Satellite Detection and Numerical Simulations of the Urban Heat Island over Mexico City

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Background

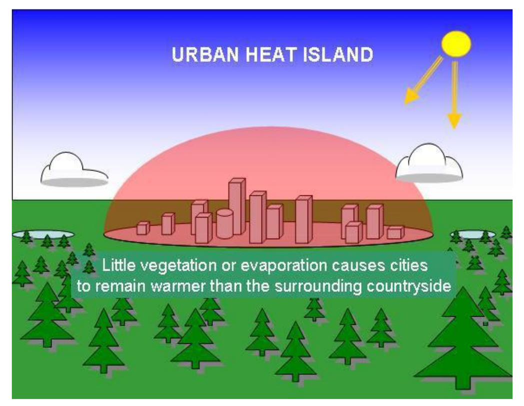
1. What is Urban Heat Island(UHI)?

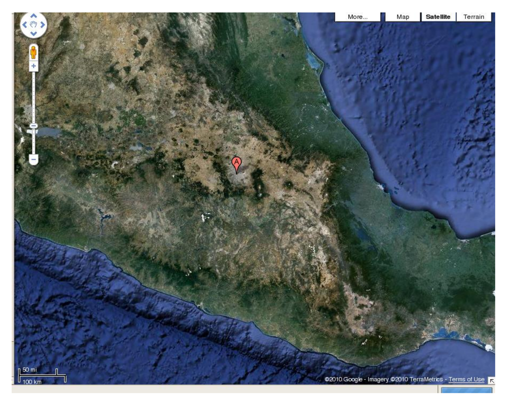
It is a metropolitan area which is significantly warmer than its surrounding rural area and is defined by the surface isotherms, which look like the topography around an island. It plays an important role in local meteorology and even influences urban citizens' health.

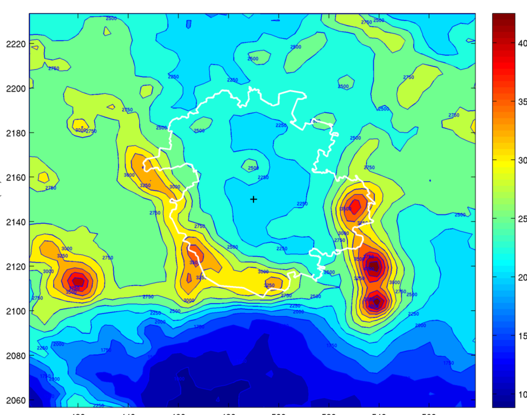
2. Mexico City Metropolitan Area (MCMA)

Mexico City is the largest metropolitan area in North America with a population of ~20 million, which situated inside a basin at 2240 m altitude and 19° N latitude, The basin is surrounded by high mountains on three sides.

The Mexico City basin meteorology is usually classified into three seasons: (1) cold dry season (Nov-Feb);(2)warm dry season(Mar-Apr); (3) rainy season(May-Oct). This classification is due to the two basic patterns on the synoptic scale: dry, westerly flow from November to April with anticyclonic conditions, and moist easterly flows due to the weaker trade winds for the other half of the year (B. de Foy et al. 2005).







Methodology

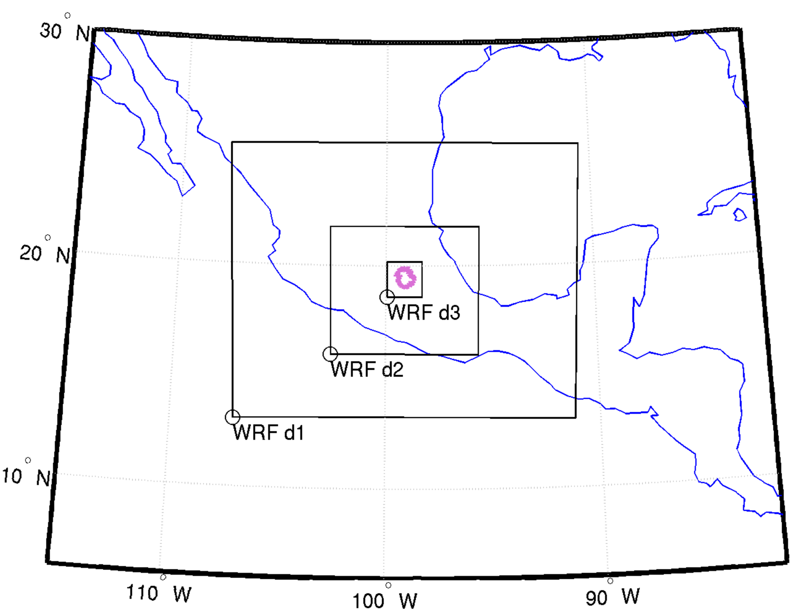
Nowadays, combining remote sensing and atmospheric model is a popular concern point on analyzing Urban Heat Island(UHI), because of the limitation of on-site human observation, while people hope can explore more spatial and temporal characteristics of UHI, such as UHI annual variation, focus on a specific location, etc. Paper uses MODIS level-3 land products and WRF model to research the Mexico City UHI.

The Moderate Resolution Imaging Spectroradiometer (MODIS) belongs to the NASA international Earth Observing System, and it launches two satellites (Terra and Aqua) to provide information for global studies of atmosphere, land and ocean processes. The strengths of the MODIS instrument include its global coverage, high radiometric resolution and dynamic ranges, and accurate calibration in visible, near-infrared and thermal infrared bands(Wan et al. 2004).

The WRF model is one of the most widely used numerical weather prediction (NWP) and atmospheric simulation systems. The model with a flexible, modular and portable code design is used to improve weather forecast quality and analyze meteorological features.

As weather simulation, there are some sources of error, for instance, in order to digest the atmospheric nonlinear systems into the model, we have to set some conditions to try to close those functions, to some extent, which break the perfectibility. And another one is the initial conditions chosen. Model needs to input the initial data, which is very important but usually we cannot avoid initial error, so nudging more correct and new initial data to model is a useful way to improve the prediction ability.

The UHI simulations need initial environmental condition and meteorological condition. The initial and boundary meteorological conditions in this paper are taken from the Global Forecast System(GFS) at a three-hour resolution. While respect to the initial geographical conditions, although WRF itself offers some default tabular geo-grid initial condition, in this paper, we ingest MODIS land observations (the MODIS 2004 land cover type data, the MODIS albedo data, the MODIS land surface temperature and emissivity data, and the MODIS global vegetation index data) to specify the land use, vegetation fraction, albedo, emissivity and land (soil) temperature in the WRF model inputs. MODIS products are derived on a sinusoidal projection with 1-km resolution. We made comparisons between the base cases and the modified cases, and the results show the nudge improves the UHI simulation.



In this paper, we use the ARW-WRF version3.2 (newest version released in April 2nd) with three nested domains (shown above) and one-way nesting. The nested domains increase resolution for each progressively smaller domain (36km, 12km and 3km, respectively).

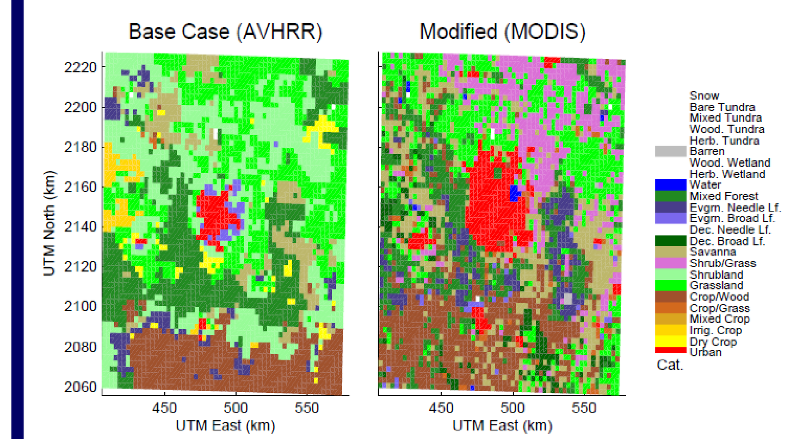
March, July and December are chosen as the representatives of warm-day season, rainy season, and cold-dry season, meanwhile, because some MODIS data is several day average data, corresponding to these satellite specific data period of 2006 year, the GFS data are chosen, in other work the periods of simulation cases are : 14(1200UTC)--20(0600UTC), March; 14(1200UTC)--20(0600UTC), July; 14(1200UTC)--20(0600UTC), December. In the model, each case, the first 32-hour is the model spin-up, and the simulation effect time is 96-hour.

Under the NOAH land surface scheme, we test urban canopy models(UCM). In the physical parameterization process, we set the sf_urban_physics equal 0 (no urban model), 1(single layer UCM). And the corresponding other WRF physical parameterization options are shown in Table (shown below), according to the prior model testing, de Foy and others already found these options were best choice for MCMA on the boundary layer scheme and the convective parameterizations, which are important factors for UHI research.

Physics	Scheme Name
Microphysics	WRF single-moment 6-class scheme (WSM-6)
Cumulus Parameterization	Kain-Fritsch scheme
Surface Layer	Monin-Obukhov scheme
Land-surface Model	Noah LSM/Single-layer Urban Canopy Model
Planetary Boundary Layer	Yonsei University (YSU) PBL
Atmospheric Radiation	Rapid Radiative Transfer Model (RRTM) Longwave Goddard Shortwave

Summary

1. High-resolution satellite observations show that the Urban Heat Island Intensity over Mexico City depends on the time of day and the time of year. At night, there is a heat island throughout the year that is strongest during the dry seasons and declines to a minimum in the wet season. During the day, there is a heat island during the wet season but a cool island during the dry season.
2. There is a larger contrast of vegetation cover between the urban core and the surrounding rural areas during the wet season which is one of the factors explaining the occurrence of the daytime UHI at that season.
3. After Modification of WRF land parameters using MODIS data, the WRF results capture the Mexico surface temperature more effectively, which will improve the next step to simulate UHI daily evolution study.
4. Using the Noah land scheme, we test whether the WRF single-layer urban canopy model have an effect for MCMA UHI. The simulations show that the urban model does not have a clear effect for MCMA UHI and will require further work.



Base case is 1992 MCMA (WRF model default use)
Modified case is 2004 MCMA (we nudge this data to WRF for our cases).
The growth of the MCMA in the 12 year gap can be clearly seen.

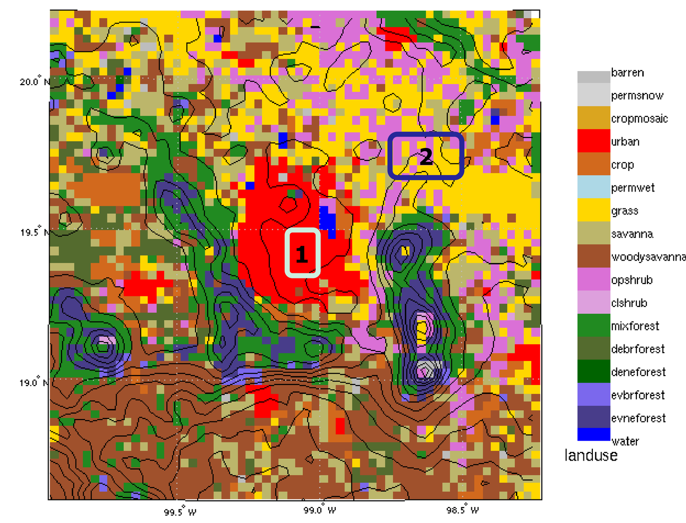
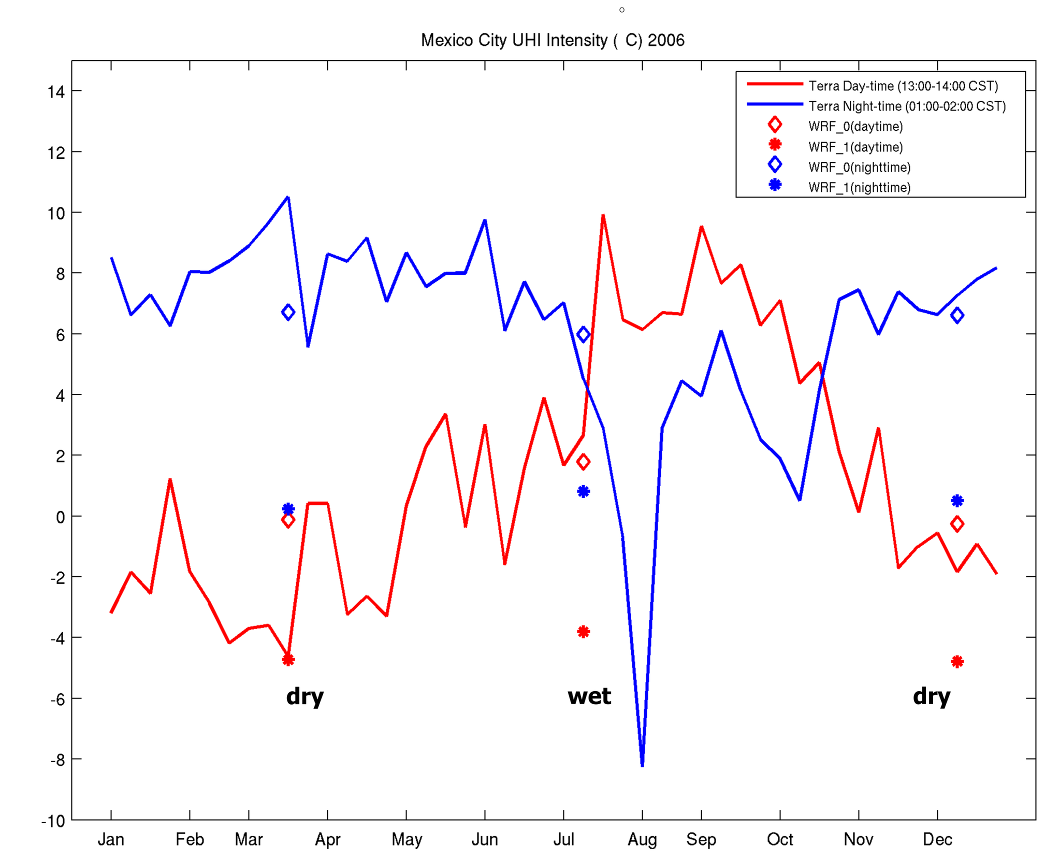
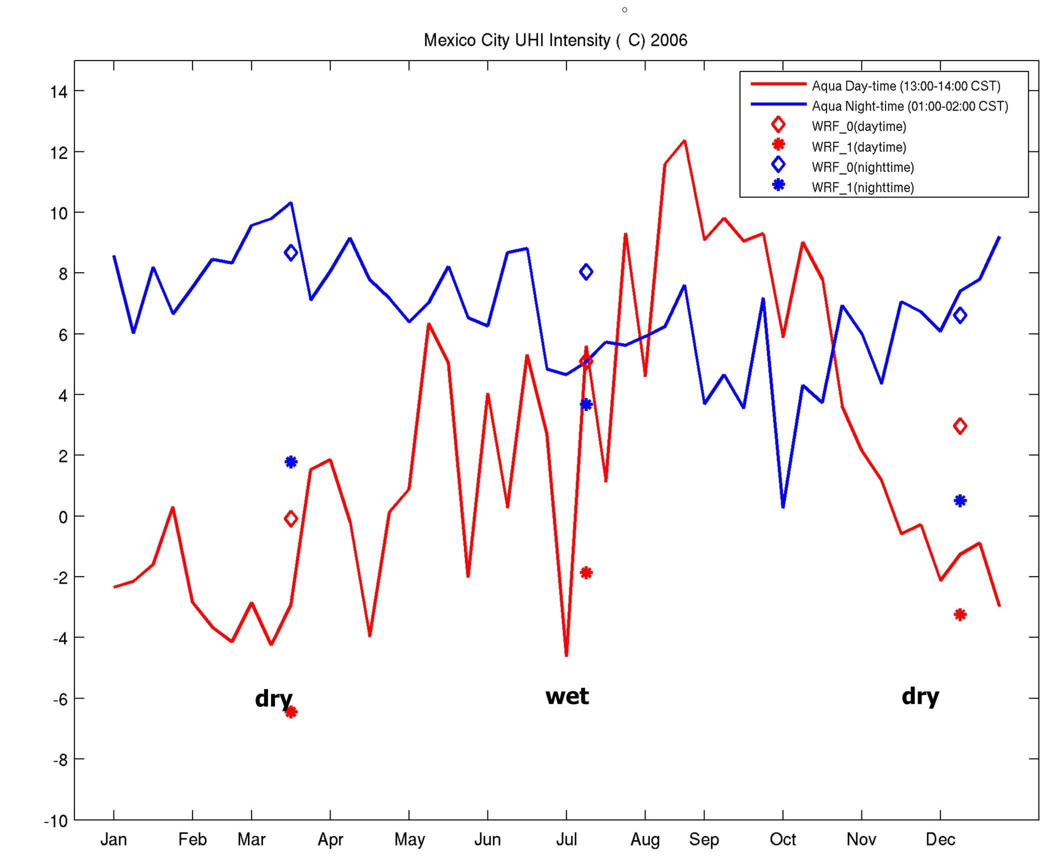


Figure on the left is MODIS Land-use Categories of the Mexico City region, using the IGBP classification scheme.

1. Urban Core domain:
   19.33° N ~19.5° N ; -99.19° W~ -99.02° W
2. Rural domain:
   19.6° N~19.8° N; -98.7° W~-98.5° W

Results





We execute Urban Core surface temperature subtract Rural Domain 's as Urban Heat Island Intensity. Figures (shown on the left) display the seasonal change of UHI intensity ,2006(We also analyze the years of 2007,2008 and they have the similar patterns). We separate daytime and nighttime to discuss.

The time of the satellites Terra and Aqua fly over the Mexico city as below, so we can get the UHI seasonal change in the morning, afternoon, evening, and small hours.

Terra daytime: 10:00-11:00 (CST); nighttime:22:00-23:00(CST)
Aqua daytime: 13:00-14:00 (CST); nighttime:01:00-02:00(CST)

Dry season:

In the daytime, Urban surfaces act as a giant reservoir of heat energy, however, warming also has the effect of generating convective winds within the urban boundary layer. The atmospheric mixing results in the air temperature of the UHI being too low or nonexistent during the day. In the nighttime, absence of solar heating, however Urban buildings (geometry, sky view factor)trap the warm urban air near the surface, and Urban and Rural surface have different thermal properties. (Oke et al. 1991)

The UHI Intensity even occur negative value (Cool Heat Island) in the daytime. For example, urban water use which leads to more latent heat flux in the urban area during the dry season. The vegetation cover impacts over the two domains have less difference in the dry time(details see below). Less solar radiation impact which is not beneficial for the pollutant (aerosol) chemical reaction and maintenance; meanwhile less energy effort to UHI form. Different from other big cities such as New York city, The geographic location of Mexico City determines the residents do not need much heat installation.

Rainy season:

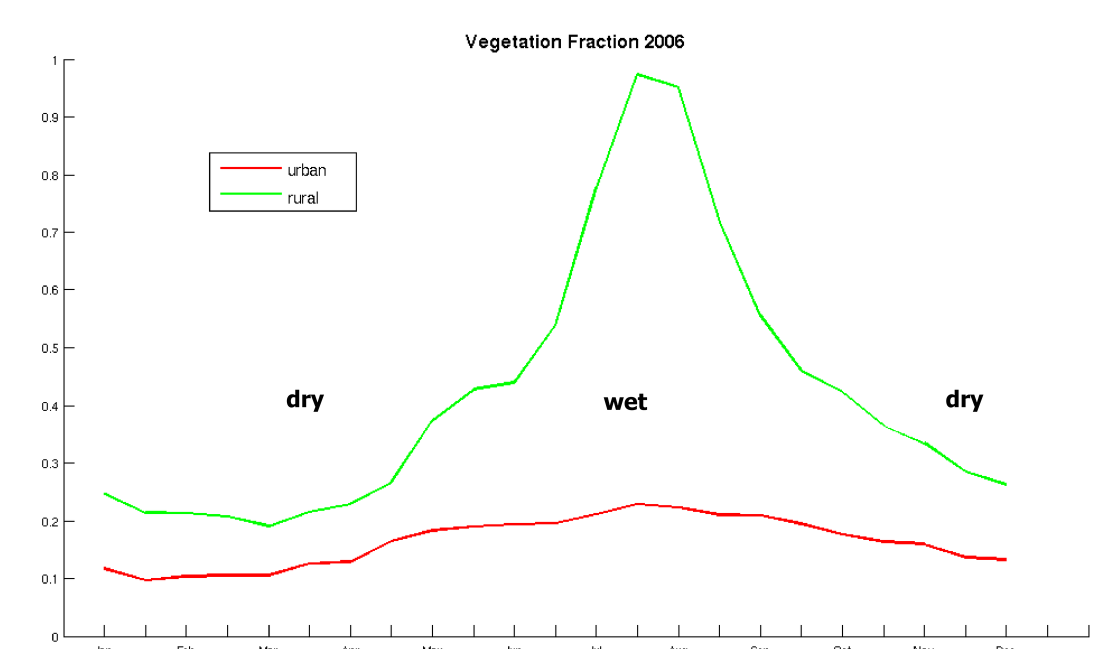
Figures illustrate the trend of UHI intensity between daytime and nighttime are opposite in the rainy season. In the wet time, when the soil in the rural region is near saturation, the nocturnal heat island decline to a minimum (Eunesto Jauregui ,1997). Daytime Urban Heat Island trend increases and even exists peak value of whole year.

For UHI intensity stimulation, we test WRF without urban canopy model (WRF_0) and with the single layer urban canopy model (WRF_1). The results shown on the left base on three representative months. The diamond points are default no urban canopy model, just simple urban parameterization(commonly used slab models in meteorological models). The star points are coupled with single-layer UCM.

For the urban canopy model, the designers consider the energy and momentum exchange between the urban surface and the atmosphere, some detail factors include the influence of street canyons, shadowing from buildings and reflection of radiation, anthropogenic heating, and multi-layer heat transfer equation for roof, building wall and road surfaces (Kusaka et al. 2001). This urban model represents more realistic geometry of the urban region and already be tested over the urban regions of Houston, Salt Lake City, Tokyo and Beijing, etc. However, it's rarely tested in low-altitude, relatively less metropolitan region, such as Mexico City.

The stimulations show us that the complicated single-layer urban canopy model does not capture the MCMA UHI quite well, we analyze because the less intensity and less height urban geometry of MCMA, the special urban construction materials (Mexico City more stone buildings), and the special low-altitude geographical location with different solar azimuth angle and sunlight time, etc. So, like these sophisticated urban models still have improvement potential.

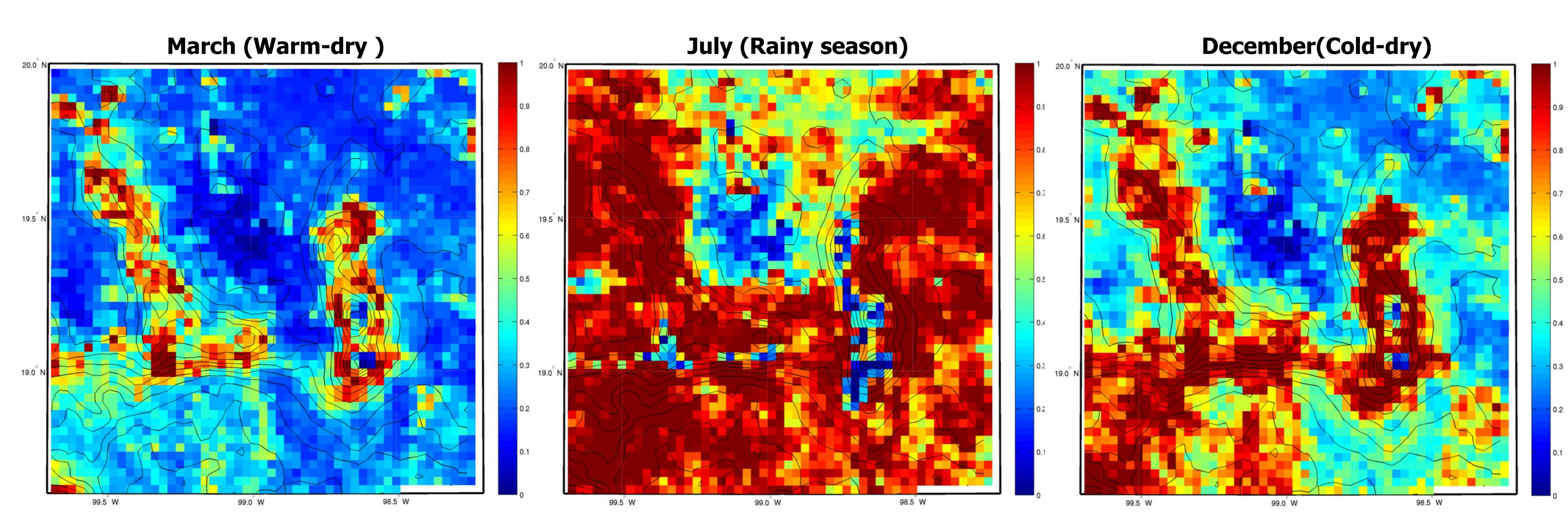
Note, because the chosen urban core average height is less 340 meters than the chosen rural region, once offset the elevation factor, the MCMA UHI intensities which are observed by MODIS will decrease, to some extent. So the cool urban island phenomena will decrease.



In this work, we derive vegetation fraction from MODIS Normalized Difference Vegetation Index (NDVI) using the method of Gutman and Ignatov (1998).

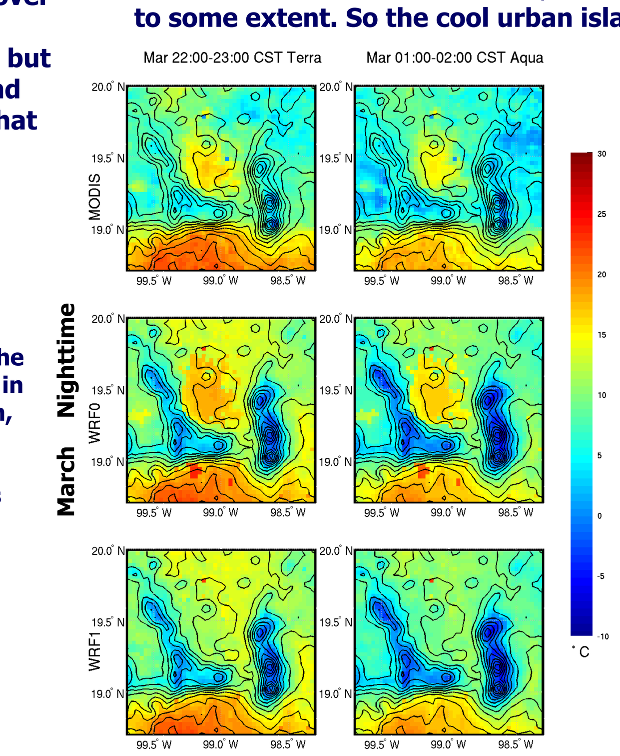
Vegetation factor plays a important role on UHI. Satellite data (shown on the left) show us the different vegetation fraction between urban core and urban region over MCMA. The vegetation fraction seasonal change is one of the important reasons for MCMA daytime UHI seasonal change. In the wet season, the much more different vegetation fraction between urban and rural goes with the quite strong daytime UHI intensity, the intense vegetation density over rural area keep cool, while bare urban area exists high temperature. So such as New York case, improving the vegetation ratio over urban area is a benefit and efficient way for decreasing urban high temperature phenomenon.

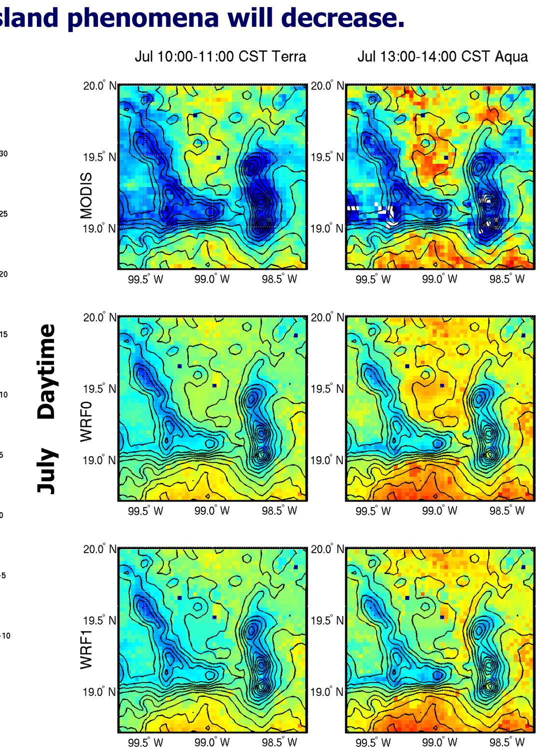
For nighttime UHI, the surface material thermodynamic difference over urban and rural is a important factor. In the dry season, the concrete urban road and dry soil rural field do not have obvious different effect, but in the wet season, the rural moisture soil thermal capacity increase and keep more heat in the daytime and release more in the nighttime, so that the nighttime UHI intensity decrease in the rainy time.



Figures (shown on the left) display the vegetation fraction spatial distribution in the three representative months (March, July and December).

Obviously, in the wet season, there is large contrast of vegetation fraction between urban and rural.





Figures (shown on the left) display the MCMA surface temperature spatial patterns (we plot three representative months, daytime and nighttime , here, just shown two of them) . The first row shows the MODIS Satellites(Terra and Aqua) observation results.

The rest of rows present The WRF prediction results. The second ones are default stimulation, just simply urban parameterization without urban model. The third ones are coupled with single-layer urban canopy model (WRF/Noah/UCM).