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Urbanized MM5 study of urban impacts on an August 2000 Houston ozone episode

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URBANIZED MM5 STUDY OF URBAN IMPACTS ON AN
AUGUST 2000 HOUSTON OZONE EPISODE

A Thesis

Presented to

The Faculty of the Department of Meteorology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Rochelle Therese F. Balmori

May 2006

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ABSTRACT

URBANIZED MM5 STUDY OF URBAN IMPACTS ON AN AUGUST 2000 HOUSTON OZONE EPISODE

by Rochelle Therese F. Balmori

The current study used the Martilli-Dupont urbanization scheme within MM5 to investigate Houston urban heat island (UHI) conditions during an August TexAQS 2000 O₃-episode. The resulting uMM5 model was used only in the (innermost) fifth domain (1-km grid spacing). Projected changes in vegetative cover for 2010, which showed areas of urban reforestation and rural deforestation, were also simulated by uMM5.

Results showed that input NNRP fields correctly captured the observed large-scale forcing and that the regular MM5 correctly captured the observed sequence of Bay, Gulf, and urban breeze effects on O₃-transport. uMM5 better reproduced observed UHI magnitudes and urban impacts on regional flows: roughness-induced deceleration, building-barrier divergence, and UHI-induced convergence. Effects from the use of a higher-resolution domain, uMM5, and/or urban reforestation showed that the first two generally increased daytime UHIs, while reforestation decreased them by an average of 2.8 K and by a maximum (at noon) of 3.3 K.

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1. Introduction

The current study uses the highly urbanized Martilli-Dupont scheme within the 5th generation Penn State-NCAR Mesoscale Modeling system (MM5, see Appendix A for list of abbreviations and acronyms) to investigate Houston urban heat island (UHI) conditions during a TexAQS 2000 O₃ episode. The study also evaluates UHI changes that would occur from a proposed Houston tree-planting scenario. A detailed analysis is also carried out of interactions between observed (synoptic and mesoscale) met forcings that produced the episode.

a. Urban heat islands

In urban areas, natural (e.g., grass, bare soil) are replaced by artificial (e.g., concrete and paved) surfaces with thermal properties (e.g., albedo, thermal conductivity, emissivity) different from non-urban areas. Howard (1833) was the first to observe that urban temperatures were higher than those in nearby rural areas, an effect Manley (1958) termed as an UHI. Urban climate summaries by Yoshino (1975), Landsberg (1981), Oke and Bornstein (1981), Bornstein (1987), Oke (1987), Ohashi and Kida (2001), and Shepherd *et al.* (2004) have shown that under clear skies and light wind conditions, cities are warmer than surrounding rural environments by up to 10°C.

UHI formation can be explained by urban-rural differences in many of the terms in the surface energy balance equation, and Imamura (2005) proposed that diurnal and seasonal UHI variations are also a function of climate type, itself a function of seasonal solar-radiation and precipitation variations (i.e., high-latitude cold versus tropical-hot, dry versus wet). Seasonal precipitation variations determine rural soil moisture content and

thus latent heat variations, while seasonal solar radiation variations determine energy consumption differences (via heating and air conditioning) and thus anthropogenic heat production variations. Diurnal variations, however, result from urban-rural land-use differences, e.g., the latent heat flux in urban areas is reduced by impervious surfaces and the storage of solar energy includes storage within urban structures.

Wet soils use more solar energy for evaporation and thus have less for heat storage and the convective heat flux, and thus soil moisture content strongly influences soil thermal inertia (TI), defined by $TI = (\rho c k)^{1/2}$, where ρ is material density, c is specific heat, and k is thermal conductivity. While urban areas are believed to have high TI values, laboratory tests by Swaid (1991) showed that dry soils have lower TI values than asphalt slabs, but wet soils have higher values.

High TI wet-soil areas thus slowly warm during daytime hours and likewise cool during nighttime hours. Wet-climate rural soils thus produce stronger daytime than nighttime UHIs, while dry-climate rural soils produce stronger nighttime than daytime UHIs. Dry-climate soils could actually even produce daytime urban cool islands (UCIs). Other factors that can produce UCIs include urban elevated haze layers and small urban-canyon sky view factors (SVFs, the fraction of sky not blocked by urban structures), both of which block incoming urban solar radiation.

At night, the loss to the atmosphere of ground-level emitted upward long-wave radiation is reduced (relative to rural values) by canyon-wall absorption. Canyon surfaces thus remain warm, and hence produce enhanced (relative to rural values) long-wave fluxes to the sky and ground, which thus contributes to 2-m nocturnal UHI formation

(Kobayashi 1979). Low urban SVF values thus reinforce the diurnal UHI variation associated with dry rural soils, but counters that with wet rural soils.

The role of soil moisture, and hence TI, on UHI-intensity diurnal-variation was shown by Taha *et al.* (2005), whose NASA-TM derived daytime rural surface radiative-temperature values in and around Davis, CA were negatively correlated with rural NDVI, as irrigated-green rural-soil plots were cool and dry-brown rural-soil plots were warm. Urbanized areas of Davis showed temperatures in between those values, making UHI existence dependent on which rural temperatures were compared to the urban values. Nighttime rural temperatures, however, showed high positive-correlation with rural NDVI values, as irrigated-green rural-soil plots were warm and dry-brown rural-soil plots were cool. Davis, however, showed a strong UHI with warm roofs, but with cold treed and urban-park areas.

Air traversing rough warm urban areas thus encounters changes in surface and atmospheric characteristics that alter existing mean and turbulent wind velocity fields (Craig 2002). In particular, UHIs cause pressure field deformations, buildings produce barrier effects, and large urban surface roughness length values increase surface frictional drag. Bornstein and Johnson (1977) showed that wind speeds over NYC were decreased below (increased above) observed rural values during high (low) regional-speed periods. Loose and Bornstein (1977), and Gaffen and Bornstein (1988) also showed that NYC retards synoptic fronts as they pass over the city during non-UHI periods, while such fronts were accelerated over the city during periods of well-developed UHIs; similar effects on sea breeze movement over NYC were found by Bornstein and Thompson (1981).

Urban areas also alter wind directions, e.g., in otherwise calm synoptic flows, UHIs produce inward directed "country breezes" that result in speed maxima and confluence over the city. With non-zero synoptic flows, the UHI is advected downwind and urban-induced flows are superimposed onto prevailing winds, the combination of which results in displacement of urban effects to the downwind urban edge.

During non-UHI periods, building-barrier induced diffidence at the upwind urban edge divides regional flows as they approach a city, especially during stable nocturnal conditions (Bornstein and LeRoy 1990). The diffidence is followed by downstream cyclonic-turning on the right-hand urban edge (looking downstream) and anticyclonic turning on the left hand urban edge (Bornstein *et al.* 1993). Barriers also produce confluence at both lateral urban edges (where air deflected around the city converges with the undisturbed prevailing flow) and downwind of the city (where the flow re-unites). These horizontal convergence/divergence effects produce urban vertical velocity patterns consistent with 3-D mass consistency and are larger during unstable daytime hours than stable nighttime hours.

Delage and Taylor (1970) used a 2-D prognostic non-linear hydrostatic Boussinesq model to study UHI-induced circulations with calm synoptic winds. Bornstein (1975) used a similar vorticity-mode model (URBMET) to simulate flow modification over warm, rough urban areas. Vukovich *et al.* (1976) were the first to use a 3-D hydrostatic model to simulate UHI-induced circulations over a realistic city (St. Louis). The model included (natural plus building height) topography, and specified surface temperature distributions. Results reproduced many features of the urban temperature, hori-

zontal velocity, and vertical velocity distributions. It also produced cyclonic inflow around the UHI during low wind speeds. Vukovich and Dunn (1978) then showed that daytime mixing layers produce comparable UHI circulations with only one-third the surface UHI intensity, while Vukovich *et al.* (1979) and Vukovich and King (1980) studied UHI effects on ozone concentrations. The model, however, could not accommodate changing synoptic conditions, and did not consider the surface energy budget, thus surface UHI intensity was prescribed.

Surface energy budget equations were first used within hydrostatic urban-area 3-D models by Atwater (1977), who considered pollutant effects on UHI development in a small ideal urban-domain. Bornstein *et al.* (1987) used URBMET to simulate NYC UHIs. The model included higher-order turbulence closure, increased urban surface roughness values, and an anthropogenic heat flux divided between the surface and atmosphere. Results reproduced the observed urban-induced slowing of sea breeze fronts. Seaman *et al.* (1989) used PBL data from the St. Louis Regional Air Pollution Study (RAPS, Ching *et al.* 1983) in MM4 simulations with two-way nested grids and realistic synoptic ICs and BCs. Results reproduced an UHI-induced downwind cyclonic vortex.

Kimura and Takahashi (1991) simulated the Tokyo UHI with a hydrostatic two-nest model that included natural topography, subgrid-scale urban land-use variability, and anthropogenic heating. Results showed anthropogenic heat effects on UHI magnitude larger at night, despite lower nocturnal energy consumption rates. Kitada *et al.* (1998) used a hydrostatic model with a k - ϵ turbulence closure to simulate interactions between flows influenced by the Sea of Japan, urbanized Nohbi Plain, and Japanese Alps. Results

showed the Alps with the largest influence on surface winds, with only insignificant effects from the urbanized area. Linked Lagrangian-particle dispersion and 3-D hydrostatic meso-met models were used by Ohashi and Kida (2001) to investigate urban effects on pollutant transport patterns. Results showed that inland urban areas strengthen and sustain sea breeze circulations.

The hydrostatic CSUMM (Pielke 1974) was used to study urban albedo (Taha 1996) and vegetation (Taha 1997) effects on LA basin UHIs and ozone. Results showed that increased use of urban trees and high-albedo white roofs reduced daytime UHIs and thus O₃ concentrations. Taha (1999) then incorporated the “objective hysteresis model” (OHM) of Grimmond *et al.* (1991) into CSUMM to estimate urban heat-storage from a non-linear regression equation that requires net radiation and regression coefficients as inputs. The urbanized model produced stronger and more accurate Atlanta UHIs than did the unmodified model.

The non-hydrostatic TVM of Schayes and Thunis (1990) was used by Bornstein *et al.* (1993) to study NYC-effects on moving sea breeze fronts. The model, an advanced version of URBMET, used grid-averaged NYC building-heights (added to natural topography heights) in addition to the traditional urbanization technique of increased urban surface roughness lengths and UHIs. Results again slowed sea breeze frontal movements over NYC, but also showed additional retardation induced by Manhattan, as observed by Bornstein and Thompson (1981). Panayiotou (1995) used TVM to simulate an observed horizontal anticyclonic and cyclonic downwind vortex-pair against the mountain range north of Phoenix. Saitoh (1996) was the first to use a non-hydrostatic formulation to

study Tokyo UHIs, and thus his modeled surface temperatures were more accurate than those of previous efforts.

While the traditional surface roughness and UHI approach underestimate urban impacts, the TVM building-block barrier approach overestimated these impacts. Recent efforts have thus focused on more realistic single or multi-layer urban canopy-layer parameterizations. Single-layer models developed in France (Masson 2000, Masson *et al.* 2002) and Japan (Kusaka *et al.* 2001; Kusaka and Kimura 2004a) involved detailed calculations of urban-canopy effects on radiative and sensible heat fluxes. Masson showed that the model correctly simulated the net radiation, surface temperatures and partitioning between the turbulent and storage heat fluxes in Mexico and Vancouver. Two-dimensional idealized simulations of daytime summertime Tokyo UHIs by Kusaka and Kimura (2004b) used a hydrostatic anelastic meso-met model. Results showed UHI-intensity is directly proportional to anthropogenic heat release and inversely proportional to both urban-wall heat capacity and SVF.

Multi-layer porous-flow urbanization schemes also involve alterations to the prognostic momentum, energy, and TKE equations. Brown and Williams (1998) were the first to apply the forest-canopy parameterization scheme of Yamada (1982) to urban-canopies. While they used the hydrostatic q^2 - l HOTMAC model, Urano (1999) and Ca *et al.* (2002) used the hydrostatic k - ϵ CSUMM model and Leach *et al.* (2001) used the non-hydrostatic COAMPS model with the same scheme.

The Martilli (2002) scheme is the most advanced multi-layer porous-flow urbanization scheme yet developed. Originally installed in FVM, it has a detailed param-

eterization that influences surface UHI development, as well as urban SBL and PBL structure. The module separately represents the effects from urban roads, roofs, and walls. Results showed nighttime thermal factors are more important in the lower urban PBL, with mechanical factors dominant in its upper part (Martilli *et al.* 2002). Additional applications have involved 2-D idealized coastal-urban interactions (Martilli 2003), Athens air quality (Martilli *et al.* 2003), and comparisons with field-campaign data over Basel (Martilli *et al.* 2006). These studies showed the urbanization scheme to more realistically reproduce urban wind speed, UHIs, turbulence, and heat fluxes.

Hamdi (2005) and Hamdi and Schayes (2005) incorporated urban vegetation effects into the Martilli-module within TVM to evaluate urban impacts on airflow over Basel and Marseilles. Results showed that the model more correctly simulated the net radiation and the partition of the turbulent and storage heat fluxes, and hence development of downwind daytime convective cells, nighttime UHIs, and convergent urban-breezes.

Dupont *et al.* (2003) had also inserted the Martilli scheme in MM5 to simulate met fields around Philadelphia. Results showed that their model correctly simulated observed features of urban roughness sub-layer shear stress, TKE, and eddy diffusivity. While urban temperatures were also better simulated than with standard MM5, the study only provided a limited evaluation of the new model, because it used incomplete urban-canopy morphology databases.

b. Houston air quality and meteorology

Houston, Texas, one of the most polluted cities in the US (and the city investigated in the current study), is located in the southeastern Texas on the Gulf Coastal Plain (at about 27 m MSL) adjacent to Galveston Bay, an inland extension of the Gulf of Mexico (Fig. 1). Its subtropical mid-summer weather is typically hot and humid, with max daytime temperatures from 30-36°C and min nighttime values from 20-25°C. Summertime afternoon convective thunderstorms are common and produce variable precipitation amounts, with average monthly values ranging between 8 and 15 cm (Lyons 1990; Nielsen-Gammon 2001).

Typical mid-summer flows around the western edge of the General Circulation (GC) Bermuda High produce southwesterly 500 hPa winds over eastern coastal-Texas, with prevailing southeasterly surface flows (Shepherd and Burian 2003; HRMC 2002). The weak pressure gradient, low speeds, warm temperatures, and high insolation associated with high-pressure areas enable formation of onshore-directed sea breeze flows (Darby *et al.* 2001). Such flows from Galveston Bay are herein called Bay Breezes and those from the Gulf are herein called Gulf Breezes. These flows move inland as pulses on the prevailing flow during periods when GC flows are onshore or they move as sea breeze fronts during periods of low-speed offshore GC flows. The convex Bay coastline produces onshore flows that inhibit resulting sea breeze convergence zones and that thus decrease formation of summertime afternoon convective thunderstorms (McPherson 1970, Pielke and Segal 1986).

Analyses of data from the summers of 1995-7 by HRMC (2002) showed that a weakened Bermuda High during 1995 favored lower wind speeds and warmer temperatures, and hence a greater number of O₃-exceedances. They found that 90% of exceedances occurred with morning northwesterly winds, which transport higher background levels of O₃ and its precursors into southeastern Texas than do southerly winds.

Intensive air-quality field-studies have been carried in and around Houston to better understand the formation of its summer O₃ episodes. The 1993 GMAQS/COAST study collected: wind velocity (60-2000 m) from seven sounder sites, O₃ and met data from 13 surface sites, and O₃ aloft from an instrumented aircraft (TNRCC 1998). The 19 August episode day (231 ppb max one-hour O₃) was characterized by the typical Gulf Coast mid-summer weather pattern described above. Prior to the episode, the Bermuda High extended into the southern US, producing south to westerly surface winds over HGA.

During the two days before the episode, however, the high weakened and shifted northwestward to the upper Texas coast, which allowed for strong land and sea breezes that penetrated inland to Houston during the following three high-O₃ days. Combining the results from these first two studies, ozone episodes are most likely when a precursor-rich early morning northwesterly flow is subsequently pushed back over Houston by an afternoon onshore-directed sea breeze flow laden with fresh emissions. On 6 September 1993, the first southward-moving weak cold front moved over the Gulf, resulting in northeasterly flow across the Texas coast. By the 8th, the now offshore front weakened, allowing formation of a Bay Breeze that passed Galveston around noon, producing high-

O₃ (214 ppb max concentration). On the 9th, another weak front moved into the area and became stationary between HGA and Beaumont/Port Arthur (Fig. 2) and Houston O₃ levels were reduced.

On 27 and 29 August 1998, several of the 36 Houston area CAMS recorded O₃ concentrations over 200 ppb. On 27 August, the GC high strengthened and moved westward to a location over Houston (McHenry and Peters-Lidard 2002). By mid-afternoon, the Gulf Breeze that had formed south of Palacios (Fig. 2) gradually expanded northeastward, carrying polluted air towards the Houston area. On 28 August, a weak synoptic surface front first moved south past the HGA, and then that night it apparently moved back to become stationary on the 29th at a location 200 km north of the HGA. This movement was said to have exposed the HGA on the 29th to the high O₃ air mass of the 27th.

The TexAQS study during 22 August-1 September 2000 obtained met parameters and O₃ concentrations from 124 surface sites, five wind profilers, a Doppler LIDAR, a GPS-sonde, two airsondes, and several buoys (Nielsen-Gammon 2001). Analyses showed two large-scale diurnal wind-cycle types during the period: (a) onshore flow (25-29 August) and (b) flow parallel to or offshore from the coast (30 August-01 September).

During the 25 August episode, when 12 of 36 CAMS sites recorded O₃ > 125 ppb (max of 194 ppb), the early morning light land breeze was generally northeasterly/offshore. Following several hours of stagnation, a light easterly noon (synoptic plus Bay) breeze advected polluted air from the Ship Channel to Houston, but by mid-afternoon, the now southeasterly onshore flow (>2 m s⁻¹) advected high O₃ air to downtown Houston.

The winds continued to strengthen and rotate clockwise throughout the rest of the afternoon, resulting in a uniform late-afternoon southerly-component flow. While analyses of LaPorte (10 km south of the Ship Channel, Fig. 3) data by Darby *et al.* (2001) showed the transition from offshore to onshore flow, they were unsure whether the early morning northeasterly flow transported pollutants from the Ship Channel to Houston, or if polluted air mixed downward as the PBL grew after sunrise.

Based on the above studies, the synthesis by Nielsen-Gammon (2002) postulated that high O₃ days in Houston (characterized by an unusually large and horizontally extended sea breeze, because of its location near 30°N latitude) typically occur when coastal-plain surface-winds are modulated by a 24 h daytime mesoscale wind-variation, in which wind rotate clockwise in an inertial circle. The rotation turns morning northerly offshore land-breeze flows into afternoon southeasterly onshore sea-breeze flows, which then transports air over the source-rich industrial Ship Channel area towards Houston. The air is finally drawn into the Houston area by an UHI-induced convergence, an effect Nielsen-Gammon (2004) named as the Houston “heat pump.” High afternoon Houston O₃ is even more likely when stagnation exists for several morning hours over Galveston Bay (with its limited vertical mixing), prior to its onshore return within the sea breeze flow.

PBL-structure during the TexAQS 2000 O₃ episode day of 30 August was studied by Banta *et al.* (2005) by use of a DIAL system. Results showed that high daytime Houston-O₃ concentrations penetrated up to 2 km, was transported over surrounding rural ar-

eas at night, and then fumigated to the surface during the next day to enhance background levels that helped cause the episode day.

c. Houston modeling studies

Field-campaign data were used in numerical simulations of Houston UHI, wind, and O₃ patterns, e.g., the September 1993 GMAQS/COAST episode was simulated with the hydrostatic SAIMM model (ENVIRON and MRC 2001a). As model wind speeds were overpredicted, FDDA nudging coefficients were increased until they slowed enough to allow the UAM photochemical model to produce sufficient O₃. The excess nudging, however, interfered with simulated observed land/sea breezes and produced anomalous divergent zones.

They thus re-simulated the episode with the non-hydrostatic RAMS model by use of 41 vertical grid-levels to 20 km, a lowest wind and temperature grid-level at 10 m, and three horizontally-nested grids: 48 km over central US and Gulf of Mexico, 16 km over COAST domain, and 4 km over HGA. They also used the Mellor-Yamada prognostic TKE scheme, while the met FDDA input included large-scale gridded NCEP/NCAR re-analysis fields; standard NWS rawinsonde and surface observations; and surface, profiler, and rawinsonde GMAQS/COAST meso-observations. While winds were better simulated (1 m s^{-1} mean absolute error), a daytime positive temperature bias (3°C) was attributed to a too-large model evaporation rate that created a negative dew point bias of 1.5°C , excess daytime atmospheric heat flux, and excess nocturnal radiative cooling. Other hypotheses for the too-low modeled nocturnal temperatures included insufficient horizontal-resolution and an inadequate accounting of urban heat capacity and surface roughness.

ENVIRON and MRC (2001b) then thus used MM5 with a higher resolution (1.33 km), but results continued to show undesirable features, i.e., underprediction of sea breeze development and over-land daytime surface speeds, as well as anomalous explicit grid-scale thunderstorm outflows. Analyses showed that the ETA and Gayno-Seaman PBL schemes did not efficiently mix sufficient heat, moisture, and momentum vertically within the PBL. The MRF (Blackadar-type) PBL scheme, however, gave fewer problems with storm development, more realistic PBL heights, and thus better sea breezes.

New MM5 simulations of this 1993 episode by ENVIRON and ATMET (2002) included more advanced physical options: (a) SSTs from the NCAR Reynolds monthly climatology, (b) OSU or Pleim-Xiu land-surfaces, and (c) “bucket” soil moisture that included precipitation, evaporation, and runoff. The cumulus parameterization was also changed from Grell to Kain-Fritsch, but results still showed over-developed grid-scale convection.

Met conditions during the August 1998 ozone episode were investigated by McHenry and Peters-Lidard (2002), who used MM5 in conjunction with the following surface-energy schemes: TOPLATS for land surfaces and SSATS for water surfaces (Famiglietti and Wood 1994; Peters-Lidard 2001). They also utilized satellite-derived downward solar radiation, remotely-sensed land-use data, and gauge-corrected precipitation to drive the hydrological cycle and surface flux evolution. The Blackadar PBL scheme was used instead of the MRF formulation because the latter overestimated PBL heights, which thus produced overestimated sea breeze penetrations. Results showed the standard

MM5 better predicted wind direction, while their version of MM5 better predicted temperatures and coastal gradients, given its more accurate SSTs.

The 25 August to 1 September 2000 TexAQS O₃ episode was first modeled at TAMU by Nielsen-Gammon (2001), who improved MM5 by inclusion of updated land-surface characteristics and assimilated observations. They used a grid with five domains (down to 1 km), one-way nesting, three-hourly EDAS FDDA in the outer three grids, satellite-derived SSTs, simple ice microphysics, Grell and Kain-Fritsch cumulus, MRF (Blackadar-type) PBL, FFRT radiation, multi-layer soil, and EDAS (rather than OSU-LSM) land characteristics (as they blend gradually toward the ocean).

Input look-up-table soil moisture availability was lowered to reflect local drought conditions, and thus MM5 reproduced the unusually highly observed temperatures during the latter half of the episode. It also produced generally realistic large-scale winds, sea breeze evolution, and precipitation. Results also showed that the MRF scheme produced better daytime PBL-structure than Gayno-Seaman. Problem areas included underprediction of max temperatures (by 1°C) and overprediction of min temperatures (by 2°C).

Nielsen-Gammon (2001) compared new simulations of this day by two MM5 versions: TAMU-Version 3.4 and MCNC-Version 2.12. While the MCNC grid was coarser (5 vs. 1 km), TAMU had more vertical sigma half-levels (43 vs. 31) and used RRTM radiation, while MCNC used Dudhia. TAMU also used the MRF and Gayno-Seaman PBL schemes, while MCNC used Blackadar. Similarities included the same simple ice scheme, one-way nesting, soil, and land use characteristics; however, TAMU used their modified soil moisture values. While TAMU more accurately predicted max tempera-

ture, wind, and precipitation, MCNC did better with min temperature, nocturnal temperature inversions, vertical wind-variations, and daytime and nighttime UHIs.

Others also simulated the 2000 O₃ episode, e.g., ATMET (2003) used the advanced NOAH LSM and RRTM radiation schemes. While the advanced model generally performed well, it overpredicted nighttime-and underpredicted daytime-temperatures. These differences mostly occurred during non-simulated daytime convective periods, which sensitivity runs showed arose due to overestimated downward momentum fluxes. Jiang and Fast (2004) RAMS simulations were unable to reproduce the high O₃ concentrations observed near the Ship Channel because of model errors associated with point-source plume-transport and vertical mixing.

Byun *et al.* (2004) used MM5 to determine impacts of LU/LC changes on air temperature, biogenic emissions, and O₃ air quality during the 2000 episode. They used a grid with five domains (down to 1 km); NCEP ETA IC/BC; Grell cumulus on outer three domains; MRF PBL; Dudhia simple-ice microphysics; and NOAH LSM. Results showed low-speed overprediction, daytime max urban temperature overprediction, nighttime domain-wide min temperature underprediction, and a 2-h delay in mixed layer wind speed development during morning to midday transition periods. The max temperature bias was corrected by addition of anthropogenic sources of canopy water, while the min temperature bias was corrected by use of the land-use dependent emissivities in NOAH LSM. An attempt to correct the speed bias by removal of convective effects in the effective friction-velocity was unsuccessful, as it produced unrealistic surface heat fluxes.

Whereas previous simulations of meteorological influences on the TexAQs 2000 O₃-episodes have used non-urbanized versions of MM5, the current study uses the highly urbanized Martilli-Dupont scheme within MM5 to investigate Houston UHI conditions during the 25 August episode. The study also evaluates UHI changes that would occur from a proposed Houston tree-planting scenario. A detailed analysis is also carried out of interactions between observed (synoptic and mesoscale) met forcings that produced the episode.

This study has been undertaken to test the hypothesis that output met fields from the uMM5 simulations could be used in photochemical models to see if they would then better reproduce observed and projected future O₃ concentrations. It has also been undertaken to see if the resulting decreased UHIs will then produce decreased daytime summer max-O₃, which could then be converted to EPA-granted emission-reduction credits for Houston.

2. Methodology

a. Urbanized MM5 (uMM5)

While the standard MM5 is described in several sources (e.g., Dudhia 1993; Dudhia *et al.* 2004), the urbanized EPA MM5 is described by Dupont *et al.* (2003) and Otte *et al.* (2005). The model is based on the urban-canyon energy balance scheme of Masson (2000) and the dynamic urbanization scheme of Martilli (2002) and Martilli *et al.* (2002). Two versions of this model are available (Dupont *et al.* 2003): roughness-length (RA) and porous-flow pressure-drag force (DA-SM2-U, which includes the RA parameterization in non-urbanized areas) approaches.

The RA model is essentially the standard MM5, but with computation of friction velocity u_* and friction potential temperature θ_* for each surface-type within a single grid, before averaging-up these to grid-scale; in standard MM5, these parameters are calculated only for the dominant land-use type in the cell. DA-SM2-U also includes the following additional sink/source terms in all prognostic equations and within the Gayno-Seaman TKE routine (based on separate effects from vertical and horizontal urban surfaces):

- **Moisture:** evaporation of building and surface intercepted-water
- **PBL momentum:** frictional-roughness effects (due to roofs and canyon floors) and porous-flow pressure effects (due to vertical surfaces)
- **Radiative-energy balance:** canyon effects from effective: albedo, geometry, and sky-view factors
- **Thermal-energy:** sensible heat-flux from roofs and anthropogenic heat-flux

- **TKE**: accelerated cascade and wake production effects, horizontal surface effects via shear production, and sensible heat-fluxes from horizontal surfaces via buoyancy production.

The EPA DA-SM2-U has been further modified by Taha (personal communication) to better use the available urban LU/LC parameters (as described below). The resulting final model configuration is herein known as uMM5.

b. SJSU uMM5 setup

The simulation period is the TexAQS August 2000 episode period, with an emphasis on the earlier high-O₃ episode on 22-26 August. Standard MM5 is used in the four outer domains, while uMM5 is used only in the innermost domain (Fig. 4 and Table 1). Domains 1-4 use 29 full- σ levels (stretched with height to 100 hPa), with the lowest half- σ level at 10m, while the 1-km uMM5 grid of Domain-5 uses 49 stretched full- σ levels (with additional near-surface points).

MM5 options selected include:

- Grell cumulus in Domains 1 and 2
- simple-ice moisture in Domains 1 to 5
- RRTM radiation in Domains 1-5
- OSU-LSM in Domains 1-4 (without snow)
- SM2-U in Domain 5
- ETA PBL in Domains 1-4
- Gayno-Seaman (only linkage to uMM5) in Domain 5
- two-way feedback in Domains 1-4 (Domain 5 is run off-line)

- large-scale forcing from NCEP/NCAR 6-h re-analyses fields and ADP observational data in Domains 1-4
- FDDA analysis-nudging at all levels (including surface) in Domain 1, but only above diagnostic MM5 PBL-top in Domains 2-4.

Nudged parameters included wind, temperature, and water vapor mixing ratio, with the following nudging-coefficients: $2.5 \times 10^{-4} \text{ s}^{-1}$ for wind and temperature and 10^{-5} s^{-1} for moisture.

The following surface properties are assigned to each LU/LC category in Domains 1-4 via the MM5 internal look-up table:

- Domains 1-5: USGS topographic heights (1.0, 0.5, 0.16, 0.08 deg resolutions)
- Domains 1-3: USGS 24-LU/LC dominant-category scheme
- Domain 4: modified LU/LC dominant-category scheme of Byun *et al.* (2004)
- Domains 1-4: albedo, TI, soil moisture, and roughness length values from MM5 internal look-up table

The look-up table values of these surface properties are those commonly used in meso-scale modeling (e.g., Pielke 1984, Taha *et al.* 2005) and are those used by Byun *et al.* (2004) for the same episode.

Comparable Domain 5 values were obtained as follows:

- Terra Point LLC LIDAR urban morphology data (1-m resolution) from Burian *et al.* (2004).
- LU/LC sub-grid scheme (30 m resolution) from Stetson (2004)

- MODIS-derived surface TI, albedo, and vegetative cover (1-km resolution) of Burian *et al.* (2004).

The LIDAR data were also used by Burian *et al.* (2004) to develop the following (needed as input-parameters to uMM5) additional gridded Domain-5 HGA geometrical and morphological data:

- LU/LC fractions
- cover-type distributions for paved surfaces, vegetation, and roofs
- mean urban canyon orientation
- percent of paved surfaces/impervious areas
- building and vegetation mean-heights and standard deviations
- wall-to-plan ratio
- height-to-width ratio
- canopy mean-height
- roughness length and displacement height for several wind approach-directions
- building and vegetation frontal area densities
- top-area density for buildings and vegetation
- plan area density for buildings and vegetation.

The boundaries of urbanized HGA (within Domain-5) were delineated by use of GLOBEIS data (Fig. 5) by the TCEQ (Taha *et al.* 2005), the current study used the project-generated TFS urban-LU/LC class-distribution for its outline (Fig. 6); the two boundaries are in agreement.

Projected HGA changes in vegetative cover by the year 2010 (Table 2) were obtained from the US-TFS (GEM 2003). Note that for 2010, LU/LC Categories 37590-37593 are collapsed into the single Category 37590; two fewer Categories (i.e., urban-vegetation16590 and southern agriculture 22591) exist; and the urban residential category is assumed wetter than crops, as yards and lawns are watered more frequently than agricultural/crop land. US-TFS distribution projects areas of urban reforestation and rural deforestation around the city (in areas slated for new suburban development). Surface properties (e.g., albedo, soil moisture, roughness length) are thus externally modified accordingly and mapped directly onto the uMM5 Domain 5 grid, so as to override MM5 look-up table values.

The following Domain 4 or 5 simulations were thus carried out:

- MM5 Case (Domains 4 and 5): for Present day forest coverage
- uMM5 Base Case (Domain 5 only): for Present day forest coverage
- uMM5 Reforestation Case (Domain 5 only): for projected 2010 forest coverage.

While a Linux-based workstation was used to preprocess data and run MM5 for Domains 1-4, uMM5 Domain-5 simulations were performed on the SJSU 108-CPU cluster, which runs on an Enterprise Linux operating system. Each CPU has a 2 GHz processor and 2 GB of memory. UCP Domain-5 simulations used 96 processors, which provided a 64-fold speedup relative to a single processor run, i.e., 4.5 h versus 16 days for a one-day simulation. All simulations began at 0000 UTC on 22 August and ended at 2300 UTC on 26 August.

3. Results

a. Synoptic forcing

On 23 August at 0000 UTC (1900 LST), the 700-hPa NWS analysis showed the Gulf Coast dominated by a broad synoptic high centered over Western Tennessee (Fig. 7a) with a central-height of 3250 m. Coastal Texas winds were mostly onshore/easterly at 5 m s^{-1} (10 kt, as a NWS barb is 8-12 kt). The corresponding NNRP reanalysis (Fig. 7b) shows the high with a central-height of only 3240 m and somewhat too far westward (over Arkansas). Its coastal speeds were correct, but directions were onshore/south-easterly. On 23 August at 1200 UTC (not shown), the NWS high was generally unchanged, except that its center had moved slightly eastward (to the Arkansas-Missouri border). The corresponding NNRP central-height was also generally unchanged, but its center was now correctly located (as it had remained stationary). After another 24 h (not shown), both highs had not changed much (now over central Arkansas).

On 25 August at 0000 UTC (evening before the episode), the NWS high (3240 m central height) had moved northwestward (north of Texas panhandle, Fig. 8a). The coastal onshore flow had changed into a northeast/alongshore flow, while inland flows over Texas showed a weak divergence. The corresponding NNRP high (not shown) was correctly located, but was weaker (3230 vs. 3240 m), but its 0600 UTC chart (Fig. 8b) had strengthened to its max of the day (3240 m). While NNRP coastal winds correctly showed the alongshore/northeasterly flow, inland winds were southerly (and non-divergent).

By 1200 UTC on the 25th (episode day, Fig. 9a), the NWS high had retreated back southeastward to the Oklahoma-Arkansas border, as opposed to only eastward to the northern Oklahoma border in the NNRP pattern (Fig. 9b); both now had a lower central pressures (3230 m). During the next 12 hours (evening of episode day), both highs continued their eastward movement (back to Arkansas). By 1200 UTC on 26 August (morning after episode), the NWS high (not shown) had weakened and split into two halves, which had continued to retreat southeastward to the western and southern Arkansas borders, while the single NNRP high had moved back to the southern Arkansas border.

The surface NWS analysis on 23 August at 0000 UTC (Fig. 10a) showed the GC Bermuda high centered off the Virginia coast with a 1026 hPa central pressure and with a “western-edge” extension to the eastern Texas border (based on the 1020 hPa contour). This high is the surface projection of the upper level high discussed above, with an axis that is found to the west (as expected) of the surface high (Atlantic coast at surface versus western Tennessee at 700 hPa). The high was over the East Coast in the concurrent surface NNRP plot (Fig. 10b), with only a 1025 hPa central pressure and a projection that extends to Arkansas at 700 hPa. A weak east-west oriented quasi-stationary synoptic-front is seen north of the NWS high; NNRP charts do not indicate such fronts. Both charts showed moderate evening onshore/southeasterly winds over coastal-Texas (at 5 m s^{-1}) due to the persistent Gulf Breeze at this latitude.

After 12 h, the NWS high (not shown) remained mostly unchanged, but its “western-edge” had moved to its max westward position (into central Texas). The NNRP high also was mostly unchanged and its western-edge seen over Texas-Louisiana border.

In association with the now weaker pressure gradient over Texas, winds on both charts were weak (calm or 2 m s^{-1}) and disorganized, as is typical during early-morning hours in areas without strong mesoscale forcing (i.e., downslope or land-breeze flows). By 24 August at 0000 UTC (not shown), the western-edge of the NWS high had retreated back/east-ward (into Louisiana), while the concurrent NNRP high had retreated even further (to the Mississippi border). The early-evening NWS and NNRP winds were again stronger (onshore/southeasterly at about 4 m s^{-1}).

By 25 August at 0000 UTC (evening before episode day), the western-edge of the NWS (Fig. 11a) and NNRP (Fig. 11b) highs had moved all the way to the Atlantic (off of Florida), producing even weaker pressure gradients. NWS onshore coastal-Texas flows were thus weaker (1 m s^{-1}) than on the previous two evenings, but NNRP winds were stronger (4 m s^{-1}) and showed evidence of flow around the northern-edge of a Gulf cyclone. North of the still-present quasi-stationary front, a weak secondary high-pressure area is seen in the NWS and NNRP charts. On the episode morning (1200 UTC), the western-edge of both the NWS (Fig. 12a) and NNRP (Fig. 12b) highs remained offshore, with coastal-Texas winds even calmer than on the two previous early-morning periods. Both show a strengthened secondary-high (1020 hPa over Indiana) and coastal-Texas winds even more weak and disorganized than two mornings before.

The 26 August 0000 UTC (evening of episode day) chart was unavailable, but by 12 h later (not shown), the NWS and NNRP offshore high was even further offshore. The secondary low was over Pennsylvania, while the eastern part of the front had finally moved southward, east of Texas.

In summary, the episode resulted during a sustained period of low-speed weak synoptic-forcing at both 700 hPa and the surface. Both the dominant upper GC level high and its surface projection (i.e., Bermuda-High) moved from a position east of Texas to one north of Texas during the night before the episode, which produced even weaker pressure-gradients that should allow mesoscale flow features to develop. Coastal-Texas surface-winds concurrently shifted from onshore to alongshore/northeasterly during the episode. The highs reverted to their original positions after the episode day. The selected large-scale forcing model (i.e., NNRP) captured most of these upper level and surface features.

The outer domains of MM5 were thus able to reproduce the weak surface GC pressure gradients and wind flow patterns (seen above in the NWS and NNRP plots), as well as a coastal mesoscale cyclone not seen on the NWS charts. Domain-1 surface-winds for 2000 UTC on 25 August (episode day) correctly show weak anticyclonic-flow over the eastern US, extending to central Texas (Fig. 13a). It also indicates the possible existence of a weak surface low in an offshore area with few observations. Concurrent Domain-2 winds show the weak surface low as offshore of HGA (Fig. 13b), while Domain-3 winds show it well-formed and producing a flow parallel to the eastern Texas coast (Fig. 13c).

b. Mesoscale coastal forcing

Domain-4 surface-winds during the episode period show the development and movement of the offshore weak surface low discussed above. The low was not present on the 22nd (Fig. 14a), started to form southeast of HGA on the 23rd (Fig. 14b), was fully

formed in the same location on the 25th (episode day, Fig. 14c), and then moved southwestward along the coast (Fig. 14d). Domain-3 surface temperatures on the 26th at 2100 UTC showed that the weak surface low had low central temperatures (Fig. 15a).

One possible contributing factor of these low temperatures is that warm Gulf waters can push colder water to the Gulf shore, as seen in the April-December 2005 averaged AVHRR satellite-derived SSTs (Fig. 15b). Another factor is that when coastal easterly atmospheric-winds produce an Ekman transport of surface water away from the coast, cooler deep-water is upwelled and somehow forms a cyclonic vortex in the surface currents. The cool water would then cool the overlaying atmosphere and again, somehow, a weak surface low would thus form in the cold atmosphere.

While concurrent ocean current observations were not available for the Gulf region, Pullen *et al.* (2006) did find such a cold-temperature cyclonic ocean circulation in NYC (Fig. 16), which has a similar (but sharper) right-angle coastline. Domain-4 air temperatures at 2 m and winds at 10 m (not shown) do not provide clear insight into the formation and evolution of the weak surface low, and thus more focused analyses are required of this event.

Concurrent Domain-5 surface-winds at 2000 UTC show in even greater detail the onshore sea-breeze flows of the days before (Fig. 17a,b) and after (Fig. 17d) the episode and the alongshore flow on the episode day (Fig. 17c), when most inland areas warmed, with the exception of areas downwind of the Bay. The alongshore flow is difficult to see in the observed TexAQS 2000 winds (Fig. 18a), which show northeasterly winds in the area northeast of HGA, as well as calm winds northwest of HGA. The smaller-scale

HGA meso-net winds (Fig. 18b,c), however, do show the alongshore flow and that the calm areas are associated with confluence into the inland Houston urban-area.

c. Ozone transport

As the GC high had its weakest influence on coastal transport patterns on the episode period, mesoscale coastal and urban forcings dominated. From 0000 to 0400 UTC on this day, the prevailing flow was southeasterly along the coast and northeasterly or easterly in the area northeast of Houston. Urban effects on the flow during this period included urban-roughness decreased speeds at 0200 UTC (Fig. 19a) weak disorganized convergent flow into the Houston UHI (discussed further below) at 0300 UTC (Fig. 19b). Low O₃ concentrations existed over the area and the highest value (44 ppb) at 0400 UTC over the coast, not shown) was far below the EPA hourly standard of 125 ppb.

After a two-hour transition period, the prevailing flow from 0700 to 1100 UTC had shifted to southerly/onshore in the eastern coastal area and to northerly/offshore in northeast-inland and western-coastal areas (not shown), which produced a convergent flow over the Bay. Ozone concentrations during this period remained low over the city and only somewhat higher over the coast. By 0900 UTC (Fig. 19c), the flow and O₃ patterns had not changed much, but titration continued to reduce O₃ levels over Houston down to about 5 ppb. The flow over Houston had remained weak and disorganized until it became generally northeasterly at 1000 UTC (not shown). By 1200 UTC (Figs. 19d), the flow in most of the area had shifted to northwesterly to north-easterly, while O₃ concentrations decreased to almost zero (max of 5.9 ppb).

The prevailing flow did not change much during the next four hours, but a north-east alongshore coastal-flow started to form along the northern coast at 1400 UTC (not shown) due to the offshore low discussed above. By 1500 UTC (not shown), this flow extended along the entire coast. During the same period, fresh O_3 started to form over the Ship Channel due to photochemical processes and concentrations reached to 84 ppb at 1600 UTC (Fig. 19e) in the area northeast of the Ship Channel, with a smaller secondary peak to the southeast. Development of an easterly Bay Breeze at 1700 UTC (Fig. 19f) destroyed the alongshore flow in the southern coastal area and advected the southern O_3 peak (which had grown rapidly to 125 ppb due to Ship Channel emissions) towards Houston. The northern peak was not advected and only slightly increased in magnitude, as it is not in an area of high emissions. The Houston UHI increased the easterly Bay Breeze flow into the city, and by 1800 UTC (Fig. 19g) max concentrations had risen to 144 ppb over Houston. The northern max is still in the same location, and in between them is a local min of 75 ppb.

At 1900 UTC (Fig. 19h), the prevailing flow over the entire area shifted to easterly, and main max O_3 concentrations thus shifted slightly to the downwind edge of Houston and reached the daily peak of 196 ppb. By 2100 UTC (Fig. 19i), a southerly Gulf Breeze had finally developed, and the O_3 was thus advected to an area northwest of the city. An apparent NO_2 titration effect within air directly downwind of the city has produced a relative min O_3 concentration between the now split peak O_3 area. During the next two hours, (Fig. 19j), the now fully-developed southeasterly Gulf Breeze advected

the O₃ max (still >125 ppb) to an area further northwest of Houston; this Figure also summarizes the trajectory of the main southern O₃-max for this episode day.

In summary, the O₃ meso-transport sequence for the episode day of 25 August sequentially showed a(n): 1) late-evening onshore-flow with a weak residual coastal O₃-max; 2) early morning northerly/offshore flow, 3) O₃ formation over the Ship Channel and westward advection into Houston by an UHI-enhanced Bay Breeze, 4) noon alongshore easterly coastal-flow from the northern edge of an offshore weak, cold, surface low, and 5) late-afternoon southeasterly Gulf Breeze that transported the O₃-max further northwest of Houston and thus produced NO₂-titration.

d. Urban effects

The cold surface-low seems centered offshore in episode-day observed temperatures at 1800 UTC (Fig. 20), as opposed to a coastal location in the MM5 results (Fig. 15a), although only one offshore observational site is available. The inland penetration of the cold marine air, however, was clearly retarded (by an urban building-barrier effect) and thus seems to wrap around Houston.

Urban effects on wind velocity were seen both in the observations and uMM5 results. The observed wind speed min (0.3 m s^{-1}) on 25 August at 0100 UTC over each of the two Houston urban-centers (Figs. 21a) is reproduced in the concurrent uMM5 results (Fig. 21b). The two observed maximum ($>3 \text{ m s}^{-1}$) over the coast were reproduced. Observed UHI-induced confluence over Houston was strongest on 24 August at 1800 UTC (Fig. 22a), while it was strongest in the uMM5 results at 1500 UTC on that day. A 2-m observed Houston UHI on 23 August at 1800 UTC (Fig. 23a) is also apparent in the con-

current uMM5 2-m values (Fig. 23b), although it is difficult to designate a single background rural temperature in either plot. The observed urban max temperature of 31°C is less than the corresponding uMM5 value of 33°C, but it is possible that no observation was taken at the max temperature location.

Domain-5 rMM5 results on 22 August at 0100 UTC (Fig. 24a) show nearly uniform 2-m temperatures with an average “end of day” 2.0 K UHI over Houston, while corresponding uMM5 values (Fig. 24b) show a more detailed distribution with an average of 3.5 K UHI over the city. The difference plot (Fig. 24c) shows the spatial distribution of the magnitude of the uMM5-produced increased daytime-UHI. The “blob” in Fig. 24a and c is due to an rMM5 LU/LC error, as the analyzed winter LANDSAT image erroneously classified that “summer-green” area as urban. Similar plots at 1400 UTC on the same day (Fig. 25a) show that rMM5 produced an “end of night” average of 2.5 K UHI, while uMM5 produced only an average of 1.0 K UHI (Fig. 25b). The difference plot (Fig. 25c) shows the spatial distribution of the magnitude of the uMM5-produced reduced nighttime-UHI.

These results are consistent with the study (discussed in Section 1) of the TI effects of different rural soil types by Imamura (2005), i.e., the TI of wet soils is greater than that of urban areas, which is greater than for dry soils. Urban areas surrounded by wet-rural soils thus have strong day-UHIs (as they warm faster than the soils) and strong night-UCIs (as they cool faster than the soils); the reverse is true for urban areas surrounded by dry rural-soils. The uMM5 results are thus consistent with an urban area surrounded by wet rural-soil, as expected because it rained east of Houston two-days before

the episode; uMM5 thus produced an enhanced daytime-UHI and a weakened nighttime-UHI.

The above Base-Case uMM5 simulation used the current HGA vegetation fraction distribution (Fig. 26a), in which Houston has a min tree density of about 0.43 and surrounding areas have a max value of 0.86. For the uMM5 reforestation simulation, the Houston fraction (Fig. 26b) was projected by the US-TFS to increase (via reforestation) by about 0.094 and decrease in surrounding areas (via suburbanization) by about 0.016. Resulting uMM5 2-m Reforestation-Case temperatures minus concurrent Base-Case uMM5 values (Fig. 27) at 2100 UTC (time of simulated max urban daytime-cooling) show reforested-Houston values decreased by up to 4 K, while those over surrounding deforested-areas warmed by up to 2 K.

The average hourly change of UHI-values over the episode period (23 August at 0000 LST to 25 August at 1800 LST) was computed by first averaging temperatures (5-hr running average) from each of the MM5/uMM5 simulations in a 0.1°lat by 0.2°long northern (to have a min sea-breeze effects) urban-area and a similar rural-area (Fig. 28). These averages were then used to calculate the diurnal variation of simulated UHIs and the difference between UHIs. The MM5 Domain 4 results (Fig. 29a) generally show UHIs during the first two nights (simulation ended before third night) and larger UCIs during all three daytime periods. The increased resolution Domain 5 reduced the daytime UCI on the first and third days and converted it into an UHI on the middle day. It also decreased the first nocturnal UHI, but increased the second one. The difference curve

thus shows that the increased resolution produced urban-warming during the entire period, except for the first night.

Urbanization of Domain 5 (Fig. 29b) further (totally) eliminated the two daytime UCIs and converted the two nighttime UCIs into UHIs. It thus produced UHIs throughout the simulation period, except for a brief period during the second night. The combined effects of urbanization and increased resolution (Fig. 29c) again show UHIs throughout the simulation period (except during the two nighttime periods) and that daytime UHIs are larger than with either change alone (except for the middle day, which was larger for the Domain-4 case).

The Reforestation (or urban-treed) Case (Fig. 29d) generally slightly increased nighttime UHIs, but greatly decreased daytime values (due to concurrently decreased urban temperatures in reforested areas and increased rural values in deforested newly suburban areas). The decrease was a maximum on 25 August (episode day) during the peak O_3 formation period of 1000-1400 LST, when the decrease reached to 3.3 K and over which it averaged to 2.8 K. In summary, the effects from use of a higher-resolution domain, uMM5, and/or urban reforestation on UHI-magnitude (Fig. 30) showed that the first two effects generally increase daytime UHIs, while reforestation has the opposite effect.

4. Conclusion

The current study used the highly urbanized Martilli-Dupont scheme within MM5 to investigate Houston UHI conditions during the 25 August TexAQS 2000 O₃-episode. The study also evaluated UHI changes that would occur from a proposed Houston tree-planting scenario. A detailed analysis was also carried out of interactions between observed (synoptic and mesoscale) met forcings that produced the episode.

The standard MM5 was used in four outer domains, while uMM5 was used only in the innermost domain (1-km grid spacing). Domain-5 urban inputs to uMM5 included externally supplied LIDAR morphology data sets (1-m resolution), a LU/LC sub-grid distribution (30-m resolution), and MODIS-derived surface TI, albedo, and vegetative-cover (1-km resolution). Projected HGA changes in vegetative cover by year 2010, obtained from the US-TFS, showed areas of urban reforestation and rural deforestation (around the city in areas slated for new suburban development); uMM5 input surface properties were thus modified accordingly. The following simulations were carried out: MM5 present day forest-coverage; uMM5 base-case present day forest-coverage; and uMM5 2010 reforestation. All simulations began at 0000 UTC on 22 August and ended at 2300 UTC on 26 August.

Results showed that NNRP fields input into MM5 correctly captured the large-scale forcing on NWS charts for the period. The episode resulted during a sustained period of low-speed weak synoptic-forcing at both 700 hPa and the surface. Both the dominant upper GC level high and its surface projection moved from a position east of Texas to one north of Texas during the night before the episode, which produced even

weaker pressure-gradients that allowed mesoscale flow features to develop. MM5 surface-winds during the episode period showed development of a weak surface offshore cold low on the episode day. Possible contributing factors for this low involve warm Gulf waters that push colder water to the Gulf shore and Ekman transport of surface water away from the coast, but a more focused analysis is required of this event, which entered MM5 via the input(assumed steady-state) initial-condition NNRP SST field.

The regular MM5 qualitatively captured the observed sequence of Bay, Gulf, and urban breezes effects on O_3 surface-transport on the episode day: formation over the Ship Channel, stagnation for several hours, westward advection into Houston by an UHI-enhanced Bay Breeze, noon alongshore easterly coastal-flow from the northern edge of the simulated offshore low, and late-afternoon southeasterly Gulf Breeze transport further northwest of Houston. The alongshore flow, associated with the MM5 offshore low, was more pronounced on the episode day than on the preceding and following days.

Urbanized MM5 better reproduced urban impacts on temperature, as end-of-day 2-m temperatures from regular MM5 showed a 2.0 K UHI, while it showed a 3.5 K value. End-of-night temperatures from regular MM5, however, showed a 2.5 K UHI, while it had only a 1.0 K value. These results are consistent with the wet rural soil that was around Houston (due to precipitation two days before the episode). uMM5 also reproduced observed urban impacts on regional wind flows: roughness-induced deceleration, building-barrier divergence, and UHI-induced convergence.

The effects from use of a higher-resolution domain, uMM5, and/or urban reforestation on UHI-magnitude showed that the first two effects generally increase daytime

UHIs, while reforestation had the opposite effect. The simulation of the US-TFS provided 2010 reforestation-projection slightly increased nighttime UHIs, but greatly decreased daytime values (due to concurrent decreased urban temperatures in reforested areas and increased rural values in deforested newly suburban areas). The decrease was a maximum on the episode day during the peak O₃ formation period, when it reached up to 3.3 K at noon and during 1000-1400 LST when it averaged to 2.8 K.

Future efforts should include improvements of poorly known MM5 inputs, such as deep soil temperature (which would correct min temperature biases); initial soil moisture (which would correct max temperature biases); SST (which would produce more accurate coastal temperature gradients and hence sea breeze flows); and sea and urban surface roughness parameters (which would produce more correct over-ocean and urban winds, respectively). The uMM5 urbanization modules could also be inserted into the new WRF model.

The current uMM5 output fields could be input into photochemical models, such as CAMx and CMAQ, to see if they would then better reproduce observed and projected future O₃ concentrations. Decreased UHIs should produce decreased max-O₃, as daytime UHIs generally worsen air quality as they: accelerate photochemical O₃ formation, increase anthropogenic emissions due to increased air conditioning usage, and increased natural emissions of O₃ precursors (e.g., VOC). While the current UHI-mitigation results are encouraging, the nonlinear interactions of these changes and their impacts on meso-scale flow fields have produced somewhat noisy results. Future decisions concerning emission-reduction credits should thus be based on simulations of additional episodes.

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Appendix A: List of abbreviations and acronyms

ADP	Administrative Data Processing
ATMET	Atmospheric, Meteorological, and Environmental Technologies
AVHRR	Advanced Very High Resolution Radar
BC	Boundary Condition
CAMS	Continuous Air Monitoring Stations
CAMx	Comprehensive Air Quality Model with Extensions
CMAQ	Community Multiscale Air Quality Model
CPU	Central Processing Unit
COAMPS	Coupled Ocean-Atmosphere Mesoscale Prediction System
COAST	Coastal Observation and Simulation with Topography
CSUMM	Colorado State University Mesoscale Model
DA	Drag-force based Approach
DA-SM2-U	Drag Approach-Soil Model 2-Urban
DIAL	Differential Absorption Lidar
DOE	Department of Energy
EDAS	Enhanced Data Acquisition System
FDDA	Four-Dimensional Data Assimilation
FFRT	Fast Forward Radiative Transfer
FVM	Finite Volume Model
GC	General Circulation
GEM	Global Environmental Management, Inc.

GMAQS	Gulf of Mexico Air Quality Study
GPS	Global Positioning System
HGA	Houston-Galveston Area
HOTMAC	High-Order Turbulence Model for Atmospheric Circulations
HRMC	Houston Regional Monitoring Corporation
IC	Initial Condition
LA	Los Angeles
LANDSAT	Land-Use Satellite
LIDAR	Light Detection And Ranging
LLC	Limited Liability Company
LSM	Land Surface Model
LU/LC	Land Use/Land Cover
MCNC	Microelectronics Center of North Carolina
MM4	4th generation Penn State-NCAR Mesoscale Modeling system
MM5	5th generation Penn State-NCAR Mesoscale Modeling system
MODIS	MODerate-resolution Imaging Spectroradiometer
MRC	Mission Research Corporation
MRF	Medium Range Forecast
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NDVI	Normalized Difference Vegetation Index

NNRP	NCEP-NCAR Reanalysis Project
NOAA	National Oceanic and Atmospheric Administration
NOAH	National Centers for Environmental Prediction (NCEP) Oregon State University (Dept of Atmospheric Sciences) Air Force Hydrology Lab; NWS Office of Hydrology
NWS	National Weather Service
NYC	New York City
O ₃	Ozone
OHM	Objective Hysteresis Model
OSU	Oregon State University
PBL	Planetary Boundary Layer
RA	Roughness-length based Approach
RAMS	Regional Atmospheric Modeling System
RAPS	Regional Air Pollution Study
rMM5	regular MM5
RRTM	Rapid Radiative Transfer Model
SAIMM	System Applications International Mesoscale Model
SoCAB	Southern California Air Basin
SSATS	Sea Surfaces Atmosphere Transfer Scheme
SST	Sea Surface Temperature
SVF	Sky View Factor
TAMU	Texas A&M University

TCEQ	Texas Commission on Environmental Quality
TexAQ5	Texas Air Quality Study
TFS	Texas Forest Service
TI	Thermal Inertia
TKE	Turbulent Kinetic Energy
TM	Topographic Map
TNRCC	Texas Natural Resource Conservation Commission
TOPLATS	Topographic Model-based Land-Atmosphere Transfer Scheme
TVM	Topographic Vorticity Model
UAM	Urban Airshed Model
UCP	Urban Canopy Parameterization
UH	University of Houston
UHI	Urban Heat Island
uMM5	urbanized MM5
URBMET	URBan METeorology
USGS	United States Geological Survey
VOC	Volatile Organic Compound
WRF	Weather Research and Forecasting

Appendix B: Tables

TABLE 1. Characteristics of MM5 domains.

Domain	Horizontal-grid resolution (km)	No. of (x,y,z) grid-points	Feedback option
1	108	43,53,28	2-way
2	36	55,55,28	2-way
3	12	100,100,28	2-way
4	4	136,151,28	2-way
5	1	133,141,48	None

TABLE 2. LU/LC classes-assignments used (shown by *) in 2000 and 2010, where η is soil moisture fraction and z_0 surface roughness-length (from Taha *et al.* 2005).

No.	Class	Year		Assigned η (non-dim)	Assigned z_0 (cm)
		2000	2010		
11590	Urban residential	*	*	0.30	30
13590	Urban built	*	*	0.10	50
16590	Urban vegetation	*		0.40	30
22590	N. Agriculture	*	*	0.25	15
22591	S. Agriculture	*		0.25	15
37590	N. Broadleaf	*	*	0.30	30
37591	N. Coniferous	*		0.30	30
37592	N. Mixed forest	*		0.30	30
37593	S. Forest	*		0.30	30
40590	Water	*	*	1.00	0.01

Appendix C: Figures

FIG. 1. Map of Texas, with Houston shown by red star. [Available online at <http://www.mapquest.com/maps/=Houston>]

FIG. 2. Locations of Houston-Galveston, Palacios, and Beaumont-Port Arthur areas, shown by red stars. [Available online at <http://www.mapquest.com/maps/=Palacios>]

FIG. 3. Location of Ship Channel. [Available online at www.houstontravelguide.com/maps/]

FIG. 4. Modeling Domains 1-5.

FIG. 6. TFS fractional coverage of urban LU/LC classes for Domain-5.

FIG. 7. 700 hPa charts on 23 August 2000 at 0000 UTC for: (a) NWS (30-m interval) and (b) NNRP (10-m interval).

FIG. 8. 700 hPa charts on 25 August 2000 at 0000 UTC for: (a) NWS (30-m interval) and (b) NNRP (10-m interval).

FIG. 9. 700 hPa charts on 25 August 2000 at 1200 UTC for: (a) NWS (30-m interval) and (b) NNRP (10-m interval).

FIG. 10. Surface charts on 23 August 2000 at 0000 UTC for: (a) NWS (4-hPa interval) and (b) NNRP (1-hPa interval).

FIG. 11. Surface charts on 25 August 2000 at 0000 UTC for: (a) NWS (4-hPa interval) and (b) NNRP (1-hPa interval).

NNRP (108 km grid) pressure
on 1000 hPa at 12 UTC on 8/25/00

FIG. 12. Surface charts on 25 August 2000 at 1200 UTC for: (a) NWS (4-hPa interval) and (b) NNRP (1-hPa interval).

FIG. 13. MM5 surface winds (1 barb is 1 m s^{-1}) on 25 August 2000 at 2000 UTC for Domains: (a) 1, (b) 2, and (c) 3; red arrow shows alongshore flow.

FIG. 15a. MM5 Domain-3, 10 m temperatures (K) on 26 August 2000 at 2100 UTC.

FIG. 15b. Gulf of Mexico April to December 2005 averaged SST (K).
[Available online at <http://www7333.nrlssc.navy.mil>]

FIG. 16. Satellite-derived: SST ($^{\circ}\text{C}$) and relative ocean surface-current (vectors) on 9 July 2004 at 0800 UTC off of NYC (from Pullen 2006).

FIG. 17. uMM5 Domain-4 surface winds (1 barb is 1 m s^{-1}) and temperature (K) at 2000 UTC on August: (a) 22, (b) 23, (c) 25, and (d) 26.

FIG. 18. Observed winds on 25 August 2000 at 1500 UTC over: (a) Texas (kt), red box is HGA-region, (b) HGA (kt), and (c) gridded HGA values (m s^{-1}), red box is HGA-region (b).

10 m Observed wind (m/s) and ozone (ppb) at 0200 UTC on 08/25/00 10 m Observed wind (m/s) and ozone (ppb) at 0300 UTC on 08/25/00

10 m Observed wind (m/s) and ozone (ppb) at 0900 UTC on 08/25/00 10 m Observed wind (m/s) and ozone (ppb) at 1200 UTC on 08/25/00

FIG. 19. Observed 10-m O_3 concentration (increment of 5 ppb until 1600 UTC and then 10 ppb thereafter) and gridded-winds ($m s^{-1}$) on 25 August 2000 at: (a) 0200, (b) 0300 (c) 0900, and (d) 1200 UTC.

10 m Observed wind (m/s) and ozone (ppb) at 1600 UTC on 08/25/10 m Observed wind (m/s) and ozone (ppb) at 1700 UTC on 08/25/00

10 m Observed wind (m/s) and ozone (ppb) at 1800 UTC on 08/25/00 10 m Observed wind (m/s) and ozone (ppb) at 1900 UTC on 08/25/00

FIG. 19. Observed 10-m O_3 concentration (increment of 5 ppb until 1600 UTC and then 10 ppb thereafter) and gridded-winds ($m s^{-1}$) on 25 August 2000 at: (e) 1600, (f) 1700, (g) 1800, and (h) 1900 UTC.

10 m Observed wind (m/s) and ozone (ppb) at 2100 UTC on 08/25/00

FIG. 19. Observed 10-m O₃ concentration (increment of 5 ppb until 1600 UTC and then 10 ppb thereafter) and gridded-winds (m s⁻¹) on 25 August 2000 at: (i) 2100, and (j) 2300 UTC; purple line shows trajectory of southern O₃ max.

2 m Observed Temperature (C) on 4 km Domain at 1800 UTC on 08/25/00

FIG. 20. Domain-4 gridded observed temperatures (°C) on 25 August 2000 at 1800 UTC, where observational sites shown as blue dots and red arrows show cold marine air penetration.

FIG. 21. 10-m wind speeds (m s^{-1}) on 25 August 2000 at 0100 UTC: (a) observed and (b) uMM5 Domain-5; where “+” and “-” are max and min speeds, respectively.

FIG. 22. UHI-induced winds (m s^{-1}) on 24 August 2000 at: (a) 800 UTC (observed) and (b) 1500 UTC (uMM5 Domain-5); where C is the area of wind convergence.

2 m Observed Temperature (C) on 1 km Domain at 1800 UTC on 08/23/00

08/23

FIG. 23. 2-m Domain-5 temperatures on 23 August 2000 at 1800 UTC for: (a) observed ($^{\circ}\text{C}$) and (b) uMM5 (K); where “+” is max.

FIG. 24. 2-m Domain-5 temperatures (K) on 22 August 2000 at 0100 UTC from: (a) rMM5, (b) uMM5, (c) difference (uMM5-rMM5).

FIG. 25. 2-m Domain-5 temperatures (K) on 22 August 2000 at 1400 UTC from: (a) rMM5, (b) uMM5, (c) difference (uMM5-rMM5) (uMM5-rMM5).

FIG. 26. Forest fractional: (a) coverage in 2000 and (b) reforestation by 2010.

FIG. 27. Temperature change (K) from 2000 to 2010 on 26 August 2000 at 2100 UTC; where W and C denote warm and cold areas, respectively.

FIG. 28. Urban and rural averaging areas in a 1°lat by 2°long boxes.

FIG. 29. Area-averaged UHI and UHI change (K) for runs: (a) rMM5 Domains 4 and 5, (b) rMM5 Domain-5 and uMM5 Base-Case.

FIG. 29. Area-averaged UHI and UHI change (K) for runs: (c) rMM5 Domain-4 and uMM5 Base-Case and (d) uMM5 Reforestation and Base-Case.

FIG. 30. Area-averaged UHI (K) for runs of FIG. 29.