P2.3 URBAN MODIFICATIONS IN A MESOSCALE METEOROLOGICAL MODEL AND THE EFFECTS ON SURFACE ENERGETICS IN AN ARID METROPOLITAN REGION

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1. Introduction

Mesoscale atmospheric models are increasingly employed to improve the understanding of processes related to neighborhood scale climate and air quality, the urban heat island and mesoscale circulations caused by urban–rural land cover differences. Those processes are strongly influenced by the energy and momentum exchange between the atmosphere and the underlying surface and hence depend on characterizing the urban and rural land cover accurately. Furthermore, other urban characteristics such as increased surface roughness, modifications to the radiation balance, heat storage and anthropogenic sources of heat contribute to the energy and momentum budgets in the urban area.

In this study, the fifth-generation Pennsylvania State University and National Center for Atmospheric Research (PSU/NCAR) Mesoscale Meteorological Model (MM5) was applied to the Phoenix (Arizona, USA) metropolitan area in order to investigate the influence of land cover changes and urban modifications to the surface energetics on the simulated near surface temperatures and the evolution of the planetary boundary layer (PBL).

The Phoenix metropolitan area consists of an urban/suburban core, surrounded by irrigated agricultural land that in turn is embedded in a dry, sparsely vegetated natural desert to the east, south and west and elevated terrain to the east and north. Phoenix is the second fastest growing major city in the USA, which leads to an ongoing conversion of agricultural and desert to urban land use.

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A new land cover classification and updated land cover data for the Phoenix metropolitan area were introduced into MM5. The physical processes in the urban land cover categories were modified by introducing a sky view factor and a diurnally varying anthropogenic heat flux in the surface long-wave radiation balance of MM5's slab land surface model (Dudhia 1996) and the tendency term of the potential temperature at the lowest prognostic level of the Medium Range Forecast (MRF) boundary layer scheme (Hong and Pan 1996) respectively. The values for the volumetric heat capacity and soil thermal conductivity for the urban land cover classes were increased to represent the effect of heat storage. The MRF scheme was chosen since it is shown to accurately capture the evolution of the boundary layer in the desert southwest (Bright and Mullen, 2000).

2. Materials and Methods

a. Land cover data

The land use/cover data in the USGS high resolution data set provided with MM5 are part of a global land cover data base with a 1-km nominal spatial resolution. The data are classified according to the 24-category USGS Land Use/Land Cover System (Anderson *et al.* 1976). Urban areas were added to the data set after being extracted from the Digital Chart of the World (Defense Mapping Agency 1992).

1998 12-category land cover data with a 30 m spatial resolution were derived for the Phoenix metropolitan region from Landsat TM reflectance data and an expert system for post-classification (Stefanov *et al.* 2001). The 1998 land cover data were incorporated into MM5's 30-second USGS data set using GIS techniques. We assigned the 12 1998 categories to those that most closely correspond to the USGS categories. Two additional urban land cover classes were introduced in the 24-category USGS land use/cover classification resulting in the three urban categories - urban built-up, urban mesic (irrigated) residential and urban xeric (arid) residential. Figures 1a-c show the land cover distributions for the inner modeling domain (2 km x 2 km grid spacing) as generated by MM5's preprocessor TERRAIN for the standard release 24-category USGS land cover use/data; with updated 1998 land cover data; and after introducing the three urban land cover classes to the 1998 data set. Significant changes can be recognized in extent and inhomogeneity of the urban land cover. Built-up urban and xeric residential areas dominate within the city. The fraction of total and irrigated vegetative cover for each of the land cover types was determined from average values obtained from a detailed ground survey at 200 randomly selected points across the entire urban area (Hope *et al.* 2003).

b. Parameterization of radiation trapping, anthropogenic heat flux and heat storage.

1) Sky view factor

An effective sky view factor, Ψ_{sky}, was implemented in the long wave radiation balance, of the urban land cover categories in MM5's slab model (Dudhia 1996). Following Masson (2000), the sky view factors for roads or building walls were calculated as functions of the road width and building height, leading to a bulk value for Ψ_{sky} of 0.8.

2) Anthropogenic heat flux

The main sources for the anthropogenic heat flux in Phoenix are traffic and air conditioners, which are typically located on roof tops. The daily varying anthropogenic heat flux was calculated according to Taha (1999) and was included as a source term in the equation of the potential temperature at the first prognostic level of the MRF scheme. A maximum anthropogenic heat flux of 50 W m^{-2} was assumed.

3) Heat storage

Following Liu et al. (2004), the heat storage capacity of the urban land cover classes was increased by specifying a larger volumetric heat capacity of $3.0 \cdot 10^{-6}$ J m^{-3} K^{-1} and an increased soil thermal conductivity of 3.24 W m^{-1} K^{-1}.

c. Design of numerical experiments

Two 72-hour nested simulations were performed with MM5 using four domains and resolutions of 54 km, 18 km, 6 km and 2 km, respectively and 32 vertical layers. The lowest prognostic level was approximately 7 m above ground level. The first simulation began 1700 Local Standard Time (LST) 7 June 1998. This period was chosen since it coincides with the Landsat images on which the land cover classification was based. We chose the second simulation episode starting at 1700 LST 27 May 2001 since it represents a typical early summer period in the region. During this time of the year, topographically driven thermal circulations are dominant and days with synoptic forcing are infrequent. Initial and boundary conditions were provided by the NCEP (National Center for Environmental Prediction) ETA grid 212 (40 km resolution) analysis and included assimilation of upper air observations. According to the fraction of vegetation in the urban land cover classes moisture availability factors of 0.005, 0.02 and 0.1 were applied to the built-up urban, the xeric and mesic residential categories.

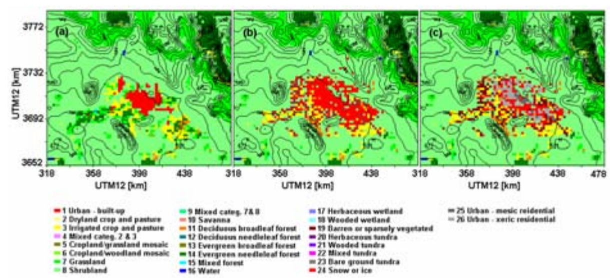

Fig. 1:

Land use and terrain as produced by MM5's preprocessor TERRAIN with (a) original 30-second 24 category USGS land use data set as provided with MM5, (b) LANDSAT Thematic Mapper 1998 image derived land cover data and (c) LANDSAT Thematic Mapper 1998 image derived land cover data and two new urban land cover classes represented by categories 25 – urban mesic (irrigated) and 26 – urban xeric (arid, partly irrigated) residential respectively.

3. Results and Discussion

a. Near-surface air temperatures

The evaluation of MM5's performance for different land cover scenarios was carried out by means of comparing simulated 2 m air temperatures, T_a, with data from twenty-five surface monitoring stations across the region. The new land use data and classification improved the daytime temperatures significantly for all stations (results not shown). However, the model significantly underestimated T_a at night for the urban stations. Particularly large discrepancies between measured and simulated 2 m air temperatures for the nighttime hours were shown for the NWS station at Sky Harbor Airport, which is located in the urban center and usually the site which experiences the highest urban heat island effect. The simulated nighttime T_a improved significantly after introducing a sky view factor, anthropogenic heat production and increased heat storage into the model. Fig. 2 shows the contributions of the three processes on the simulated T_a for the Sky Harbor Airport station. The decreased sky view factor reduces the extreme surface radiative cooling during night typically present in the region due to dry air aloft. The anthropogenic heat term enhances mixing of warmer air towards the surface, which further reduces the modeled nighttime cooling rate. The model changes do not have as large an influence on the daytime T_a. This is due in part to the extreme solar forcing that occurs during the day. Maximum shortwave fluxes are on the order of 1000 W/m^2, and any of the other forcing factors are on the order of 10 % of this value. Results at the other stations and for the year 2001 were qualitatively similar.

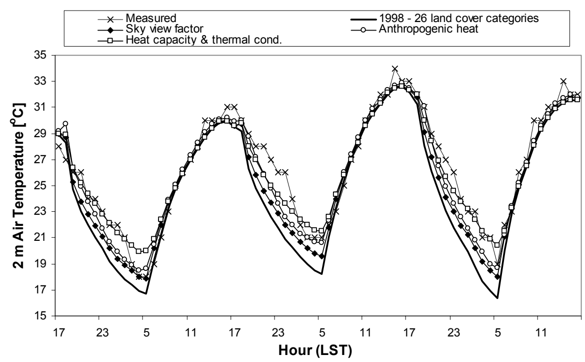

Fig. 2:
Simulated (1998 USGS 26-category land use data) and observed 2 m air temperatures for 7-10 June 1998 at Sky Harbor Airport showing the sequential effects of including sky view factor, anthropogenic heat flux, increased volumetric heat storage capacity and soil thermal conductivity.

b. Regional characteristics of the near-surface temperatures and PBL heights

In order to illustrate the regional effect of changes in land cover and surface characteristics on the near-surface temperatures, areal plots of the simulated differences in T_a at 2 m are presented for 0500 LST 9 June 1998 and 1400 LST June 9 1998 respectively (Figure 3a and b) for the 24-category USGS land cover data and the 1998 26-category classification data. The plots are difference fields of (new – old) land cover. The introduction of the new urban land cover classes differentiated by water availability lead to an overall simulated increase in air temperatures in the urban area.

During the early morning (0500 LST) there is evidence of an increase in the temperatures through the urban region of between 2 and 5 K with relatively little variation in the temperature depending on the particular class of urban cover. There tends to be a more or less uniform warm core, surrounded by increasingly cooler temperatures. This confirms the results found for the Sky harbor Airport station, i.e. that the nighttime temperatures are driven by the model physics rather than land cover, and that the increased expansion of the urban region may lead to an increase of temperatures in the urban center.

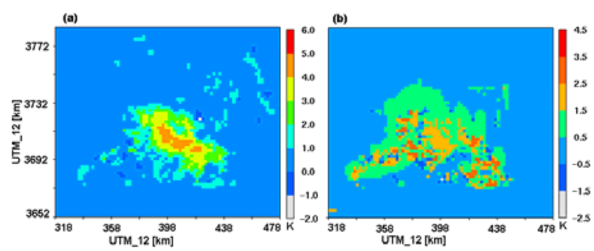

Fig. 3:
Differences (new land use/cover – old land use/cover) in simulated 2 m air temperatures in Kelvin between MM5's original USGS 24-category and 1998 26-category for (a) 0500 LST 9 June 1998 and (b) 1400 LST 9 June 1998.

At the time of the diurnal maximum (1400 LST, Fig. 3b) the simulations show a much larger degree of heterogeneity throughout the region, with some of the urban zone increasing in temperature and some regions decreasing. In some cases, the reclassification has resulted in desert being reclassified as active agriculture, or urban being subdivided into mesic residential, both of which would lead to a decrease in T_a. In other areas, particularly in the west part of the metropolitan area, active agriculture is replaced by bare soil, which leads to an increase in temperature. It is also worthwhile to point out that during daytime even with the 26-category 1998 scenario many parts of the city, particularly the mesic and xeric residential areas, were cooler than the desert areas to the southeast, south and southwest by about 1.5 K. This is further evidence that in this arid region the urban heat island is primarily a nighttime phenomenon.

In the MRF scheme, sensible heat fluxes between the ground level and the prognostic levels in the atmosphere determine the Richardson number and the height of the planetary boundary layer (Zhang & Anthes 1982).

An increase in sensible heat fluxes (not shown) of about 350 $W \cdot m^{-2}$ in the model within the urban area due to the new land cover classification led to a significant increase in the simulated PBL heights of 300 m to 400 m over the central part of the city during daytime. The increases in boundary layer were also quite heterogeneous, with the largest values confined to the southwest and southeast quadrants of the valley. These regions have experienced the largest conversion from agricultural to urban in recent years. During night, significant differences of about 150 m between the two model versions simulated PBL heights were detected for the urban core area.

4. Conclusions

The results of this study show that modifying the urban land cover by correcting the land cover classifications to reflect current conditions and also introducing additional categories to reflect variations in urban types, along with some simple modifications to the surface energetics and temperature tendency in the lower atmosphere can significantly improve the diurnal temperature cycle, turbulent heat fluxes and also influences PBL heights in the mesoscale meteorological model MM5.

Acknowledgments

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