF), Colorado Forest (>600m 17% LEF), Elfin Forest (>750m 2% LEF) and Palm Forest (11% LEF) in limited areas of all elevations.

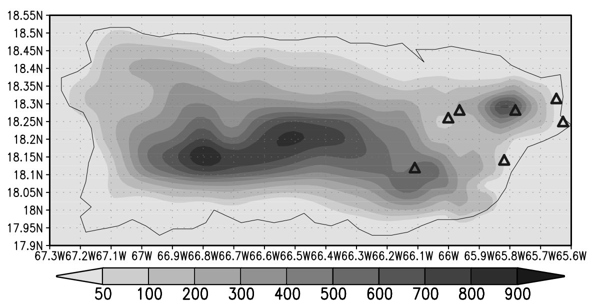


FIG. 1: Puerto Rico elevation map (meters).

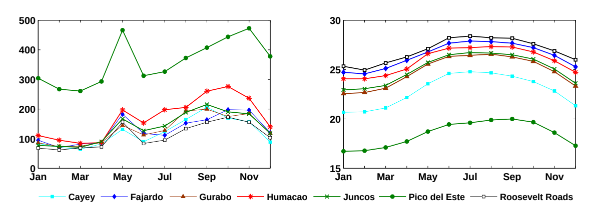


FIG. 2: Precipitation (left) and Temperature (right) Climatology of some stations of the eastern Puerto Rico (locations in Figure 1).

1.2 ***Climatology***

The Eastern part of Puerto Rico has a similar monthly accumulated precipitation and mean temperature climatology behaviour, as depicted in figure 2. Puerto Rico has a condition of a tropical rainforest climate (Kottek et al., 2006) (Peel et al., 2007); then has a warm and humid subtropical maritime climate (Scatena, 2006) with an increasing rainfall with elevation; where the mean air temperature in El Yunque has a lapse rate of 5.58℃ per kilometer increase in elevation (Melendez-Colom, 2004). It can be seen in figure 2 that there is a time interval in which the monthly accumulated precipitation is continuously less than other months of the year, and the mean temperatures are minimum during these months, Climatologically speaking this period is known as Dry Season (January to March).

1.3 ***Tropical Montane Cloud Forest***

A TMCF is defined as an area where the mountains are frequently enveloped by tradewind-derived orographic clouds and mist in combination with convective rainfall (Still et al., 1999). El Yunque, a TMCF, also is greatly influenced by different variables of its surroundings; for example the Sea Surface Temperature (SST) variability influences its climatologic variables (Waide et al., 2006); and Land use, with incresing urban areas. Quantifying the impact of both land use change and GHG, and the combined effect is the main focus of this research.

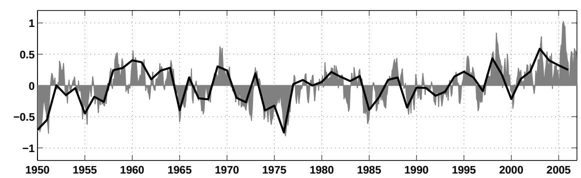


FIG. 3: Monthly SST anomaly around Puerto Rico, black line represents the mean value for the Dry Season.

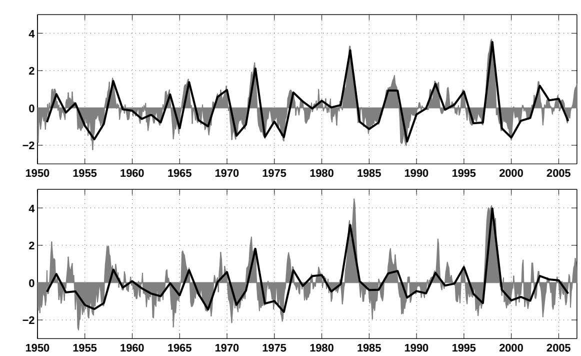


FIG. 4: Monthly ENSO anomaly Niño 3 (upper) and Niño 1+2 (bottom), black line represents the mean value between November and January months.

2. DRY SEASON

This section characterizes the climatology of the Dry Season in Puerto Rico Which is considered between January and March.

2.1 ***SST around Puerto Rico***

To characterize the Sea Surface Temperature (SST) around Puerto Rico the data corresponding to the Extended Reconstructed SST version 2 (Smith and Reynolds, 2003), (Smith and Reynolds, 2004) was selected, which has long term monthly data, starting in January 1854 with 2° grid resolution. Averaging grid data between 76° W - 56° W and 10° N - 26° N; was obtained. It represents monthly and average Dry Season SST anomaly value (figure 3) around the island since 1950. El Niño Southern Oscillation (ENSO) is a factor that affects the Atlantic Ocean and Caribbean Sea (Giannini et al., 2001), and appears two months later in warm events and one month later in cold events, based on ENSO 3 index (Chikamoto and Tanimoto, 2005). Figure 4 shows the monthly ENSO 3 and ENSO 1+2 anomalies during the same period of time. The black line represents the mean value for the months between November and January in consideration of the fact that it appears two months before (Chikamoto and Tanimoto, 2005) in the Pacific Ocean during the complete period of time. There is a clear correspondence between the ENSO and SST during the Dry Season.

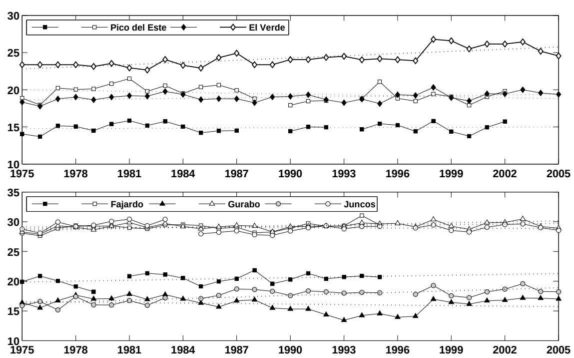


FIG. 5: Mean maximum and minimum temperature (℃) around El Yunque during Dry Season (Jan - Mar).

2.2 ***Temperature and Precipitation***

During the Dry Season, the average maximum and minimum temperatures in the surrounding areas of El Yunque (figure 5) show that in Pico del Este there is a decreasing tendency in the maximum temperatures and an increasing in the minimum temperatures, i.e. most uniform temperature conditions at this location; but in El Verde there is a significant (45the maximum temperatures. Data for Juncos show significant change (Table 1). Figure 6 shows the Dry Season accumulated precipitation with an

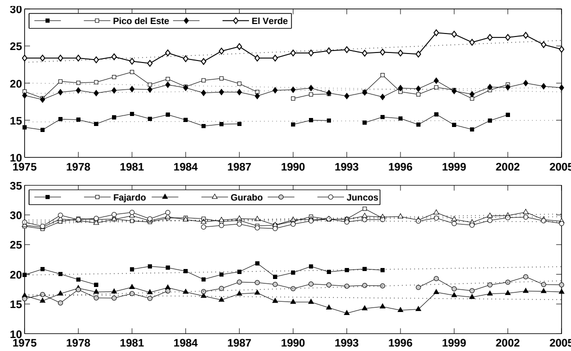


FIG. 6: Total Accumulated precipitation (mm) during Dry Season.

increasing tendency in El Yunque and a decreasing tendency in the eastern area. Table 1 summarises the information of stations with precipitation showing a more appreciable change than temperature during the Dry Season, particularly in the western area of EL Yunque (Gurabo and Juncos).

2.3 ***ATLAS Mission Campaign***

The ATLAS Mission Campaign was conducted during February of 2004 and consisted of an onboard remote sensor of 14 channels mostly in the infrared (González et al., 2005). Part of this mission covers the areas of El Yunque and SJMA, with a resolution of 10 meters. During this time period, a measured air field campaign around El Yunque, to obtain data profile (air temperature, dew temperature, relative humidity and absolute humidity) in the direction of the easterly trade winds took place. The locations of these stations are depicted in figure 7. The common total time interval of meassured data,

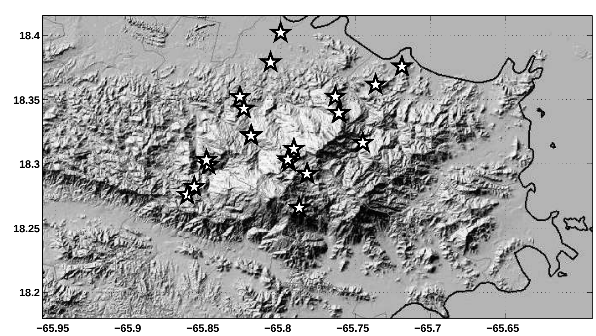


FIG. 7: Location of the HOBOS sensors data logger during ATLAS mission campaign.

for all HOBOS stations (24) was February 2004, with 5 minutes time step. The mean hourly pro-

Station	Max.Temp. Trend	p(%)
Pico del Este	-0.03995±0.90452	-
El Verde	0.09074±0.97820	45
R. Blanco Lower	-	-
Paraiso	-	-
Gurabo Sub.	0.03165±1.28036	-
Juncos	-0.00158±1.28040	-
Roosevelt R.	-	-
Fajardo	0.05947±2.22700	-
Station	Min.Temp. Trend	p(%)
Pico del Este	0.00986±0.4000	-
El Verde	0.02777±1.5645	-
R. Blanco Lower	-	-
Paraiso	-	-
Gurabo Sub.	-0.02168±0.1414	-
Juncos	0.0953±1.4258	45
Roosevelt R.	-	-
Fajardo	0.04883±1.2303	-
Station	Precip. Trend	p(%)
Pico del Este	4.34775±66.218	45
El Verde	6.74275±36.818	35
R. Blanco Lower	7.83765±42.312	40
Paraiso	3.4711±28.626	45
Gurabo Sub.	3.8702±13.9622	30
Juncos	4.37886±15.1500	30
Roosevelt R.	-1.05239±17.7756	-
Fajardo	0.08445±26.140	-

Table 1: Dry Season Maximum, Minimum and Precipitation Trends and Significance testing value.

file of the month, and mean average for the complete month was obtained (not shown). Because of the high number of stations in the analysis for each of the 4 variables measured, a field (three dimensional) interpolation was performed, resulting in a grid that enclosed the measured stations, i.e. El Yunque (figure 8). It was noticed that Absolute Humidity and Dew Temperature minimum values do not occur at the peaks. Additionally, the plots show that mean temperature on the area does not have a completely linear profile in the domain (Melendez-Colom, 2004), with a decreasing temperature with elevation, because there are some areas in which the mean minimum temperature is not at the mountain peaks. Consequently to the temperature variation in the peaks results in the maximum value of relative humidity (RH) surrounding the peaks, with a diminished RH value at the maximum altitudes.

2.4 *Urban Development - Land Use 2004*

The urban density per km^2 in the eastern part ofPuerto Rico (figure 9) was obtained from the the ATLAS imagery, with 10 meters resolution and

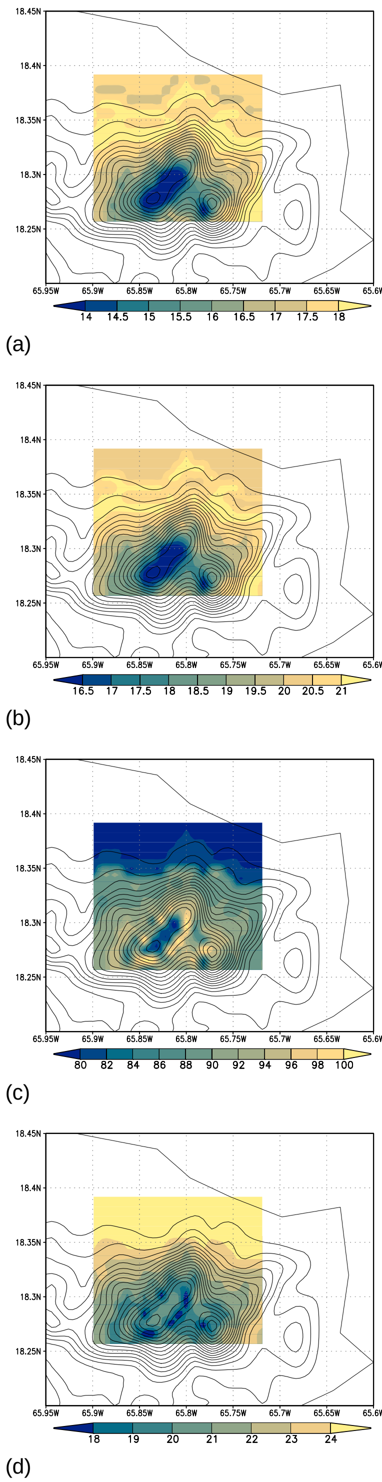


FIG. 8: Mean February 2004 HOBOS sensors data field interpolation around El Yunque. (a) Absolute Humidity (g/m^3); (b) Dew Temperature (℃); (c) Relative Humidity (%); (d) Temperature (℃).

presents similar visual pattern to other research projects (Martinuzzi et al., 2007). There are urban areas around El Yunque mountain area, including the close position of the SJMA in the north western area, and Caguas in the eastern zone.

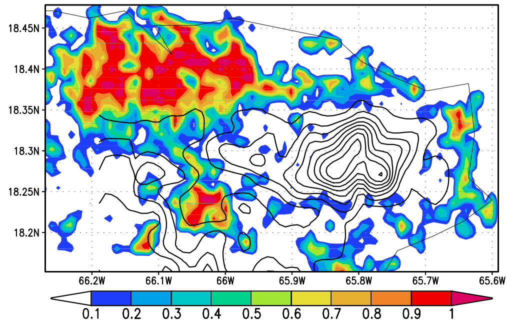
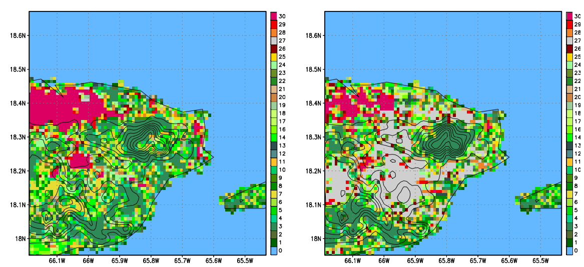


FIG. 9: ATLAS imagery - Urban density per 1km^2 (February 2004).



(a) (b)

FIG. 10: (a) Present Land use configuration - February 2004; and (b) Past Land use configuration (1977-1978).

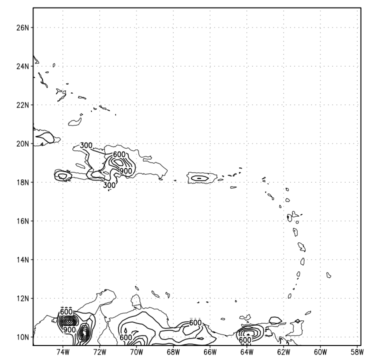
3. MODEL CONFIGURATION

3.1 *Regional Atmospheric Modeling System - RAMS*

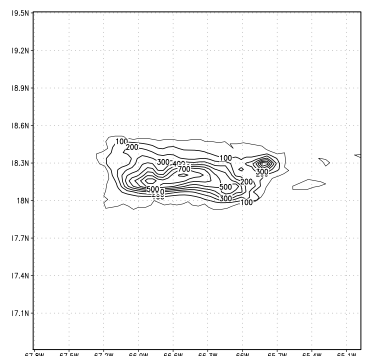
The Regional Atmospheric Modeling System (RAMS), was developed by Colorado State University, its version 4.3 was used during this research (Pielke et al., 1992). RAMS presents different capabilities and configuration characteristics for different simulation assessments, such as high resolution cloud scale grids (Walko and Tremback, 2003), synoptic climate patterns (Malaspina, 2005), and hemispheric scales. RAMS solves numerically the complete set of momentum equations, mass conservation, heat equation and water species (mixing ratio) continuity equation (ATMET, 2003). These present simulations use 3 nested grids of analysis, consisting of a coarse parent grid of 100 km horizontal resolution with an extension of 2000 km

Index	Land-Use	GHG
C1	Present	Present
C2	Present	Past
C3	Past	Present
C4	Past	Past

Table 2: RAMS configurations used to analyze the Land-Use and GHG effects.



(a)



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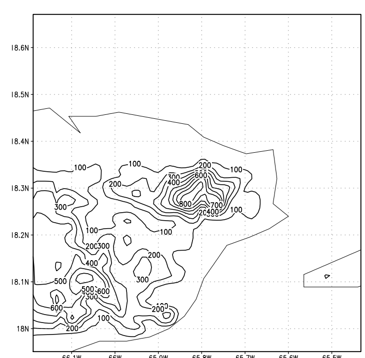


(c)

FIG. 11: Topography of the three grids used in RAMS. (a) Parent Grid. (b) Second Grid. (c) Finer Grid.

x 2000 km enclosing the Caribbean region (Figure 11(a)), the second grid has 5 km resolution and an extension of 310 km x 310 km, enclosing Puerto Rico island (Figure 11(b)), and the finer nested grid with 1 km resolution covering the eastern part of the island, centered on El Yunque mountain area and enclosing its surroundings (Figure 11(c)). The model was configured with terrain following high resoltion vertical levels, with grid spacing stretched at a constant ratio of 1.1 until 1000 meters maximum. The soil moisture and temperature initial condition profiles were considered uniform in the complete non water domain. The models were initialized with 17 pressure levels atmospheric variables with 2.5° resolution of National Center of Environmental Prediction (NCEP) Reanalysis data. Reynolds-Smith Extended Reconstructed SST (ERSST) with 2.5° resolution was used for the model. Each configuration was considered a complete month for the simulation time, similar to February 2004, to capture total atmospheric monthly interaction.

To analyze and quantify the individual Land Use effects in the area, it is necessary to remove the GHG effects in the analysis system. The same can be done in reverse, that is analyze and quantify the GHG effects by removing the Land Use effects. The Land Use and GHG individual influences can then be measured in the varaiables such as air temperatures, cloud cover, precipitation and cloud base for the present and past conditions as shown in Table 2. C1-C2 presents the individual influence of GHG, under a constant Land-Use configuration; C1-C3 shows the local Land-Use influence; C1-C4 presents the total change produced in the area by the combined effects.

3.2 *Average February Past Conditions*

To remove the ENSO effect on the Caribbean and to quantify the influence of GHG during Dry Season, the average ENSO 3 index (figure 4) from November to January during 8 years was taken as a reference (Average past conditions). The ENSO 3 index difference between 2004 Dry Season and the average past conditions was 0.05. A reference to the Febraury synoptic and SST conditions was obtained by selecting the second month of these average past conditions, which represents the GHG past conditions (Table 2). Figure 12, clearly shows the increase SST in the Caribbean, that is reflected in the increasing air temperature tendency (figure 13) and relative humidity (figure 13(b)) in the lower atmosphere (1000 mb and 700 mb). In the opposite way, shows a reduction in temperature and relative humidity in the higher atmosphere (300 mb), as shown in Figure 14. The average February includes Land Use type classification (1977-1978) of Puerto Rico (Helmer, 2004) (Kennaway and Helmer, 2007),representing deforested and agriculture areas in eastern Puerto Rico around El Yunque, with less urban development than at present (figure 10(b)).

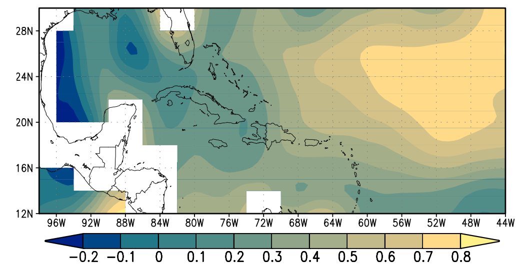
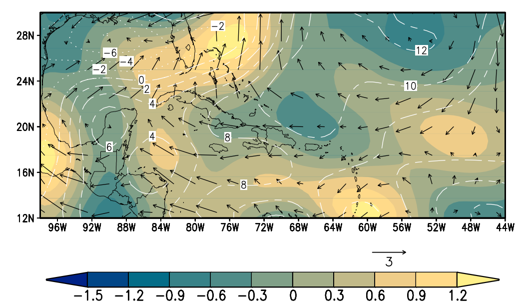
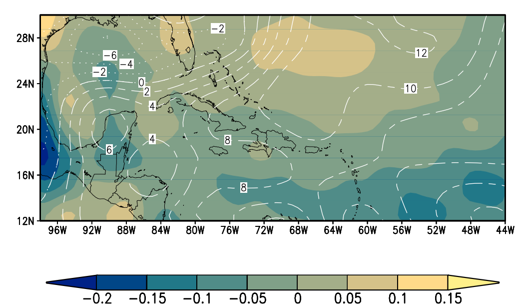


FIG. 12: SST difference between February 2004 and Average February past conditions.

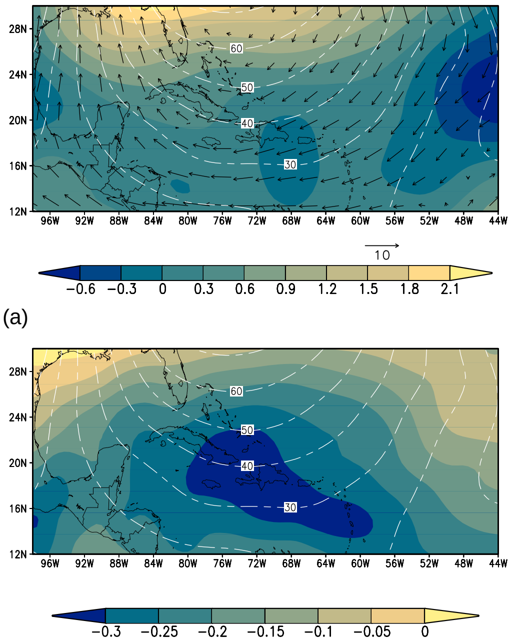


(a)



(b)

FIG. 13: NCEP - 1000 mb difference between average conditions during February 2004 and average February past condiions, (a) air temperature (℃) and vector difference(m/s); (b) relative humidity (%). White contour represent the Geopotential Heigh.



(a)

(b)

FIG. 14: Same as figure 13, but for 300 mb.

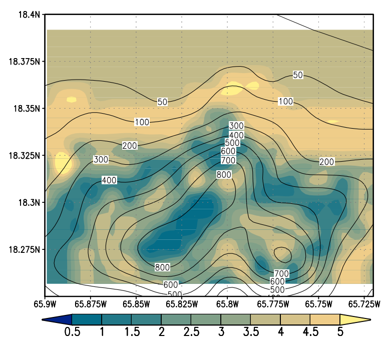


FIG. 15: Confidence interval (±) of HOBOS air temperature measured data, February 2004.

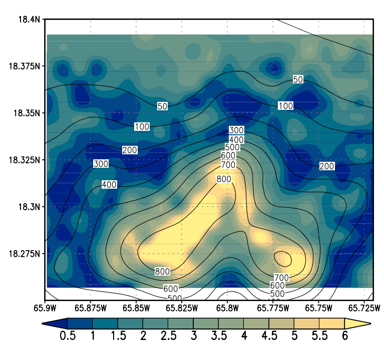


FIG. 16: Absolute diference between month average 2 meter air temperature RAMS simulated and month average HOBOS air temperature data, February 2004.

4. SIMULATION RESULTS

4.1 *Model Calibration*

To calibrate the model air temperature measured during February 2004 in the ATLAS mission was used. The network HOBOS stations shown in figure 7 and their average field interpolation (figure 8(d)); were compared with air temperature 2 meters above the surface, that was also an output field variable from RAMS. Figure 15 depicts the field confidence interval of the measured temperature data in the El Yunque area, obtained from the HOBOS network stations data interpolation in a 20 km by 15 km grid (1 km resolution), with the nodes located at the same location of third grid nodes from RAMS; this plot shows less variability of the measured data above 800 meters. The maximum variability is shown in the low land areas between the sea level and 200 meters above; between 500 and 700 meters there is an increasing data variability than its surrounding with lower values. The maximum values are presented in the coast and minimum at the peaks, but reduction is not linear. Figure 16 shows the absolute difference value between the monthly average 2 meters air temperature calculated by RAMS and the monthly average HOBOS temperature measured data during February 2004. The accuracy is good for the most part of the grid with a maximum difference between 2 and 2.5℃. However, above the 700 there is a rapid increase in the absolute difference, getting a maximum value of 6℃ in the peak of el Yunque, above the 800 meters, the simulation shows lower values than reported by the measured data with greater values and less variability in this area.

4.2 *February 2004*

From C1 configuration to RAMS (Table 2), were calculated the monthly accumulated precipiation (figure 17(a)), month average air temperature 2 meter above the surface (figure 17(b)), month average cloud cover (figure 18(a)), and month average cloud base high (figure 18(b)). The total accumulated precipitation in the RAMS simulation for February 2004, shows clearly orographic tendency on El Yunque area and variability in the surrounding (windward and leeward) areas. In the same way the simulated monthly average air temperature, 2 meters above the surface, shows the orographic effect. The monthly average cloud base simulated for February 2004, expressed in meters above the surface; (considering the topography) shows an average cloud base between 800-1000 meters above

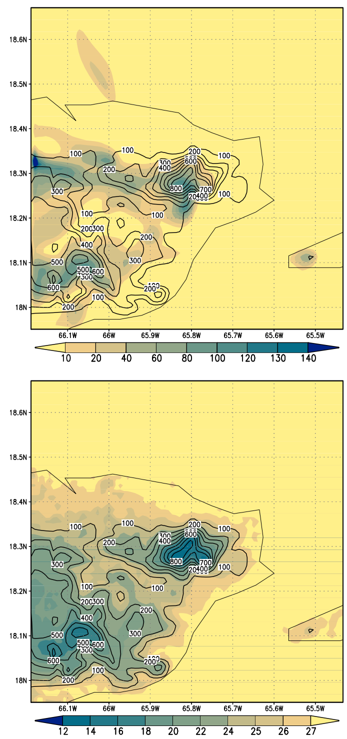


FIG. 17: Third grid, C1 RAMS simulation. (up) Total precipitation (mm); and (down) Air temperature (℃).

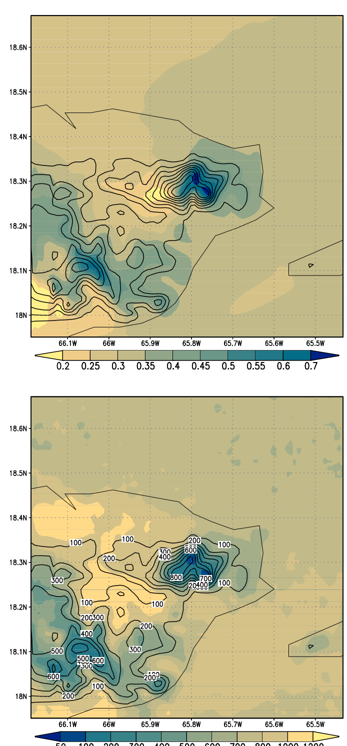


FIG. 18: Third grid, C1 RAMS simulation. (up) Cloud cover (%); and (down) Cloud base (m).

the mean sea level. The average cloud base is minimum in both, El Yunque area and its eastern (windward) area. The average cloud cover maximum values are on the windward areas of El Yunque by the orographic effect, which generates low cloud base. This matches with the low probability cloud cover on El Yunque during Dry Season, low probabilities during day hours and high values during night hours in February (Wu et al., 2006). On the leeward areas of El Yunque there are low average cloud cover values with a clear increase of the cloud base by the leeward wind convergence and vertical wind gradient. On the SJMA there are low average cloud cover values, because of a high average cloud base as a consequence of the convective nature of the UHI effect (Gonzalez et al., 2006) (Velazquez-Lozada et al., 2006).

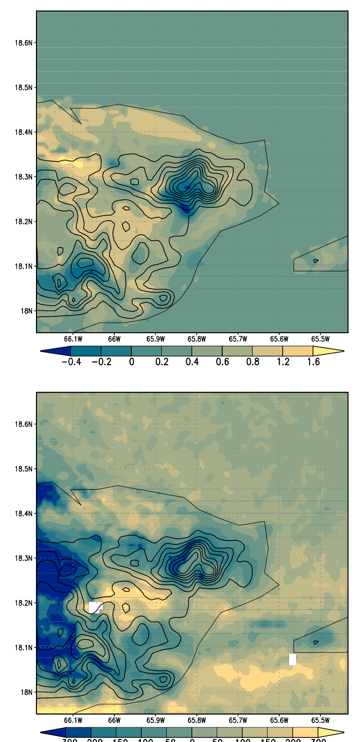


FIG. 19: Third grid, C1-C2 RAMS simulation. (up) 2m Air Temperature (℃); and (down) Cloud base (m).

4.3 *GHG effect*

RAMS simulation difference C1-C2 (Table 2), present a clearly concentrated reduction of 2m air temperature (figure 19(a)) on the leeward mountain area of El Yunque, getting a minimum value of -0.4℃; but on the winward side there are hotter areas. There is a maximum temperature difference greater than of 1.6℃ South of the SJMA.

The coastal areas have differences between 0.4 and 1.0℃. El Yunque has a cloud base reduction between 200-300 meters as a result of the GHG influences on the north-western hills; the opposite effect is produced around Gurabo and Juncos, with higher clouds.

5. PRELIMINARY CONCLUSIONS

The increasing SSTs are causing increasing air temperatures in the Coastal areas of Puerto Rico and higher humidity content in the higher pressures leves of the atmopshere. The warmer and more humidity air is transported through north-easterly trade winds to Puerto Rico, generating low formation of clouds (reduced cloud base) in the windward areas of El Yunque. El Yunque is more sensitive to the changes in the SST than the coastal regions in Puerto Rico.

6. FUTURE WORKS

Include the analyze of the Land use change impact, and the combined effects of GHG and Land use change, in the eastern Puerto Rico.

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