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MM5 simulations of urban induced convective precipitation over Atlanta, GA

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**MM5 SIMULATIONS OF URBAN INDUCED CONVECTIVE PRECIPITATION
OVER ATLANTA, GA**

**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
Kenneth Johnson Craig Jr.**

May 2002

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ABSTRACT

MM5 SIMULATIONS OF URBAN INDUCED CONVECTIVE PRECIPITATION OVER ATLANTA, GA

by Kenneth J. Craig Jr.

Many efforts to simulate urban effects on convective precipitation omitted microphysical effects, while others produced convection as an undesired by-product of urban heat island (UHI) simulations. The current study thus uses Project ATLANTA data, and MM5 with quadruple nested grids to investigate a UHI initiated convection case over Atlanta, Georgia. The specific hypothesis tested is that urban-induced convergence zones initiate convective precipitation.

Results show significant precipitation from a quasi-stationary front south of Atlanta and from UHI-induced convergence around the urban edges. When Atlanta roughness lengths and thermal properties were removed, the second precipitation region was eliminated, thus showing its urban origin. Results show good correlation between the surface UHI, convergence, and vertical velocity. Urban precipitation, however, was simulated somewhat northeast of the observations, about 3 h too early, but around the correct magnitude. Future simulations will focus on correcting these differences by further refinements of input urban surface parameters.

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1. Introduction

The lower urban atmosphere has a vertical structure more complex than simple rural areas, as it consists of canopy and roughness sublayers (Fig. 1). This complexity is, however, comparable to rural areas with multiple layers of vegetation (e.g., forests). Urban canopy layers (UCLs) are composed of diverse individual street canyons, while roughness sublayers are non-equilibrium transition layers (in which Monin-Obukhov similarity theory is thus invalid), where vertical momentum, energy, moisture, and pollutant fluxes from individual canyons blend (Rotach 1993a,b; Mestayer and Anquetin 1994). Determination of roughness sublayer boundaries is difficult, and thus urban PBLs are difficult to simulate. Techniques of varied sophistication can link UCL and PBL models. The following reviews urban climate effects on atmospheric flow fields and precipitation patterns, as well as past urban modeling efforts.

a. Urban climate

Urban reviews (e.g., Bornstein and Oke 1981; Bornstein 1987; Oke 1987; Imamura and Bornstein 1992) show consensus on the causes and nature of various urban climate impacts on temperature, humidity, and flow. No such consensus can be found, however, on urban effects on precipitation.

Buildings and other non-natural urban surfaces lead to the formation of urban heat islands (UHIs) due to the following simultaneous upsets (relative to rural areas) to the surface energy balance (Bornstein 1987):

- anthropogenic heat release (Leach et al. 2001) from vehicles, buildings, and industry

- increased absorption of incoming solar radiation due to urban canyons
- decreased outgoing long-wave radiation due to reduced urban sky-view factors
- greater daytime storage (and nocturnal release) of solar energy due to thermal properties of building materials
- decreased outgoing long-wave radiation due to elevated pollution layers
- increased thermal convective heat fluxes due to reduced latent heat fluxes from nonporous urban surfaces
- increased mechanical convective heat fluxes due to rough urban surfaces.

Air traversing warm rough urban areas thus encounters changes in surface and atmospheric characteristics that alter existing mean and turbulent wind velocity fields (Bornstein and Johnson 1977). In particular, UHIs cause pressure field deformations, buildings produce barrier effects, and large urban surface roughness length values increase surface frictional drag. In otherwise calm synoptic flows, the UHI produces 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 diffluence at the upwind urban edge divides regional flows as they approach a city, especially during stable nocturnal conditions (Bornstein and LeRoy 1990). The diffluence produces cyclonic turning over the left-hand urban edge (looking downstream) and anticyclonic turning over the right-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.

Altered urban dynamic and thermodynamic fields, in conjunction with possible cloud condensation nuclei (CCN) effects, thus affect urban cloud and precipitation patterns. Climatological and case-event urban precipitation studies, summarized by Lowry (1998) and Lin (2000), indicate that urban areas influence the formation and/or movement of precipitation areas, especially during summer convection. Altered precipitation characteristics include: timing, amount, frequency, and location, with enhancement up to 65 km downwind of a city (Changnon et al. 1981). These alterations have been attributed (mostly without supporting analyses) to urban: convergence/uplift from UHIs, roughness, moisture from combustion, increased CCN, and/or building-barrier effects.

Climatological analyses of summer convective radar echoes over New York City (NYC) by Bornstein and LeRoy (1990) showed convection initiated over the city by a UHI convergence zone during calm synoptic flows. Thunderstorms moving with regional flows, however, tended to move around the city (dubbed “urban bifurcation” by Lin 2000), possibly due to building-barrier effects. This produced an echo minimum over the city, with surrounding lateral and downwind maxima.

Recent climatological precipitation studies (Selover 1997) and case studies of thunderstorms (Lin 2000) found possible urban barrier-influenced precipitation minima

over Phoenix and Atlanta, respectively. Jauregue and Romales (1996) documented climatological UHI enhancement of convective storms over Mexico City. Lin and Bornstein (2000) documented UHI initiation of Atlanta convective storms by use of mesonet data to find spatial and temporal agreements between UHI intensity, confluence, convergence, cloud cover, relative humidity, and precipitation. These recent observational studies have thus provided new insights into urban alteration of precipitation patterns.

As shown in the following section, meso-modeling efforts have also provided insights into the effects of urbanization on various aspects of urban climate. They have, however, generally not focused on urban effects on precipitation.

b. Urban models

The urbanization of numerical models began with the 1-D diagnostic parameterized surface energy balance and UHI model of Myrup (1969). While infrared radiative flux divergence was not included, roughness length, albedo, soil heat capacity, and relative humidity were specified for an urban area represented by a “flat concrete slab.” Results showed that reduced urban surface moisture and increased thermal inertia caused UHI formation, but without prognostic dynamical equations the model could not predict the urban flow field nor account for feedback between the flow and surface energy fluxes. Numerous studies extended this work, e.g., Tapper et al. (1981) included a multi-layer soil heat diffusion equation with anthropogenic heating (Q_A), while Ackerman (1977) included radiative effects of urban gaseous and particulate pollutants. Urban canyon effects on surface energy budgets were studied by Johnson et al. (1991) using the 1-

D force-restore SHIM model, which considered heat fluxes from buildings and single-reflection of infrared radiation within urban canyons.

The first 2-D (vertical plane) urban PBL models consisted of analytical solutions to simplified “linearized” equations, e.g., Vukovich (1971, 1973, 1975) used a three-layer model with no Coriolis force, linear friction, and specified differential heating rates. Olfe and Lee (1971) used an invicid, Boussinesq, linearized two-layer model that included the Coriolis force to obtain steady-state solutions for wind and temperature perturbations.

Delage and Taylor (1970) were the first to use a 2-D non-linear, zero topography, numerical, hydrostatic model with prognostic dynamical equations (but not a surface energy balance) to study UHI-induced circulations (neglecting roughness differences) under zero synoptic wind conditions. Similar 2-D models simulated UHI-induced circulations with non-zero synoptic flows (Yamada 1972, McElroy 1973; SethuRaman et al. 1974, 1975; Lee and Olfe 1974; Yu and Wagner 1975; Welch et al. 1978). The 2-D hydrostatic, Boussinesq, vorticity-mode boundary layer model (URBMET) of Bornstein (1972, 1975) was the first to simulate flows over a warm and rough urban area. Simulations reproduced roughness deceleration at the upwind urban edge, UHI-induced maximum speeds at the downwind edge, and weakened near-surface return flow downwind of the city. Yoshikado (1992) studied interactions between the Tokyo UHI and sea breeze circulations with a similar model.

Vukovich et al. (1976) was 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 reproduced many features of observed urban tem-

perature, horizontal velocity, and vertical velocity distributions. It also produced cyclonic inflow around the UHI during low wind speeds, but at higher speeds, UHI intensity decreased and the downwind thermal plume lengthened. Vukovich and Dunn (1978) 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 Vukovich model, however, could not accommodate changing synoptic conditions, and did not consider the surface energy budget (thus surface UHI intensity was prescribed).

Feedback from predicted flow field parameters to surface UHI intensity requires inclusion of prognostic equations linked through iterative solutions to the surface energy balance equation. This was first achieved in the non-linear PBL models of Atwater (1972) who used the time dependent 1-D model of Pandolfo (1966), and of McElroy (1973) who used a flat steady 2-D extension of the Estoque (1963) model. Atwater also was first to include radiative effects from pollutants (with steady state concentrations) and moisture, while Bergstrom and Viskanta (1973a, b, c) used a 1-D model with an enhanced radiation scheme.

Sawai (1978) utilized a steady-state 2-D non-topographic, Boussinesq, hydrostatic model with soil heat and moisture equations. A constant Q_A was added to the temperature tendency at the lowest model level, and not to the surface energy budget. Dieterle (1979) used a $Q_A(t)$ in the surface energy balance equation of his 1-D version of URBMET, which thus predicted realistic diurnal temperature waves and UHIs. More recent modeling efforts (see below) have divided Q_A between the surface and lower atmos-

phere. Schultz and Warner (1982) used the 2-D non-steady state hydrostatic predecessor of MM4 (Anthes and Warner 1978) to study urban, coastal, and topographic circulations in the Los Angeles Basin. They found urban effects (including Q_A) smaller than those from sea breeze and mountain/valley circulations, but did note the need to correctly represent urban surfaces.

Hydrostatic 3-D models with linked prognostic dynamic and surface energy budget equations have also been applied to urban areas, e.g., Atwater (1975) considered natural topographic and pollutant effects on UHI development. While this application came before the Vukovich et al. (1976) study discussed above, it was computationally limited to a small idealized domain, whereas Vukovich et al. used a realistic St. Louis domain. Bornstein et al. (1986) expanded the 2-D URBMET model into a non-topographic 3-D model linked to a 3-D air quality dispersion model for NYC. The model included higher-order turbulence closure and a prognostic energy balance equation with $Q_A(t)$ divided between the surface and atmosphere. Detailed PBL data collected over St. Louis during the Regional Air Pollution Study (RAPS) (Ching et al. 1983) was used by Seaman et al. (1989) in an MM4 simulation with two-way nested grids and realistic synoptic initial and boundary conditions. Results reproduced a UHI-induced downwind cyclonic vortex. Kimura and Takahashi (1991) simulated the Tokyo UHI with a Boussinesq model that contained two nested domains, natural topography, subgrid-scale urban land-use variability, and Q_A .

Thunis (1990) incorporated natural topography and higher-order turbulence effects into the Topographic Vorticity Model (TVM) version of URBMET, while Bornstein

et al. (1993) used TVM with urban “building blocks,” i.e., grid-averaged urban-building heights added to natural topography heights. The model simulated slowed sea breeze frontal movement over NYC, as well as daytime convergence into and nighttime divergence out of the city. Panayiotou (1995) used TVM to produce a horizontal anticyclonic and cyclonic downwind vortex pair against the mountain range north of Phoenix. The primitive equation, hydrostatic, incompressible Colorado State University Mesoscale Model (CSUMM) (Pielke 1974) was used to study urban albedo (Taha 1997) and vegetation (Taha 1998) effects over the Los Angeles Basin. CSUMM has also been used to investigate Atlanta soil moisture (Hafner and Kidder 1999) and air quality impacts (Taha 1999).

Kitada et al. (1998) simulated interactions between flows over the Nohbi Plain induced by the Sea of Japan and natural topography with a hydrostatic model that included advanced k- ϵ turbulence closure. While Saitoh (1996) used a Boussinesq model with only first-order turbulence, he was the first to use a non-hydrostatic formulation to study the Tokyo UHI. Modeled surface temperatures were more accurate than from the hydrostatic studies of Kimura and Takahashi (1991).

c. Urbanization details

The above section summarized the evolution of numerical models of the urban PBL from their 1-D energy balance origins up to the current 3-D higher-order non-hydrostatic versions. This section focuses on the details of the 1-D urban parameterization used in all such models.

Many urban effects have been simulated with a flat (zero building height) sand-box approach, in which urban and non-urban surface grid points have different specified values of aerodynamic, thermal, and radiative coefficients in the surface energy and moisture balance equations. This approach qualitatively reproduces many urban effects, such as: UHIs, roughness-induced decelerations, UHI-induced accelerations, and frictional retardation of moving synoptic and sea breeze fronts. Observed frontal distortions, however, can only be reproduced by building-barrier approaches (Bornstein et al. 1993). Furthermore, aerodynamic and thermodynamic effects are only *indirectly* transmitted to the atmosphere via the SBL and surface energy balance equations.

Many studies also represent urban areas by a single land-use category, but this approach assumes a homogeneous urban zone and fails to account for intra- and inter-cell variability. Urban areas consist of downtown, industrial, and suburban regions with different building heights/densities and anthropogenic heat releases, and only multiple urban land-use categories with different surface properties (e.g., Hjelmfelt 1982) can account for this variability.

Urban grid cells also contain a mixture of roofs, concrete, asphalt, and green spaces, again with different surface properties that significantly impact urban meteorology (Taha et al. 1994) and pollutant concentrations (Taha 1996). Since typical mesoscale model grid cells (even at 1 km^2) are too large to resolve this variability, parameterizations are necessary. For example, the heat flux for an urban grid cell may be determined from the average of individual heat fluxes from each surface-type, weighted by surface area occupied within the cell (Kimura 1989; Kimura and Takahashi 1991). Urban surface pa-

rameters are often derived from scarce *in-situ* observations (Grimmond and Oke 1999a), and recent efforts have thus focused on the use of satellite-retrieved surface thermal and moisture characteristics for use in urban numerical models (Hafner and Kidder 1999).

Heat from combustion, internal space heating, and air conditioning are accounted for by the Q_A term, which is arbitrarily specified or based on energy consumption data. Until recently, this term has been added solely to the surface energy budget equation (except Sawai 1978), but it is unclear whether all or some of it should heat the SBL and UCL via the thermodynamic equation (Brown 2000).

Buildings produce pressure and viscous forces (Panton 1984), which alter wind speeds and increase turbulent mixing (Brown 2000). To reproduce urban deceleration effects in the simplest way, most models increase urban roughness length (roughness length approach); drag (but not barrier) effects are thus only implicitly modeled. Application of Monin-Obukhov (M-O) similarity theory over urban areas causes problems, as the lower boundary of urban models is rooftop level and the theory is only valid in horizontally homogeneous equilibrium SBLs (a problem even in “real world” non-urban areas). It therefore does not apply below the urban displacement height (nor below rural vegetation canopies), but no theory exists to specify the vertical structure of the urban roughness sub-layer. Turbulent flux measurements in and above urban canyons have shown that local-scaling (parameters variable with height) is better than SBL-scaling (Rotach 1993a,b; Rotach 1995). Such observations could support development of new SBL formulations for urban models. With respect to the second problem, equilibrium boundary layer (EBL) slopes downwind of changed surface characteristics are about 1/100. As long as

the model ratio of SBL top (depth of lowest grid cell) to horizontal grid spacing is less than 1/100 (as is the case with small vertical grid spacing), the EBL will be deeper than the SBL. M-O theory will thus apply (forgetting about lower boundary problems) if each horizontal grid cell is assumed horizontally homogeneous (Shir and Bornstein 1977).

Recent efforts with 3-D meso- and building-scale models have thus focused on improved urbanization schemes for the momentum, energy, and/or turbulence kinetic energy (TKE) equations, e.g., the: hydrostatic q^2 - l HOTMAC (Brown and Williams 1998), hydrostatic Boussinesq k - ϵ CSUMM (Urano 1999), non-hydrostatic Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) (Leach et al. 2001), and nonhydrostatic Boussinesq anelastic Finite Volume Model with one-equation TKE closure (Martilli et al. 2000). The building-scale k - ϵ models of Maruyama (1999) and Ca et al. (1999), as well as the vorticity model of Sievers (1995), also include similar urbanizations.

Recent models have also moved Q_A from the surface energy budget to the thermodynamic equation (Brown and Williams 1998; Ca et al. 1999; Taha 1999; Urano et al. 1999). This releases anthropogenic heat directly into the atmosphere (e.g., internal building heat escaping through windows and walls), and allows for more accurate prediction of UCL temperatures in models with grid levels within this layer. Urano et al. (1999) used Q_A from the first floor of buildings (and half the vehicular heat emission) in the surface energy budget, while Q_A from building levels above the first floor (and the other half of vehicular heat) were used to heat the atmosphere.

Other models replace the surface energy balance equation by a more accurate finite volume equation, i.e.,

$$R_N = Q + Q_A + Q_L + Q_G + \Delta H_S,$$

where R_N is net all-wave radiation, Q is sensible heat flux, Q_G is ground heat flux, and Q_L is latent heat flux. The parameterized thermal storage term ΔH_S represents the net uptake or release of energy from buildings, vegetation, and the ground (Grimmond et al. 1991). Some schemes (e.g., Peikorz 1987) require numerous input data, such as building orientation, as well as interior and exterior temperatures for all walls and horizontal surfaces. The model of Kerschgens and Hacker (1985) demands less input, as it computes ΔH_S as the area-weighted sum of observed heat fluxes.

Thermal storage may also be parameterized in terms of R_N . Oke et al. (1981) first expressed ΔH_S by a linear function. Because maximum daytime ground heat flux/heat storage precedes maximum R_N (Lettau 1951; Sellers 1965; Monteith 1973; Idso et al. 1975), when R_N is plotted against ΔH_S , a hysteresis loop (that linear models failed to reproduce) results. Grimmond et al. (1991) generalized the Camuffo and Bernardi (1982) non-linear regression for ΔH_S to the “objective hysteresis model” (OHM), which only requires R_N , surface cover data, and regression coefficients as inputs. Taha (1999) incorporated OHM into CSUMM via a daytime urban-weighted temperature tendency term in the surface energy balance. The urbanized model produced a stronger, more accurate Atlanta UHI than that simulated by the unmodified CSUMM. Grimmond and Oke (1999b) discuss strengths and weaknesses of OHM.

A recent parameterization for urban surface effects is the Town Energy Budget (TEB) scheme of Masson (2000), the first parameterization (for mesoscale models) to explicitly consider the simultaneous effects of buildings, roads, and other artificial materials on the urban surface energy budget. The model parameterizes local canyon geometry, as well as the roughness sublayer, and thus provides the lower-boundary constant-flux condition for an atmospheric model. The French non-hydrostatic mesoscale model linked with TEB reproduced the main urban effects of Paris (Masson et al. 2000).

Until recently, only building-scale urban models (e.g., Arnfeld 1982; Mills 1997; Ca et al. 1999) considered radiative attenuation by buildings via schemes that determine separate energy balances (and thus solve for separate temperatures) for walls, roofs, and streets. Recently, Brown and Williams (1998) and Martilli et al. (2001) have modified mesoscale models to consider the bulk effects of this attenuation on thermodynamic variables within the urban canopy via modifications of the thermodynamic equation. Brown and Williams divided urban areas into roof and canyon fractions, included Q_A , and added terms to account for rooftop heat flux and radiative flux divergence within canyons, but neglected heating due to walls. Martilli et al. (2001) used a variation of the TEB model to account for shadow effects and multiple urban canyon reflections, and thus solved separate energy budget equations for roofs, walls, and streets.

As log-law profiles are invalid within UCLs, empirical formulae, often extensions of those derived for vegetative canopies (Cionco and Ellefsen 1998), can be used to modify SBL wind profiles. However, as coefficients for these formulae have not been

developed for urban canopies, until recently only roughness length approaches have been used in mesoscale models to account for urban effects on wind velocity.

Newer approaches do not rely solely on M-O theory to implicitly transmit building effects to the velocity field (via increased roughness length), but also directly transmit these effects through sink terms in the horizontal momentum equations. This approach is an extension of plant canopy formulations (Wilson and Shaw 1977; Yamada 1982; Liu et al. 1996) and has been used in HOTMAC (Brown and Williams 1998), CSUMM (Urano et al. 1999), and the vorticity model of Sievers (1995, 2001).

Building area density profiles (building surface area perpendicular to the wind per unit volume) are required for these terms, and Brown and Williams hypothesized a pyramid-shaped building mixture profile. They further likened the new momentum sink term to a “drag” effect. Martilli et al. (2001) also used the drag term to account for wall effects, and added two additional “frictional” sinks to the momentum equations to account for horizontal roof and canyon floor surfaces. Bornstein (2001) has suggested that the original sink term name be changed from “drag” to “barrier,” as it arises from building-wall effects. He has also suggested that the names of the two horizontal terms thus be changed from “friction” to “drag,” as they arise from drags induced by horizontal surfaces.

Treatment of urban effects also requires additional parameterizations of the enhanced TKE production and dissipation within urban canopies. Sorbjan and Uliasz (1982) thus used a modified eddy diffusivity in their first-order TKE model, while Sievers (1995; 2001) modified the turbulence length scale and exchange coefficient based on

wall area density. For models with higher-order turbulence closure, an additional source term is added to the TKE equation (Maruyama 1999; Urano et al. 1999), while drag terms are added to the dissipation (Maruyama 1999) and/or q^2 -/ equations (Brown and Williams 1998). These terms again are derived from those suggested by Yamada (1982) for vegetative canopies. The TKE source term in Martilli et al. (2001) accounts for wall impacts, while additional street- and roof-level source terms consider shear and buoyancy production due to appropriate friction velocities and surface heat fluxes. A second (below roof level) length scale was also added, as buildings induce circulations comparable to their size.

All the above approaches assume that while buildings affect the flow field, they do not occupy space within grid cells. Porous flow approaches, however, treat airflow through urban canyons similarly to flow through pores. To account for air-volume reduction in grid cells due to buildings, Maruyama (1999) and Ca et al. (1999) included a fractional-volume term in their equations, while Sievers (1995; 2001) used a porosity parameter to determine the “effective grid-cell density” of a group of urban canyons. Martilli et al. (2001), however, are the only ones to currently consider this effect in a mesoscale model.

In summary, various parameterizations are available for simulations of urban PBLs. In particular, they provide impetus for well-posed simulations of urban effects on precipitation.

d. Urban precipitation modeling

Despite observations that suggest that urban areas alter precipitation patterns, few modeling studies of the phenomenon have been performed. Metropolitan Meteorological Experiment (METROMEX) precipitation field study data (Changnon et al. 1981) were used with two early models to study urban-induced precipitation. Ochs (1975) used a 2-D time-dependent shallow Boussinesq cloud model to show that UHIs produce preferred regions of cumulus initiation during two observational periods. Hjelmfelt (1982) used the 3-D University of Virginia (Pielke 1974) hydrostatic Boussinesq model to show that the St. Louis UHI produced regions of upward vertical velocity downwind of the city that correlated well with METROMEX regions of maximum first-echo frequency. This result was consistent with the hypothesis that observed downwind cloud and precipitation anomalies were related to UHI- and roughness-induced PBL convergence and upward motion areas. He could not establish a physical link between these urban PBL forcings and precipitation initiation, however, as the model did not consider cloud processes.

Recent idealized investigations have used 2- and 3-D non-hydrostatic models to study urban precipitation. Thielen et al. (2000) urbanized the 2-D anelastic model of Clark (1977) and Clark and Farley (1984) to consider effects of natural topography, Bowen ratio, roughness length, and sensible heat flux on Paris precipitation. Strong UHIs induced greater precipitation near the city, while weak UHIs promoted downwind rainfall; urban roughness played only a secondary role.

Baik and Kim (2001) used a 2-D version of the University of Oklahoma Advanced Regional Prediction System (ARPS) to study responses of vertically uniform sta-

bly stratified flows to specified heating rates, but without radiation, topography, land-use, roughness, rotation, and ice-cloud processes. Small heating rates and large wind speeds produced flow fields consistent with linear theory, as thermally-induced stationary gravity waves formed over and downwind of the heated region. Larger heating rates produced non-linear flows, characterized both by stationary gravity waves near the heated region and by an updraft cell that propagated downwind with the mean flow and triggered moist convection under favorable thermodynamic conditions. Rozoff and Cotton (2001) presented results from a 3-D Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992) simulation using a non-nested grid (with a horizontal grid spacing of 1.5 km) and a single sounding initialization to study summertime convective initiation by the St. Louis UHI.

Recent 3-D simulations of the interactions between urban- and water-induced circulations with non-idealized, fully coupled mesoscale models have produced serendipitous results with respect to convection. Simulations with MM5 (Nielsen-Gammon 2000) focused on interactions between the Houston UHI and sea-breeze circulations from the Gulf of Mexico and Galveston Bay during otherwise calm conditions. The UHI apparently initiated model convection, as shown by their simulated divergent outflow region, even before sea breeze flow penetrated to the city. Qiu et al. (2000) used the Canadian mesoscale model (MC2) to study interactions between the Toronto UHI and Lake Ontario lake-breeze. Their presentation showed that convection occurred when the lake-breeze convergence zone combined with the inland urban induced convergence zone.

The few previous modeling studies of urban-induced convective precipitation have either made numerical (dimensions and/or resolution) or dynamic (e.g., single sounding initialization) simplifications, omitted microphysical effects, or did not analyze their serendipitous results. MM5 will thus be used in the current study to test the hypothesis that urban-induced convergence zones can initiate convective precipitation during weak regional flows over warm, rough cities. Results from the Project ATLANTA observational study have provided the impetus for this study.

2. Methodology

a. Project ATLANTA

The overall goal of Project ATLANTA (Atlanta Land use Analysis: Temperature and Air quality) was investigation of regional climate and air quality impacts from past, current, and future urbanization of Atlanta, Georgia (Quattrochi et al. 1998). Results include those from modeling studies of the Atlanta UHI with the hydrostatic CSUMM (Taha 1999) and non-hydrostatic RAMS (Hafner and Kidder 1999). RAMS was used in conjunction with satellite-derived surface/soil parameters, while the CSUMM surface energy storage term was urbanized with the OHM.

Bornstein and Lin (2000) and Lin (2000) collected and analyzed project ATLANTA data from 26 July to 3 August 1996 for 32 surface sites (Figs. 2 and 3) in a mesoscale meteorological network (Hoogenboom 1996). Mesonet data at 15 min intervals were augmented with hourly data from eight regional National Weather Service (NWS) surface sites, as well as from the twice-daily NWS Peachtree City (FFC) rawinsonde launch. From these data, six summer convective precipitation events over Atlanta during the nine-day period were studied. The current study focuses on the 26 July case, the only daytime convective case that may have been initiated by the Atlanta UHI (Lin 2000).

b. MM5 application

The study utilizes the non-hydrostatic 3-D PSU/NCAR MM5 mesoscale model (Version 3-4), which uses a terrain-influenced vertical coordinate and split semi-implicit

temporal integration scheme (Dudhia 1993). The current simulations use quadruple nested domains in Lambert conformal projection (Fig. 4). Domain 1 (outermost) is centered at 36.00°N, 84.36°W, has a horizontal grid resolution of 81 km, contains 38x39 horizontal grid points in the E-W and N-S directions, respectively, and encompasses the eastern two-thirds of the U.S. Domain 2 has a grid resolution of 27 km and dimensions of 55x55, Domain 3 a resolution of 9 km and dimensions of 52x52, and Domain 4 (inner domain centered over Atlanta) a resolution of 3 km and dimensions of 55x55. All domains have 30 vertical layers (10 below 1 km), with a minimum sigma level (closest to surface) that corresponds to 46 m; wind and temperatures are calculated at half sigma levels.

Resolved-scale precipitation is represented by the simple ice scheme of Dudhia (1989), which has explicit prognostic equations for suspended cloud water, cloud ice, rainwater, and snow. This scheme does not, however, represent mixed-phase processes (i.e., supercooled liquid water). For higher-resolution studies of convection and thunderstorms, a more complex moisture scheme is necessary, but here the Dudhia scheme is used for computational efficiency. Convective precipitation in Domains 1 and 2 is parameterized with the Kain and Fritsch (1993) scheme, while no parameterization is employed in Domains 3 and 4, as such schemes are not valid on such small scales (Wang and Seaman 1997). Other options selected for the current simulations include: Dudhia (1989) radiation, Deardorff (1972) force-restore surface temperature, and Gayno (1994) 1.5 order TKE. Gridded model analyses (at 2.5x2.5 degree resolution) from the

NCEP/NCAR Reanalysis Project (Kalany et al. 1996) provide initial and boundary conditions, the latter at 6 h intervals with linear interpolation at 0600 and 1800 UTC.

The 25-category U. S. Geological Survey (USGS) land-use distributions for each domain were created from global 30 s (1 km) values derived from April 1992-March 1993 AVHRR data (Dudhia 1993). Sea surface temperatures were obtained from GDAS global data at a resolution of 2.5x2.5 degrees, while grid averaged topographic height values were derived from USGS EROS Data Center global 30 s data. A terrain-height correction on the inner domain was required for Lake Sidney Lanier (also called Bufford Reservoir) located northeast of Atlanta, as MM5 terrain files erroneously set its elevation to zero. The value was reset to 325.8 m (average height listed by the U.S. Army Corps of Engineers for the ATLANTA study period) within the MM5 terrain preprocessor and then smoothed with terrain-height values from surrounding land grid points.

The Atlanta area in the inner domain is represented by a single urban land-use category. The urban area was expanded somewhat to approximate recent urbanization (Fig. 5), as determined by eye from LANDSAT-derived land-use data (not shown). Most new urban grid points were added in the northwest gap that separates downtown Atlanta from its northwest suburbs. A higher resolution grid would allow a more precise determination of additional urbanization and would allow the representation of intra-city variability. The flat-sandbox urbanization approach is used in this study. Urban land-use parameters, however, were changed from MM5 default values to better represent urban surface characteristics, e.g., albedo was decreased from 0.18 to 0.15 and roughness length was increased from 0.5 to 1 m, both within urban ranges (Oke 1973).

Results are presented from three simulations. Case 1 represents the “Base Case” simulation that includes the urban area. Since Domain 1 (81 km grid) results do not vary from case to case, all Domain 1 results presented are Case 1, unless otherwise noted. In Case 2, the Atlanta urban area (USGS category 1) is replaced by dry crop/pasture land (USGS category 2), the dominant neighboring land-use type. In Case 3, the urban area is maintained, but the Case 1 initial 3-D MM5 temperature field is perturbed to test sensitivity to initial conditions.

Simulations were carried out on a PC LINUX operating system driven by a 1100 MHz processor and supported by 1 gigabyte of RAM. Each 30 h simulation, which required about 8 h of CPU-time, began during the evening prior to the convective episode (at 26 July 0000 UTC, i.e., 25 July 2000 EDT), and ended on 27 July 0600 UTC.

3. Observational Analyses

a. Synoptic

On 26 July at 0000 UTC (Fig. 6), a 500 hPa long-wave trough extended from Quebec to Mississippi, with a prevailing westerly flow of 15 kt (7 m s^{-1}) at its southern end over Atlanta. The 500 hPa height field also shows short-waves embedded in the flow east and west of the trough axis (near 80°W and 95°W , respectively). The coldest air associated with this weak trough was only about -16°C over northern Michigan, and eastern Tennessee was the southern-most extent of the -10°C isotherm. The 500 hPa reflection of the surface subtropical high was positioned east of Florida, with an axis oriented east to west.

During the next 24 h (Figs. 7 and 8) the 500 hPa trough slowly moved east and its axis passed over Atlanta. Atlanta winds at 1200 UTC on the 26th were still westerly, but strengthened to 25 kt (12 m s^{-1}); however, 12 h later they shifted to west-northwesterly. Arrival of the trough in the Northeast from the west (during the 24 h period) dropped the -10°C isotherm over the eastern U.S. (southeast from Pennsylvania to central Virginia), cooling 500 hPa temperatures there by $1\text{--}4^\circ\text{C}$. A weak ridge had built (in response to a strengthening high in the southwest) behind this trough (to its west). Temperatures behind the trough warmed by $1\text{--}3^\circ\text{C}$, as noted by the northward shift of the -10°C isotherm through Kansas and Missouri. Temperatures remained nearly unchanged in the Southeast, as cooler air did not reach south to Georgia and Alabama.

The subtropical high weakened slightly during this 24 h period, while its center moved northwest over the Florida coast. The two 500 hPa short-waves also progressed eastward during this period, so that the western one was over Oklahoma at 27 July 0000 UTC. The eastern one was over the east coast by 1200 UTC (and offshore 12 h later), perhaps aiding the ongoing coastal surface cyclogenesis.

Both the long-wave trough and subtropical high were also visible at 850 hPa on 26 July at 0000 UTC (Fig. 9), with northwest flow at 10 kt over Atlanta and westerly or west-southwesterly flow (15-30 kt) south of the city. A wind shear line thus existed south of Atlanta, approximately along the 1560 m height contour. West of the trough, a ridge was centered over Kansas and Oklahoma, with a maximum height of 1570 m. As the upper-air trough moved eastward, 850 hPa heights rose behind it (by as much as 50 m over Illinois). After 24 h (at 0000 UTC on the 27th) a broad ridge thus replaced the trough over the upper Midwest, reducing speeds to 5-10 kt (Fig. 10). The 850 hPa wind over Atlanta (now influenced by the subtropical high to the southeast) shifted to westerly, but remained at 10 kt.

On 26 July 0000 UTC, the NWS surface analysis (Fig. 11) showed a weak southwest to northeast oriented cold front advancing slowly southward towards Atlanta in association with the upper-level trough. Parts of this front coincided with a wind-shift (with northwest flow north of it to southwest flow south of it) and a moisture gradient (indicated by dew point temperature), but not with strong winds or a significant temperature gradient. The surface high pressure (maximum pressure 1019 hPa) over the Iowa-Nebraska border is a reflection of the upper-level ridge that built behind the upper-

level trough. East of the front, the low over North Carolina is associated with a surface trough that extends from New York to North Carolina and then west through Atlanta.

The current re-analysis indicates that the cold front over Arkansas and Mississippi in Fig. 11 is a wind-shift boundary and the southern boundary of a strong dew point gradient; however, these distinctions are less obvious further north (occluded portion in New York). The surface trough (associated with the North Carolina low) also represents a dew point gradient that connects to the stronger cold-front gradient to the west. A continuous moisture boundary (i.e., front) thus seems to unify the NWS trough and cold front into a single entity. While the NWS chart shows the front northwest of Atlanta and the trough over the city, the current re-analysis indicates that the southern end of the trough was really the front that was already over Atlanta at 0000 UTC.

This new interpretation is consistent with the next (0600 UTC) NWS surface analysis (Fig. 12), when the weak low is further north over Virginia and its trough is shown as a weak (eastern) cold front. It connects in Mississippi with the other (western) cold front, whose lower half is depicted as stationary and whose decaying northern section runs from Alabama to Pennsylvania, where it almost joins the occluded portion of the eastern front. It is thus apparent that the merger suggested by Lin (2000) did not occur, as the western front decayed before it could overtake the (apparently) pre-existing eastern front (not originally analyzed as such by the NWS).

On 26 July 1200 UTC (morning prior to convective event) (Fig. 13), the NWS depicted a single quasi-stationary front that extended from southern Arkansas, eastward through Atlanta, and northwest to the (now 3 hPa deeper) low pressure center off the Vir-

ginia coast. Temperature contrasts across the front were still weak and the dew point gradient also still existed, with moist unstable air south of the front and drier more stable air to its north.

The exact location of the quasi-stationary front over north Georgia during the next 12 h remains uncertain, but the NWS positioned it just south of Atlanta at 1800 UTC (Fig. 14) and over Atlanta 6 h later (Fig. 15). NWS dew point temperatures indicate Atlanta at or near the southern boundary of the dew point gradient, as Atlanta values were 68-72°F (20-22°C) throughout the period of interest. The high pressure region centered over eastern Nebraska at 0000 UTC strengthened as it expanded southeast behind the dissipating front. Maximum surface pressures increased to 1022 hPa by 1800 UTC and to 1024 hPa by 27 July 0000 UTC.

The FFC morning (26 July 1200 UTC, Fig. 16) and evening (27 July 0000 UTC, Fig. 17) soundings indicate a relatively moist environment through much of the lowest 4 km. The evening sounding is used to estimate average afternoon (when convection occurred) thermodynamic conditions over Atlanta, as it still shows a well-mixed, adiabatic PBL above a newly formed surface radiative inversion.

The convective available potential energy (CAPE), or vertically integrated buoyant energy of adiabatically lifted air parcels, of this evening sounding was 979 J kg^{-1} , indicative of only marginal convective instability. This value was obtained by lifting an air parcel with the average pressure, temperature, and dew point of the lowest 500 m sounding layer. As shown by its thermodynamic path (Fig. 17), a parcel lifted beyond its level of free convection (LFC) would be warmer than its environment until its equilibrium

level (about 182 hPa). Since CAPE is sensitive to low-level moisture, it is larger ($>2500 \text{ J kg}^{-1}$) well south of the front in Tallahassee (not shown), but practically non-existent in the drier air to the north (Nashville, not shown). The evening sounding also indicates the presence of weak elevated capping inversions near the 550, 700, and 800 hPa levels, while a stronger cap is present in the stable Nashville sounding.

Given the moderately small CAPE and weak vertical wind shear (Figs. 16-17), severe thunderstorms were unlikely. A low Severe WEather Threat (SWEAT) index of 188 also does not typically support severe thunderstorm formation (>300 required). Other evening-sounding stability parameters, however, in conjunction with the CAPE value, do support a potential for scattered non-severe air mass thunderstorms. The K (KINX), Lifted (LIFT), Showalter (SHOW), and Total Totals (TOTL) indices equaled 36, -2.35, -0.5, and 45, respectively. In particular, the large KINX value results from the deep moist layer below 5 km (note the 44 mm of precipitable water, PWAT).

Deep cumulus convection in such a thermodynamic environment is not automatic, however, as parcels require a sufficient upward push to overcome low level convective inhibition (CIN), i.e., the negative buoyant energy of the isothermal layer from 950 to 875 hPa in the morning sounding. CIN is overcome by surface heating and/or other mechanisms sufficient to lift air beyond its LFC (approximately 1.8 km or 835 hPa in the evening sounding). Air lifted only to its lifting condensation level (LCL) ($<1 \text{ km}$ or 915 hPa), but not to its LFC produces cumulus clouds but not deep cumulus convection. Temperature profiles in the morning and evening soundings suggest that afternoon convective eddies warmed the atmosphere to about 1.5 km (850 hPa), i.e., above the LCL but

slightly below the LFC. Mixing generated by surface heating alone would thus only support development of afternoon cumulus clouds over north Georgia, as observed in afternoon visible satellite images (not shown). Additional forcing (e.g., from large-scale frontal convergence, mesoscale boundaries, local land-surface and topographic variations, or UHI-induced convergence) would thus be required to lift air beyond its LFC and initiate deep convection.

b. Mesoscale

Lin (2000) and Bornstein and Lin (2000) show a generally weak 1.5 m daytime UHI during 26 July (Fig. 18) advected northeast of Atlanta by a generally southwest (about 2.5 m s^{-1}) regional flow south of the city. Maximum UHI values on this day ranged from 2.0-2.5 K from 1600 to 1815 UTC (1200 to 1415 EDT), after which clouds were initiated and solar blockage weakened the UHI over the subsequent two hours.

Observed mesoscale near-surface winds (Fig. 18) showed confluence over Atlanta from the predominantly northwesterly flow north of the city and the southwesterly flow south of the city. As confluence is one of the two aspects of convergence (the other is along-streamline deceleration), the observed winds at 1900 UTC produced a local convergence maximum over the city (Fig. 19), with three somewhat weaker lobes extending to the south, east, and northwest. Note that the 1800 UTC UHI center is unexpectedly displaced somewhat northeastward from the 1800 (not shown) and 1900 UTC (Fig. 19) convergence centers. Additional evidence for urban-induced convergence is the ring of

local divergence centers around the city, probably formed as air was drawn out (by the Atlanta UHI) from the surrounding rural area.

This convergence maximum appears superimposed on a possible synoptic-scale frontal convergence zone, which extends from west of the city, through the city, and up to the northeast domain corner. It also coincides in time and space with the NWS front described above; however, because dense ATLANTA observations only exist over a localized region, the exact location of the frontal boundary is unclear. The strong variation in relative humidity (85% south of Atlanta compared to 55% to the north) also suggests a moisture gradient existed over Atlanta (Fig. 20), but dew point analyses are necessary to confirm this.

According to Lin (2000), thermal IR satellite images at 30 min intervals first showed significant localized (deep) convective clouds over the southern-extension of the convergence region at 1815 UTC (1415 EDT), which reached peak intensity at 2145 UTC, and dissipated by 27 July 0000 UTC. Precipitation was initiated at 1845 UTC in the convergence lobe 25 km south (i.e., locally upwind) of the center of Atlanta. Precipitation lasted until 0000 UTC on 27 July, but its center slowly moved 40 km further upwind (i.e., to the SW). A maximum of 14 mm of precipitation (Fig. 21) fell about 60 km south (i.e., generally upwind) of the center of Atlanta.

Additional analysis during the current study shows that two convective cells produced precipitation south of Atlanta. The first was initiated on the southwest urban edge around 1815 UTC (Fig. 22), near the southern convergence lobe in Lin (2000). As this cell intensified and moved eastward (Fig. 23), a cool thunderstorm outflow reached the

surface southwest of Atlanta, as seen in the 1900 UTC temperature field (Fig. 24). As the cell moved east-southeastward (Fig. 25) it matured, as did other convective cells along a line in which it was embedded. It is unclear if this line of convection resulted from quasi-stationary frontal convergence or from some other mesoscale boundary. The radiative cloud-top temperature of the cell (about -50°C) indicates an approximate vertical development to about 225 hPa, close to the equilibrium level denoted in the FFC sounding.

The outflow then strengthened by 2000 UTC (Fig. 26) and the storm produced approximately 10-15 mm of precipitation over the southeastern urban edge between 1945 and 2100 UTC, forming the local maximum north of the absolute maximum in Fig. 21. Diffuence from the outflow also exists over the same region at 2000 UTC, as does the resulting divergence (Fig. 27), which helps maintain the northern and southern remnants of the original urban convergence region. By 2100 UTC, precipitation from this cell ended and cool surface outflow air remained (Fig. 28), but divergence weakened (Fig. 29).

While the first cell was maturing, a new cell was initiated at 1945 UTC, 10-20 km southwest of the first initiation site (Fig. 25). The new cell may have resulted from a combined convergence from the UHI and outflow from the first cell (not captured in the mesoscale analysis). As this second cell moved eastward (Fig. 30) it produced a cool downdraft (Fig. 31) and strong divergent outflow south of the city (Fig. 32). It also produced 10-15 mm of precipitation (between 2145 UTC and 27 July 0000 UTC) in its southern sector, i.e., about 20-30 km south of precipitation produced by the first storm, and was responsible for the absolute maximum value in Fig. 21.

From the above analysis, the afternoon precipitation event analyzed by Lin (2000) seems to have been two related events. The first was probably initiated by UHI-induced convergence superimposed on a regional convergence boundary, while the second was possibly produced from combined convergences from the urban area and a thunderstorm outflow.

4. MM5 Synoptic-Scale Results

MM5 initialization of the outer (81 km) domain (Fig. 33) shows the 500 hPa trough (based on height contours) somewhat too far (about 50-100 km) south and with an axis about 80 km too far east (with respect to a 10 m mesoscale analysis of NWS height data), especially at its southern edge near Atlanta. This edge is a broad area of weak gradients, in which axis-location is difficult in the original 60 m NWS analysis. The initial MM5 wind field is not exactly consistent with its height field, however, as it indicates a trough axis further west (and thus closer to that in the NWS analysis) than indicated by the height field. Regardless, MM5 winds over Atlanta show a correct (relative to the concurrent NWS 500 hPa chart) slightly south of west direction.

The two observed short-waves are also captured by the MM5 initialization, i.e., one east of the trough axis over the eastern U.S. and one west of the axis over Nebraska. A third short-wave over Arkansas and Missouri, not represented in the NWS analysis, is also apparent. While the southeasterly flow over south Florida and the speed over north Florida are both accurate, speeds over central Florida are too strong by 10-15 kt, as the subtropical high in that region is somewhat too strong. Wind speed and direction in the ridge west of the trough are well initialized, but ridge intensity appears too strong, e.g., the 5820 m contour is about 80-100 km too northeast over Missouri. In addition, the 5880 m contour is initialized over Nebraska, but observed well southeast of Nebraska. Temperatures over Kansas and Nebraska are also too high, as noted by the northward displacement (compared to observations) of the -10°C isotherm (Fig. 34).

The 850 hPa reflection of this ridge (Fig. 35) is also initialized too strong, as the peak MM5 height is 1590 m, compared to the 1570 m observation. The clockwise circulation around this high is reproduced with reasonably accurate velocities, as winds are northwesterly over Arkansas and southerly over west Kansas. The MM5 trough, however, is not deep enough at 850 hPa, most easily noted by the too far north (by 90 km) location of both its 1560 m contour over the Southeast and its 1500 m contour over Michigan.

The observed 850 hPa wind-shift region over the southeast is initialized in MM5, as noted by the stronger southwest winds over southern Georgia and the weaker northwest winds over northern Georgia. This wind-shift region appears to extend from central Alabama, through northern Georgia, and northeast to North Carolina, and is coincident with the 850 hPa pressure trough. The MM5-initialized northwest wind of 3 to 5 m s⁻¹ over north Georgia is somewhat weaker than the 5 m s⁻¹ (10 kt) observation, but the west-southwest wind of 12-14 m s⁻¹ over the Florida panhandle coincides with the 15 m s⁻¹ (30 kt) observed wind. Based on the MM5 winds, the initial position of the subtropical high is displaced eastward from its observed location.

The initial MM5 near-surface winds (Fig. 36) indicate a broad transition zone of weak, disorganized flow over northern Mississippi, Alabama, and Georgia that separates stronger areas of southwesterly flow to the south from northwesterly flow to the north. Since this zone is too wide to pinpoint frontal position, inspection of sea level pressure and near-surface dew point temperatures is necessary (Fig. 37). The two MM5 pressure troughs (over Ohio and Kentucky and over the Carolinas) coincide with the front and

trough indicated on the NWS analysis, respectively. While the first (western) trough is not coincident with a significant MM5 wind-direction shift, the second (eastern) one is located at the northern boundary of southwesterly flow.

This eastern trough is also coincident with the southern and eastern edges of a dew point gradient that extends from Virginia, southwest through Georgia, and east to Texas. This boundary thus coincides with what the current study has concluded is a pre-existing cold front, while the western trough (at least from Tennessee north) may be what the current study has called the decaying cold front. The initial MM5 large-scale near-surface fields thus reasonably reproduced the frontal features of this complex situation.

The exact position of the initialized front over north Georgia is, however, uncertain, and analysis of the 9-km MM5 domain initialization (Fig. 38) does not provide further clarification. Atlanta is 40-50 km north of the moisture-gradient edge, but south of the northwesterly flow. The initial dew point temperature at Atlanta, however, is 1.5°C too low, an indication that the PBL may be initialized too dry.

Despite errors in the initial upper-level ridge over the central Plains, its surface reflection (Fig. 36) shows a correct location, size, and strength. The initial leading edge of northeasterly flow over east Texas, Arkansas, and northwest Louisiana is located as observed.

Twelve hours into the simulation (26 July 1200 UTC), the 500 hPa MM5 trough (Fig. 39) had moved eastward and deepened slightly, while the observed trough had moved somewhat quicker and did not deepen; the trough axis is thus now correctly located. Modeled winds over Atlanta have a slightly over-predicted southerly component

and speed (by about 2.5 m s^{-1}). The central Plains ridge (west of the trough) is still stronger than observed, as noted by the 5880 m contour over southern Kansas (instead of over Oklahoma) and by the 5820 and 5760 m contours still somewhat too far north. This over-prediction produces wind-field errors, as northwest winds are predicted over Oklahoma, eastern Kansas, and Arkansas, where they should be westerly to west-southwesterly. Predicted northeasterly flow over parts of Louisiana and Texas should also be westerly, while speeds over Missouri are over-predicted by 5 m s^{-1} due to an over-predicted pressure gradient. Finally, 500 hPa temperatures (Fig. 40) over the Plains are over-predicted, as the -10°C isotherm is again too far north.

The over-predicted MM5 upper-air ridge is reflected at 1200 UTC (Fig. 41) in sea level pressure and near-surface wind errors. While MM5 correctly predicted maximum pressure (1021 hPa), it over-predicted ridge size. The surface high was centered correctly over Missouri with its correct strength (1021 hPa), but its 1020 hPa isobar extends too far south (over Arkansas). Though this error seems minor, its effect on wind velocities was significant, e.g., observed winds over central Tennessee and southeast Missouri were from the west while MM5 winds were from the north. While many stations reported calm winds (e.g., Kansas City, Springfield, and St. Louis), MM5 predicted speeds of $2\text{--}4 \text{ m s}^{-1}$. This over-predicted ridge also affected Atlanta, where predicted winds were northwest while observations showed westerly flow.

Another possible factor in the over-predicted northerly flow over Tennessee and north Georgia is misplacement of the low pressure center over the east coast (analyzed just east of Delaware), as MM5 placed it too far south (east of Virginia and North Caro-

lina). Some unobserved northerly flows on the western side of this misplaced MM5 low may have advected too much dry air to the south into Georgia and Atlanta. Though MM5 accurately depicted the dew point at Atlanta (67°F) (Fig. 42), it under-predicted values by 2°F in much of north Georgia and Alabama (where values were reported higher than at Atlanta). Since the quasi-stationary front is a moisture boundary, this caused MM5 to locate the front too far south. Output from the 9 km domain (Fig. 43) at 1200 UTC does show the southern edge of the dew point gradient and wind-shift zone about 80-100 km south of Atlanta.

By 1800 UTC (Fig. 44), MM5 over-predicted both the strength and size of the Great Plains surface high. This may (in part) have caused an under-prediction of near-surface wind speeds over the Plains and parts of the Southeast, as MM5 speeds became nearly calm during the afternoon (observed winds were 2-3 m s⁻¹). Ironically, modeled wind speeds 50 hPa above the surface over north Georgia (not shown) were 2-4 m s⁻¹, and not zero, which suggests that the MM5 SBL parameterization may under-predict afternoon near-surface wind speeds (Zilitinkevich et al. 1999).

MM5 23 m dew points also fell throughout the Southeast (Fig. 45-46) by 1800 UTC, as the unobserved northerly flow continued; Atlanta thus reported a dew point of 72°F, while MM5 predicted 66°F. Based on the locations of the wind-shift region and southern edge of the dew point gradient, the modeled quasi-stationary front was too far (100-140 km) south of Atlanta.

The predicted morning FFC sounding on 26 July 1200 UTC (Fig. 47) shows that MM5 reproduced the observed moist layers near the surface and between 600 and 700

hPa. MM5 temperatures also generally corresponded to observed profiles, except that the observed isothermal layer was not well captured. The MM5 evening sounding (Fig. 48), a 24 h prediction, deviates more from the observed sounding, as it under-predicts surface-to-600 hPa dew points, consistent with dryer air advected from the north. Furthermore, the simulated near-surface moist layer is shallower than observed; however, clouds can drastically alter dew point profiles. MM5 does capture the observed mid-level dry layer, but its base is too low and its minimum dew points are under-predicted.

Predicted afternoon mixed layer depth at FFC matches observations, as the morning and afternoon MM5 soundings indicate PBL warming through about 2 km (800 hPa). CAPE values were not computed for these soundings; however, the profiles imply lower CAPE values (and thus decreased convective instability) than computed from observed soundings, given the limited positive buoyancy of a lifted surface parcel. North of Atlanta (not shown) CAPE values drop to zero, due to the dryer, more stable air well north of the quasi-stationary front. The other key feature that affects modeled CAPE is the stable “cap,” i.e., an over-predicted isothermal layer, between 600 and 500 hPa. Thus, even if MM5 cumulus convection penetrated beyond 700 hPa, this cap would stunt continued development.

As MM5 apparently misplaced the quasi-stationary front, and therefore wrongly placed Atlanta on the dry side of the front, the simulated atmosphere over Atlanta differs from observations with respect to PBL wind direction (northwest versus southwest) and thermodynamic structure. These discrepancies preclude specific conclusions regarding the observed urban-initiated convection documented by Lin (2000) and Bornstein and Lin

(2000). The MM5 atmosphere was still marginally unstable, which suggests that an MM5 UHI can initiate cumulus convection and precipitation, especially given the “serendipitous” results from Nielsen-Gammon (2000) and Qui et al. (2000).

5. MM5 Mesoscale Results

The following three cases were simulated: base (urban), on-urban, and perturbed initial conditions.

a. Case 1: Base Case

With the inception of solar radiative forcing, MM5 produced a 23 m AGL UHI over Atlanta starting at 1200 UTC (0800 EDT), which built to a maximum at 1500 UTC, an hour before the onset of modeled convective precipitation. At 1500 UTC, the simulated UHI was over the entire city (with a maximum intensity of about 1.5 K), but with three separate maxima (Fig. 49). A weak UHI-maximum was south of the city, while the two stronger (southeastern and northwestern) sections were separated by the Chattahoochee River Valley (modeled as a dry rural area) that cuts into Atlanta from the southwest. Thus the 26.5°C contour approximately outlines both the urban grid-points and the river valley. Given the dearth of observations in (and northwest of) the valley, it was not possible for Lin (2000) to resolve its effects. After 1600 UTC, simulated UHIs (still present) were disrupted by cloud cover and convective outflows (which were up to 5 K cooler than the surrounding environment) (Fig. 50).

The observed pre-storm UHI intensity of 1.5 K (Lin 2000) is comparable to the MM5 value. Because MM5 initiated convection at about 1600 UTC (3 h too early, discussed below), however, this comparison is between triggering UHIs the hour prior to initiation. The observed UHI center was advected (as a single entity) about 15 km northwest of the urban edge by the observed regional southwest flow, while the simulated

UHI was generally centered over the urban area, as near-surface wind speeds became nearly calm by 1400 UTC.

Potential temperature cross-sections through the MM5 UHI core at 1500 UTC (Fig. 51) show it extending from the surface to the PBL top (about 1.3 km MSL or 875 hPa), where surface elevations in the section range from about 250-370 m MSL. UHI values decreased from >1.5 K at the surface to about 0.5-1.0 K near the PBL top, whose depth increased to about 2 km MSL by 1800 UTC (not shown). The near surface superadiabatic SBL at 1500 UTC extends from about 200 m AGL over rural areas to about 350 m AGL over the city. The near-neutral layer above the urban SBL extends to the UHI top, with horizontally uniform temperatures above.

The near-calm 23 m AGL MM5 regional winds allowed a confluent flow (of $1\text{--}2$ m s^{-1}) into the UHI to develop by 1500 UTC (1100 EDT) (Fig. 52). The confluent flow intensified (to $3\text{--}4$ m s^{-1}) over the next 2 h (Fig. 53), but was then disrupted by diffluent convective outflows. Instead of a single confluence region over the UHI, however, MM5 produced three distinct sub-regions associated with the temperature maxima over the northwestern, eastern, and southern sides of the city. The strongest (eastern) region drew air in from a radius of about 15 km. Slightly stronger (1 to 2 m s^{-1}) westerly and northwesterly regional winds were simulated over Atlanta at the 950 (Fig. 54) and 900 hPa (not shown) levels. The UHI and confluence regions were also apparent at these levels.

As with the above MM5 synoptic-scale comparison with NWS observations, predicted 23 m regional flows in the 3 km domain under-predicted 10 m observed values.

The under-prediction allowed urban confluence areas to develop earlier and produce faster inflow speeds than observed.

As previously explained, the simulated quasi-stationary front was (erroneously) located south of Atlanta. Since the southern boundary of the inner domain is about 80 km from the center of Atlanta, the frontal boundary lies generally south of the inner domain, although effects of its convergence sometimes impacted this domain. Further analysis of MM5 results (not shown) also indicates a lack of overrunning, a situation that could produce lift and subsequent convection well north of a quasi-stationary front. While the front may have thus been a factor in the observed convection, it appears not to be a factor in the development of MM5 precipitation over Atlanta.

Modeled 23 m divergence fields at 1500 and 1600 UTC (Figs. 55 and 56, respectively) show urban-induced convergence centers in the three (eastern, southern, and northwestern) MM5 temperature maxima, which correspond to the MM5 confluence regions described above. The over-prediction of modeled convergence values is expected, as: 1) confluence was over-predicted and 2) model grid-points are denser than the observations from which divergence was computed in Lin (2000).

The MM5 divergence ring around Atlanta at 1500 UTC (Fig. 55) results as the UHI draws surrounding rural air inward toward the city, an effect also seen in the observations. The simulated divergence directly over the city, however, was not observed, but results (from mass continuity) as air was drawn outward to UHI maxima on the urban edges to complete the urban circulation cells.

Divergence replaces part of the strongest (eastern) convergence region by 1615 UTC (Fig. 57), which indicates the arrival of a cool downdraft that strikes the surface and forms a concentric divergence region. The region grows outward through 1700 UTC (Fig. 58) and further erodes the original eastern convergence region. It also produces convergence at its downwind (down-shear) edge, and strengthens the pre-existing urban convergence at its upwind (up-shear) edge. Also by 1700 UTC, another downdraft forms in association with a convective cell that originated in the southern convergence region. The convergence area northwest of the city weakened (but was not replaced by a downdraft), while a new convergence region formed on the north side of the city.

During this time, a second, more intense convective cell formed in the strengthened eastern convergence zone. From 1715 to 1745 UTC (Figs. 59 and 60), this cell produced a downdraft and a larger near-surface divergence (slightly up-shear of first eastern downdraft) that eventually replaced the entire original eastern convergence zone. The maximum MM5 urban-induced precipitation is associated with this second eastern downdraft, accompanied by a 5 K near-surface cold pool (Fig. 61). A new divergence region also replaced the northern urban edge convergence area, and both outflows produced new convergence regions further outside the city. By 1800 UTC (Fig. 62), the three divergence regions grew horizontally, weakened, and moved with the mean northwesterly flow aloft.

The above discussed low-level convergence into the UHI warm-core low pressure areas thus produced upward vertical motion. Pressure gradients thus also reversed at upper levels, and divergence areas formed (discussed below). The 1500 UTC vertical ve-

locity plots (Fig. 63) at 900 hPa indicate three areas of upward motion (centered over the three surface UHI-induced convergence regions) surrounded by broad, weak compensating down-motion areas. During the next hour (Fig. 64), the southern and eastern updrafts strengthened to 90 cm s^{-1} as they propagated downwind (i.e., toward the southeast) and produced the two clouds in Fig. 65. From 1600 to 1700 UTC, the downdrafts enhanced upwind convergence regions (as discussed above), which resulted in new, stronger updrafts (Fig. 66) and subsequent cloud development (Fig. 67). While the stronger eastern updraft shows vertical speeds $>2 \text{ m s}^{-1}$ at 900 hPa, they are not necessarily maximum core values.

The vertical structure of the cloud areas are best seen in cross sections oriented east to west through the center of Atlanta (Fig. 68). The three near-surface convergence centers in the 1500 UTC cross section (Fig. 69) correspond (from right to left) to the eastern, southern, and northwestern UHI-induced convergence regions of Fig. 55. While this section cuts through the center of the eastern convergence region, it only cuts through the edges of the other two. The stronger (eastern) convergence area starts from the surface, reaches a peak at 450 m, and extends to 1 km MSL, with a weaker compensatory divergence above it extending to about 2.5 km. Consistent with the near-surface convergence regions (Fig. 55), the corresponding vertical section (Fig. 70) shows two overlying updraft regions, which peak at 1 km and extend beyond 2 km. The weak western up-motion area is only denoted by upward-pointing wind vectors. From mass continuity, peak upward motions correspond to a convergence-zone top and cease atop the compen-

sating upper-level divergence area; weaker compensatory downward motions are only captured by downward-pointing wind vectors.

Upward vertical velocities in all three 1500 UTC updrafts (Fig. 70) extend beyond 1 km MSL, higher than the predicted and observed LCLs (just below 1 km). All three regions thus produced clouds with bases at about 1 km MSL, as seen in the corresponding cloud liquid water cross section (Fig. 71). The eastern cloud is deeper due to a stronger UHI convergence. As convergence forced air beyond its LFC, the updraft strengthened and deepened, and its associated cloud grew and produced rainwater within and below the cloud during the next hour (Fig. 72).

The deeper cumulus cloud generated by the second (stronger) eastern updraft at 1700 UTC (Fig. 73) is approximately 4 km deep, and supported by a maximum updraft of 4.3 m s^{-1} (Fig. 74). Because the freezing level is above 4 km, it can be inferred that the cloud does not contain ice crystals. Furthermore, because the cloud neither extends to the upper troposphere nor is supported by an updraft $> 10 \text{ m s}^{-1}$ (Weisman and Klemp 1986), it cannot be cumulonimbus (thunderstorm). Given the marginally stable MM5 thermodynamic environment, this is not surprising. The low value of cloud water mixing ratios ($< 1.4 \text{ g kg}^{-1}$) compared to those in typical towering cumulus clouds (Pruppacher and Klett 1997) does, however, suggest that MM5 may have over-predicted entrainment during explicit convection. Corroboration for this is that predicted equivalent potential temperature profiles (not shown) do not show an expected (approximate) conservation for moist adiabatic ascent. While a detailed study of MM5 entrainment processes is beyond the scope of this study, the apparent under-predicted cloud water suggests that even with

an unfavorable MM5 environment (from both microphysical and thermodynamic perspectives), a persistent forcing mechanism was able to produce precipitating convection.

The towering cumulus cloud associated with the eastern updraft ultimately produced 3 mm of precipitation on the eastern urban edge between 1700 and 1715 UTC, another 4 mm by 1730 UTC, and <1 mm during the next 15 min, for a total of 7-8 mm by 1800 UTC (Fig. 75). By 1800 UTC, the cell dissipated as a cool downdraft overtook its updraft. Subsequent cells produced only minimal precipitation amounts: 1 mm just south of Atlanta between 1645 and 1715 UTC in conjunction with the southern urban-induced convergence region, and a small amount just north of the city from 1730 to 1800 UTC.

Most MM5 precipitation around Atlanta thus fell between 1700 and 1800 UTC, but after 1800 UTC afternoon convection produced precipitation throughout the domain. The cumulative post-sundown precipitation plot (Fig. 76) shows a 20 km wide urban-induced precipitation region centered over the eastern Atlanta urban edge, with a peak of 8.24 mm over the eastern urban edge and two smaller urban-induced regions (< 2 mm) north and south of Atlanta.

MM5 also produced several other regions (> 1 mm) not coincident with urban-induced convergences, mostly near the southern domain boundary. This precipitation was probably associated with the MM5 quasi-stationary synoptic frontal convergence zone (generally located just south of this boundary). This conclusion is supported an east-west precipitation line produced by the cumulus parameterization scheme on the 81 km domain (not shown). Some of this precipitation fell before local noon (1600 UTC) (indicative of synoptic convergence), while the rest (including the domain-maximum

value in its southwest corner) resulted from afternoon convective cells that formed between 26 July 1800 and 27 July 0100 UTC.

b. Case 2: No-Urban case

A link has been established above between modeled UHI, confluence, convergence, vertical velocity, cumulus clouds, and precipitation values. Given the almost chaotic nature of cumulus convection, especially in marginally unstable and low wind shear conditions, this linkage alone, however, does not guarantee that daytime solar heating alone could have not produced MM5 cumulus convection around the urban area. To show that the precipitation presented above as “urban-induced” occurred due to urban-induced convergences, and was not a coincidental artifact of afternoon convection, Case 2 repeats the above Base Case simulation, but without the urban area.

Removal of all urban land-use grid points did, as expected, precluded formation of an afternoon 23 m UHI (Figs. 77 and 78). The positive difference (Fig. 79) between the urban and non-urban temperatures at 1500 UTC (hour before cool downdrafts eroded the UHI) clearly shows urban land-use effects. It also outlines the three modeled UHIs on the east, northwest, and south sides of the city. The six regions of positive temperature difference around Atlanta are (except for largest one) miniature UHIs from one or two urban grid points also eliminated in the No-Urban case. The maximum temperature difference between these two simulations at 1500 UTC was about 1.5°C, comparable to the UHI-intensity observed by Lin (2000) just before convection. Regions in which

positive urban/non-urban temperature differences disappear at 1800 UTC (Fig. 80) indicate cool convective outflows on the southern, eastern, and northern urban edges.

The absence of a No-Urban case UHI resulted in the absence of confluence over Atlanta at 1600 UTC (Fig. 81). As modeled UHI confluence in the Base Case was superimposed on a near-calm 23 m wind field, the absence of UHI-modified winds produced near-calm near-surface winds over the urban area, and at 950 hPa (Fig. 82) the mean northwest flow is thus not disturbed by urban influences as it was in the Base Case.

The wind field in Fig. 81 produced the 23 m divergence field in Fig. 83, and although one small convergence region is apparent on the eastern side of the city, the other significant UHI-induced regions of the Base Case are not present. The divergence difference field two hours earlier at 1500 UTC (Fig. 84) reveals three negative-difference regions that correspond to the urban-induced Base-Case convergences, while positive-difference regions indicate the Base-Case ring of divergence around the city.

Without urban-induced convergence regions at 1500 UTC in Case 2, significant regions of vertical velocity (not shown) are also not expected over the urban area. Without such vertical velocities, clouds (not shown) also did not form over the urban area from 1500 to 1800 UTC. Thus, the No-Urban simulation failed to produce the Base-Case precipitation over or around Atlanta between 1500 and 1800 UTC (Fig. 85), but minor (< 0.5 mm) precipitation differences did occur elsewhere in the domain.

After 1900 UTC, clouds formed throughout the domain in both cases, including over Atlanta, in response to updrafts generated by afternoon heating. This resulted in rainfall at various locations, including a small amount (< 0.5 mm) over the center of At-

lanta. By 27 July 0100 UTC, numerous regions of precipitation (< 1.0 mm) had formed, including two cells that formed due to synoptic convergence in the southern part of the domain.

The final cumulative precipitation plots of both cases (Figs. 76 and 85) reveal that many precipitation regions outside Atlanta formed in both cases at the same locations, but the cumulative precipitation difference field (Fig. 86) reveals several differences. The largest (in the southwest part of the domain) is due to a convective cell that produced significant precipitation (> 50 mm) in the Base Case after 2000 UTC, but did not occur in the No-Urban case. Most other significant differences (> 0.5 mm) outside Atlanta resulted primarily from changes in location and/or intensity of weak cells formed in both cases, with some small differences from cells that formed in only one simulation.

The No-Urban simulation thus shows that removal of urban thermal forcing had the effect of eliminating the major precipitation area over Atlanta; however, it also had the effect of altering minor precipitation areas throughout the domain in locations not directly impacted by UHI forcing. These differences resulted from chaotic non-linear interactions between various atmospheric variables, a result not surprising in a fully coupled primitive-equations numerical model. While it now thus seems that the urban area initiated MM5 precipitation, it is not totally conclusive that the precipitation did not occur due to chaotic non-linear interactions.

c. Case 3: Perturbed initial conditions

Since the timing and location of modeled convection are often highly dependent on initial conditions, as well as on physical parameterizations used, a third simulation

was performed to test the robustness of the modeled urban precipitation. The Case 3 simulation is performed with a perturbed initial condition, in which temperature values at each grid point on the 81 km domain were perturbed by a random value from a uniform distribution between 0.5 and -0.5°C . While this approach does not replicate a Gaussian-distributed instrument error, it does produce a more severe perturbation, as maximum values are equally likely as zero-perturbation values. The perturbed temperatures were then interpolated to the inner domain initial conditions.

Effects of the random perturbation are seen in the noisy isotherms (Fig. 87), as compared to the unperturbed temperature field from the Base Case (Fig. 88). These effects are also seen on inner domains (not shown).

As expected, the perturbed initial condition resulted in differences in model solutions, but the final cumulative precipitation field (Fig. 89) still shows a precipitation region over the eastern urban edge. The maximum value is lower than in the Base Case, and the precipitation pattern is changed over both the urban and rural areas. This simulation thus shows that while the details of modeled convection are sensitive to initial conditions, the modeled UHI forcing was still sufficient to initiate cumulus convection and produce precipitation over the eastern urban edge.

6. Conclusion

The hypothesis that UHIs produce convergence that (under the right stability conditions) can initiate cumulus convection was tested using the MM5 mesoscale model. The impetus for the study was the 26 July 1996 project ATLANTA case for which Lin (2000) showed an afternoon convective cell apparently initiated by the Atlanta UHI; this case was thus simulated.

The study contended with two complicating processes that could also produce cumulus convection in the proper thermodynamic environment, even without urban forcing: the quasi-stationary synoptic front analyzed by Lin (2000) as over Atlanta, and afternoon heating. MM5 was unfortunately unable to accurately reproduce several key features of the observed environment around Atlanta. According to both the analyses of Lin (2000) and the NWS, a quasi-stationary front was positioned over or near the Atlanta area, as determined from both the locations of a wind-shift zone (northwesterly and southwesterly flow to the north and south, respectively) and the southern boundary of a dew point temperature gradient. The simulations, however, placed the front 100-150 km too far south by local noon (1600 UTC), due to the combined effects of a surface ridge that built too strongly to the southeast, and to an east-coast low pressure system that did not progress far enough northeastward. These factors produced a westerly and northwesterly flow that penetrated too far south, and thus pushed the quasi-stationary front further south than observed. Too-dry air was thus advected into the Atlanta area, and its near-surface dew point temperatures were under-predicted after 1600 UTC. A westerly

to northwesterly flow over and around the city up to 850 hPa was likewise predicted, instead of the observed southwest/northwest flow south and north of the city. Finally, a somewhat less stable environment (i.e., reduced CAPE) than observed resulted. As local meteorological conditions did not sufficiently verify with observations, the study cannot verify the contention of Lin (2000) that the storm was totally urban-initiated.

Despite these differences, the MM5 simulations did successfully produce urban-induced precipitation. The flat-sandbox urbanization approach used in the first simulation produced a UHI with an intensity that matched the observed intensity at the time of convective initiation. The UHI produced various confluence regions, which in turn produced convergence, upward vertical motion, cumulus convection, and precipitation. The strongest MM5 precipitation region was over the eastern urban edge, but two other smaller regions were also produced on the northern and southern urban edges. MM5 convective updrafts were expectedly less intense and shallower than those observed because of the drier than observed near-surface air, and the stronger than observed MM5 capping inversion that suppressed updrafts that penetrated beyond 650 hPa. Simulated convective elements thus did not evolve into cumulonimbus clouds, but produced towering cumuli of sufficient depth to precipitate and produce cool divergent outflows. A simulation without the urban area verified the relationship between UHI forcing and precipitation, as the lack of a modeled UHI precluded development of significant precipitation over the urban area.

Initial temperatures were randomly perturbed in the final simulation to study sensitivity of modeled precipitation fields to initial conditions, and to rule out the possibility

that ordinary afternoon convective surface heating could have anyway produced the observed and simulated precipitation over the urban area. Results showed perturbations of temperature-field details in the inner domain, particularly over the urban area, but that UHI forcing was still sufficient to produce convergence, upward vertical motion, cumulus convection, and precipitation.

Future simulations of the 26 July case should first focus on a more accurate simulation of synoptic meteorological conditions. Enlargement of the outer domain would capture more large-scale transient features in the initial conditions and would thus reduce reliance on boundary conditions to bring them into the domain. NCAR/NCEP reanalysis data and/or local ATLANTA mesoscale data could be assimilated into the solution through analyses produced by the Local Analysis and Prediction System (LAPS) meteorological preprocessor. The same data could also be used to nudge the basic equations via the MM5 four-dimensional data assimilation module. Both techniques would allow MM5 to have a shorter spin-up time, as the simulations started at 0000 UTC, while urban-induced precipitation was observed only after 1700 UTC. Although NCEP/NCAR reanalysis data are available every 6 hours, analyses at 0600 and 1800 UTC are interpolations from analyses produced at 0000 and 1200 UTC, and thus are less accurate than initial conditions at 0000 or 1200 UTC. If simulations were initialized at 1200 UTC, it is also unclear if enough time exists for proper MM5 moisture scheme spin-up. When the synoptic background is more accurately simulated, however, it is more likely that the observed deeper convection will be reproduced.

Both the MM5 horizontal and vertical grid resolution should be increased to correctly simulate the small horizontal areas containing the large vertical velocities produced by cumulus convection. Furthermore, since UHI forcing is dominant in the lower PBL, higher resolution there would better reproduce vertical UHI structure. Since the horizontal scale of convective elements can be less than 10 km, the current 3 km grid spacing is too large to simulate all observed thunderstorm features, as simulated updrafts encompass only 2-5 grid points. Increased horizontal resolution requires more computational time, however, especially for the current inner domain area, and thus might require the addition of a fifth nested domain.

The study showed the sandbox urbanization approach (applied to a city of homogeneous surface characteristics surrounded by rural areas of higher surface albedo and thermal inertia and lower roughness length) was sufficient to produce afternoon UHIs because anthropogenic heat fluxes are less significant than solar radiative forcing. During the nighttime hours that preceded the focus of these simulations, however, MM5 failed to reproduce a UHI. Though project ATLANTA observations were not available for this night, anthropogenic heat is important in the absence of solar radiation, and observations from other ATLANTA nights showed UHIs that MM5 would not reproduce without this flux. The magnitude and time-variability of this flux has not been determined for Atlanta during humid nighttime conditions, when heat release from air conditioners is significant.

The urban surface was also represented as homogeneous, a simplification as Atlanta (like most urban areas) is not homogeneous. A 3-km grid-spacing is probably small enough to represent gross differences between industrial areas (tall buildings and little

green space) and residential areas (short buildings and more green space), but a 1 km grid-spacing would incorporate more detailed urban land-use variability. Such data are available from other ATLANTA activities, and thus gridded satellite derived albedo values will also soon be available.

In summary, the current simulations provide additional evidence that UHIs can trigger convective storms, but additional work is required to completely prove the hypothesis. Additional research is also required to determine if pre-existing convective storms are bifurcated as they advect over urban areas.

References

- Ackerman, T. P., 1977: A model of the effect of aerosols on urban climate with particular attention to the Los Angeles Basin. *J. Atmos. Sci.*, **34**, 531-547.
- Anthes, R. A., and T. T. Warner, 1978: Development of mesoscale models suitable for air pollution and other mesometeorological studies. *Mon. Wea. Rev.*, **106**, 1045-1078.
- Arnfeld, A., 1982: An approach to the estimation of the surface radiative properties and radiation budgets of cities. *Phys. Geog.*, **3**, 97-122.
- Atwater, M., 1972: Thermal effects of urbanization and industrialization in the boundary layer: a numerical study. *Bound.-Layer Meteor.*, **3**, 229-245.
- Atwater, M., 1975: Thermal changes induced by urbanization and pollutants. *J. Appl. Meteor.*, **14**, 1061-1071.
- Baik, J. -J., and Y. -H. Kim, 2001: Dry and moist convection forced by an urban heat island. *J. Appl. Meteor.*, **40**, 1462-1475.
- Bergstrom, R., and R. Viskanta, 1973a: Prediction of the spectral absorption and extinction coefficients of an urban air pollution aerosol model. *Tellus*, **25**, 468-498.
- Bergstrom, R., and R. Viskanta, 1973b: Modeling of the effects of gaseous and particulate pollutants in the urban atmosphere. Part I: Thermal structure. *J. Appl. Meteor.*, **12**, 901-912.
- Bergstrom, R., and R. Viskanta, 1973c: Modeling of the effects of gaseous and particulate pollutants in the urban atmosphere. Part II: Pollutant dispersion. *J. Appl. Meteor.*, **12**, 913-918.
- Bornstein, R. D., 1972: Two dimensional non-steady numerical simulations of nighttime flow of a stable planetary boundary layer over a rough warm city. Preprints, *Conference on Urban Environment*, Amer. Meteor. Soc., Philadelphia, PA, 89-94.
- Bornstein, R. D., 1975: The two-dimensional URBMET urban boundary layer model. *J. Appl. Meteor.*, **14**, 1459-1477.
- Bornstein, R. D., 1984: Urban climate models: nature, limitations and applications. Preprints, WMO Conference on Urban Climatology and its Applications with Special Regard to Tropical Areas, Mexico City, Mexico, 26-30 November.

- Bornstein, R. D., 1987: Mean diurnal circulation and thermodynamic evolution of urban boundary layers. In *Modeling the Urban Boundary Layer*, A. Blackadar, Ed., AMS, Boston, MA, 53-93.
- Bornstein, R. D., and A. D. Johnson, 1977: Urban-rural wind velocity differences. *Atmos. Environ.*, **11**, 597-604.
- Bornstein, R. D., and G. M. LeRoy, 1990: Urban barrier effects on convective and frontal thunderstorms. Preprints, 4th *Conference on Mesoscale Processes*, Amer. Meteor. Soc., 25-29 June, Boulder, CO.
- Bornstein, R. D., and Q. Lin, 2000: Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmos. Environ.*, **34**, 507-516.
- Bornstein, R. D., and T. R. Oke, 1981: Influence of pollution on urban climatology. *Adv. Environ. Soc. And Engin.*, **2**, 171-202.
- Bornstein, R. D., P. Thunis, and G. Schayes, 1993a: Simulation of urban barrier effects on polluted urban boundary layers using three-dimensional URBMET/TVM model with urban topography. New results from NYC. *Air Pollution*, P. Zannetti, et al., Eds., Computational Mechanics Publications, 15-34.
- Bornstein, R. D., S. Klotz, U. Pechinger, R. Salvador, R. Street, L. J. Shieh, F. Ludwig, and R. Miller, 1986: Application of linked three-dimensional PBL and dispersion models to New York City. *Air Pollution Modeling and its Applications V*, Plenum Press, 543-564.
- Bornstein, R. D., P. Thunis, P. Grossi, and G. Schayes, 1996: Topographic vorticity-mode mesoscale- β (TVM) model. Part II: Evaluation. *J. Appl. Meteor.*, **35**, 1824-1834.
- Brown, M., and M. Williams, 1998: An urban canopy parameterization for mesoscale meteorological models. Preprints, 2nd *Urban Environment Symposium*, Amer. Meteor. Soc., Albuquerque, NM.
- Ca, V., T. Asaeda, and Y. Ashie, 1999: Development of a numerical model for the evaluation of the urban thermal environment. *J. Wind Eng. Ind. Aerodyn.*, **81**, 181-196.
- Camuffo, D., and A. Bernardi, 1982: An observational study of heat fluxes and the relationship with net radiation. *Bound.-Layer Meteor.*, **23**, 359-368.
- Changnon, S. A., F. A. Huff, and R. G. Semonin, 1971: METROMEX: An investigation on inadvertent weather modification. *Bull. Amer. Meteor. Soc.*, **52**, 958-967.

- Changnon, S. A., R. G. Semonin, A. H. Auer, R. R. Brahan, and J. M. Hales, 1981: METROMEX: *A Review and Summary*. Meteor. Monogr., No. 40, Amer. Meteor. Soc., 181 pp.
- Changnon, S. A., R. T. Shealy, and R. W. Scott, 1991: Precipitation changes in fall, winter, and spring caused by St. Louis. *J. Appl. Meteor.*, **30**, 126-134.
- Ching, J. K. S., J. F. Clarke, J. S. Irwin, and J. M. Godowitch, 1983: Relevance of mixed layer scaling for daytime dispersion based on RAPS and other field programs. *Atmos. Environ.*, **17**, 859-871.
- Cionco, R., and R. Ellefsen, 1998: High resolution urban morphology data for urban wind flow modeling. *Atmos. Environ.*, **32**, 7-17.
- Clark, T. L., 1977: A small-scale dynamic model using a terrain following coordinate transformation. *J. Comp. Phys.*, **24**, 186-215.
- Clark, T. L., and D. Farley, 1984: Severe downslope windstorm calculations in two and three spatial dimensions using anelastic interactive grid nesting: a possible mechanism for gustiness. *J. Atmos. Sci.*, **41**, 329-350.
- Clarke, J. A., 1985: *Energy Simulation in Building Design*. Adam Higler, Bristol.
- Deardorff, J. W., 1972: Parameterization of the PBL for use in general circulation models. *Mon. Wea. Rev.*, **100**, 93-106.
- Delage, Y., and P. Taylor, 1970: Numerical studies of heat island circulations. *Bound.-Layer Meteor.*, **1**, 201-226.
- Dieterle, D., 1979: Simulation of urban surface energy balance, including effects of anthropogenic heat. M.S. Thesis, San Jose State University, 65 pp.
- Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale, two-dimensional model. *J. Atmos. Sci.*, **46**, 3077-3107.
- Dudhia, J., 1993: A nonhydrostatic version of the Penn State/NCAR mesoscale model: Validation tests and simulations of an Atlantic cyclone and cold front. *Mon. Wea. Rev.*, **121**, 1493-1513.
- Gayno, G. A., 1994: Development of a higher-order, fog-producing boundary layer model suitable for use in numerical weather prediction. M.S. Thesis, The Pennsylvania State University, 104 pp.

- Grell, G., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.*, **121**, 764-787.
- Grimmond, C. S. B., H. A. Cleugh, and T. R. Oke, 1991: An objective urban heat storage model and its comparison with other schemes. *Atmos. Environ.*, **25B**, 311-326.
- Grimmond, C. S. B., and T. R. Oke, 1999a: Aerodynamic properties of urban areas derived from analysis of surface form. *J. Appl. Meteor.*, **38**, 1262-1292.
- Grimmond, C. S. B., and T. R. Oke, 1999b: Heat storage in urban areas: local-scale observations and evaluation of a simple model. *J. Appl. Meteor.*, **38**, 922-940.
- Hafner, J., and S. Q. Kidder, 1999: Urban heat island modeling in conjunction with satellite-derived surface/soil parameters. *J. Appl. Meteor.*, **38**, 448-465.
- Hjelmfelt, M., 1982: Numerical simulation of the effects of St. Louis in mesoscale boundary-layer airflow and vertical air motion: simulations of urban vs. non-urban effects. *J. Appl. Meteor.*, **21**, 1239-1257.
- Idso, S. B., J. K. Aase, and R. D. Jackson, 1975: Net radiation-soil heat flux relations as influenced by soil water content variations. *Bound.-Layer Meteor.*, **9**, 113-122.
- Imamura, I., and R. D. Bornstein, 1992: Review of urban climate and dispersion. Final report to U.S. Army, Atmospheric Sciences Laboratory, Contract No. DAA103-86-D-0001, 259 pp.
- Jauregue, E., and E. Romales, 1996: Urban effects on convective precipitation in Mexico City. *Atmos. Environ.*, **30**, 3383-3389.
- Kain, J. S., and J. M. Fritsch, 1993: Convective parameterization for mesoscale models: the Kain-Fritsch scheme. *The representation of cumulus convection in numerical models*, K. A. Emanuel and D. J. Raymond, Eds., Amer. Meteor. Soc., 246 pp.
- Kalany, E., et al., 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.
- Kerschgens, M. J., and J. M. Hacker, 1985: On the energy budget of the convective boundary layer over an urban and rural environment. *Contrib. Atmos. Phys.*, **58**, 171-185.
- Kimura, R., 1976: Effects of general flows on a heated island convection. Part 1: Linear theory for the uniform flow. *J. Meteor. Soc. Japan*, **54**, 308-320.

- Kimura, F., 1989: Heat flux on mixture of different land-use surface: test of a new parameterization scheme. *J. Meteor. Soc. Japan*, **67**, 401-409.
- Kimura, F., and S. Takahashi, 1991: The effects of land-use and anthropogenic heating on the surface temperature in the Tokyo metropolitan area: a numerical experiment. *Atmos. Environ.*, **25B**, 155-164.
- Kimura, R., N. Misawa, J. Sakagami, and T. L. Kunii, 1977: Effects of general flows on a heated island convection. Part 2: Numerical and laboratory experiments for the shear flow. *J. Meteor. Soc. Japan*, **55**, 32-51.
- Kitada, T., K. Okamura, and S. Tanaka, 1998: Effects of topography and urbanization on local winds and thermal environment in the Nohbi Plain, coastal region of Central Japan: A numerical analysis by mesoscale meteorological model with a k- ϵ turbulence model. *J. Appl. Meteor.*, **37**, 1026-1046.
- Leach, M. J., N. S. Chin, and M. J. Brown, 2001: Validation of an urban parameterization in a mesoscale model. Presented at *International Symposium on Environmental Hydraulics*, 5-8 December, Tempe, Arizona.
- Lee, R. L., and Olfe, D. B., 1974: Numerical calculations of temperature profiles over an urban heat island. *Bound.-Layer Meteor.*, **7**, 39-52.
- Lettau, H. H., 1951: Theory of surface temperature and heat transfer oscillations near a level ground surface. *Trans. Am. Geophys. Union*, **32**, 189-200.
- Lin, Q., 2000: Urban Influences of Summertime Convective Thunderstorms in Atlanta. M.S. Thesis, San Jose State University, 117 pp.
- Liu, J., J. Chen, T. Black, and M. Novak, 1996: E-e modeling of turbulent airflow downwind of a model forest edge. *Bound.-Layer Meteor.*, **77**, 21-44.
- Lowry, W. P., 1998: Urban effects on precipitation amount. *Prog. Phys. Geog.*, **22**, 477-520.
- Lozej, C., and R. Bornstein, 1999: Comparison of nesting techniques within a meteorological model. Preprints, *Eighth Conference on Mesoscale Processes*, Amer. Meteor. Soc., Boulder, CO, 372-375.
- Martilli, A. A., 2001: Development of an urban turbulence parameterisation for mesoscale atmospheric models. Ph.D. dissertation, École Polytechnique Fédérale de Lausanne, 165 pp.

- Martilli, A., A. Clappier, and M. W. Rotach, 2000: A parameterization of heat and momentum fluxes in urban areas for mesoscale models. Proceedings, COST715 Expert Meeting, 12 April, Antwerp, Belgium.
- Maruyama, T., 1999: Surface and inlet boundary conditions for the simulation of turbulent boundary layer over complex rough surfaces. *J. Wind Eng. Ind. Aerodyn.*, **81**, 311-322.
- Masson, V., 2000: A physically-based scheme for the urban energy budget in atmospheric models. *Bound.-Layer Meteor.*, **94**, 357-397.
- Masson, V., A. Lemonsu, and D. Brion, 2000: Numerical study of urban mesoscale effects on the atmospheric boundary layer. Proceedings, *Third Symposium on the Urban Environment*, 14-18 August 2000, Davis, CA.
- McElroy, J., 1973: A numerical study of the nocturnal heat island over a medium-sized mid-latitude city (Columbus, Ohio). *Bound.-Layer Meteor.*, **3**, 442-453.
- Mills, G., 1997: An urban canopy-layer climate model. *Theor. Appl. Climatol.*, **57**, 229-244.
- Monteith, J. L., 1973: *Principles of Environmental Physics*. Edward Arnold, London.
- Morgan, D. L., L. Myrup, D. Rogers, and R. Baskett, 1977: Microclimates within an urban area. *Ann. Assoc. Amer. Geogr.*, **67**, 55-65.
- Myrup, L., 1969: A numerical model of the urban heat island. *J. Appl. Meteor.*, **8**, 908-918.
- Nielsen-Gammon, J. W., 2000: The Houston heat pump: modulation of a land-sea breeze by an urban heat island. Preprints, *11th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA*, Amer. Meteor. Soc., Long Beach, CA, 65-69.
- Ochs, H. T., 1975: Modeling of cumulus initiation in METROMEX. *J. Appl. Meteor.*, **14**, 873-882.
- Oke, T. R., 1973: City size and the urban heat island. *Atmos. Environ.*, **7**, 769-779.
- Oke, T. R., 1987: *Boundary Layer Climates*, 2nd ed., Methuen, London, 435 pp.
- Oke, T. R., B. D. Kalanda, and D. G. Steyn, 1981: Parameterisation of heat storage in urban areas. *Urban Ecol.*, **5**, 45-54.

- Oke, T., G. Johnson, D. Steyn, and I. Watson, 1991: Simulation of surface urban heat islands under "ideal" conditions at night, Part 2: Diagnosis of causation. *Bound.-Layer Meteor.*, **56**, 339-358.
- Olfe, D. B., and R. L. Lee, 1971: Linearized calculations of urban heat island convection events. *J. Atmos. Sci.*, **28**, 1374-1388.
- Outcalt, S. I., 1971: A numerical surface climate simulator. *Geogr. Anal.*, **3**, 379-393.
- Outcalt, S. I., 1972a: The development and application of a simple digital surface-climate simulator. *J. Appl. Meteor.*, **11**, 629-636.
- Outcalt, S. I., 1972b: A reconnaissance experiment in mapping and modeling the effect of land use on the urban thermal regime. *Arch. Meteor. Geophys. Bioklim.*, **B20**, 253-260.
- Panayiotou, C., 1995: Application of the prognostic URBMET/TVM meso- β meteorological model to Phoenix, Arizona. M.S. Thesis, San Jose State University, 86 pp.
- Pandolfo, J. P., 1966: Wind and temperature profiles for constant flux boundary layers in lapse conditions with a variable eddy conductivity to eddy viscosity ratio. *J. Atmos. Sci.*, **23**, 495-502.
- Panton, R., 1984: *Incompressible Flow*. John Wiley and Sons, New York.
- Peikorz, G., 1987: Die energiebilanz einer stadtischen struktur. Dipl. Meteorologie, Rheinische Friedrich-Wilhelm-Universität, Bonn.
- Pielke, R., 1974: A three-dimensional numerical model of the sea breeze over South Florida. *Mon. Wea. Rev.*, **102**, 115-139.
- Pielke, R. A., and Y. Mahrer, 1978: Verification analysis of the University of Virginia three-dimensional mesoscale model prediction over south Florida for July 1, 1973. *Mon. Wea. Rev.*, **106**, 1568-1589.
- Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, 1992: A comprehensive meteorological modeling system—RAMS. *Meteor. Atmos. Phys.*, **49**, 69-91.
- Pruppacher, H. R., and J. D. Klett, 1997: *Microphysics of Clouds and Precipitation*. Kluwer Academic, 954 pp.

- Qiu, X., P. A. Taylor, and F. Conway, 2000: High resolution MC2 meteorology simulations for a lower Great Lakes region air quality study. Preprints (title only), *11th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA*, Amer. Meteor. Soc., Long Beach, CA.
- Quattrochi, D., J. Luvall, M. Estes, C. Lo, S. Kidder, J. Hafner, H. Taha, R. Bornstein, R. Gillies, and K. Gallo, 1998: Project Atlanta: A study of how the urban landscape affects meteorology and air quality through time. Preprints, *2nd AMS Urban Environment Conference*, Albuquerque, NM, 104-107.
- Rotach, M., 1993a: Turbulence close to a rough urban surface, Part I: Reynolds stress. *Bound.-Layer Meteor.*, **65**, 1-28.
- Rotach, M., 1993b: Turbulence close to a rough urban surface, Part II: Variances and gradients. *Bound.-Layer Meteor.*, **66**, 75-92.
- Rotach, M., 1995: Profiles of turbulence statistics in and above an urban street canyon. *Atmos. Environ.*, **29**, 1473-1486.
- Roth, M., 1998: Vertical structure of turbulence over cities. *2nd AMS Urban Environment Symposium*, Albuquerque, NM.
- Rozoff, C. M., and W. R. Cotton, 2001: METROMEX revisited. Preprints, *15th Conference on Planned and Inadvertent Weather Modification*, Amer. Meteor. Soc., Albuquerque, NM, 125-126.
- Sailor, D., 1993: Role of surface characteristics in urban meteorology and air quality. Ph.D. dissertation, University of California, Berkeley, 174 pp. [Available from Dr. David Sailor, Dept. of Mechanical Engineering, Tulane University, New Orleans, LA 70118.]
- Saitoh, T. S., T. Shimada, and H. Hoshi, 1996: Modeling and simulation of the Tokyo urban heat island. *Atmos. Environ.*, **30**, 3431-3442.
- Sawai, T., 1978: Formation of the urban air mass and associated local circulation. *J. Meteor. Soc. Japan*, **56**, 159-174.
- Schultz, P., and T. Warner, 1982: Characteristics of summertime circulations and pollutant ventilation in the Los Angeles basin. *J. Appl. Meteor.*, **21**, 672-682.
- Seaman, N. L., et al. 1989: Numerical studies of urban boundary layer structure under realistic synoptic conditions. *J. Appl. Meteor.*, **28**, 760-781.
- Sellers, W. D., 1965: *Physical Climatology*. University of Chicago Press, Chicago.

- Selover, N., 1997: Convective precipitation patterns in an urban desert – topographic or urban influences? AAG Conference, Fort Worth, TX, 78-82.
- SethuRaman, S., and J. E. Cermak, 1974: Physical modeling of flow and diffusion over an urban heat island. *Advances in Geophysics*, **18**, 223-240.
- SethuRaman, S., and J. E. Cermak, 1975: Mean temperature and mean concentration distributions over a physically modeled three-dimensional heat island for different stability conditions. *Bound.-Layer Meteor.*, **9**, 427-440.
- Shir, C. C., and R. D. Bornstein, 1977: Eddy exchange coefficients in numerical models of the planetary boundary layer. *Bound.-Layer Meteor.*, **11**, 171-185.
- Sievers, U., 1995: Verallgemeinerung der Stromfunktionsmethode auf drei Dimensionen. *Metrol. Zeitschrift*, N. F., **4**, 3-15.
- Sievers, U., 2001: *The Model MUKLIMO_3, Special Aspects and Extensions*. Deutscher Wetterdienst, Offenbach, January 2001.
- Sorbjan, Z., and M. Uliasz, 1982: Some numerical urban boundary-layer studies. *Bound.-Layer Meteor.*, **22**, 481-502.
- Taha, H., 1996: Modeling impacts of increased urban vegetation on ozone air quality in the south coast air basin. *Atmos. Environ.*, **30**, 3423-3430.
- Taha, H., 1997: Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air basin. *Atmos. Environ.*, **31**, 1667-1676.
- Taha, H., 1999: Modifying a mesoscale meteorological model to better incorporate urban heat storage: a bulk-parameterization approach. *J. Appl. Meteor.*, **38**, 466-473.
- Taha, H., H. Akbari, and D. Sailor, 1992: Causes and effects of heat islands: The sensitivity of urban microclimates to surface parameters and anthropogenic heat. Lawrence Berkeley National Laboratory Tech. Rep. LBL-29864.
- Taha, H., X. Liu, D. Sailor, A. Meier, M. Benjamin, L. Bloch, A. Winer, S. Douglas, and J. Haney, 1994: Analysis of energy efficient and air quality in the SoCAB—Phase II report. Lawrence Berkeley National Laboratory Report No. LBNL-35728, Berkeley, CA.
- Thielen, J., W. Wobrock, A. Gadian, P. G. Mestayer, and J. –D. Creutin, 2000: The possible influence of urban surfaces on rainfall development: a sensitivity study in 2D in the meso- γ -scale. *Atmos. Res.*, **54**, 15-39.

- Urano, A., T. Ichinose, and K. Hanaki, 1999: Thermal environment simulation for three dimensional replacement of urban activity. *J. Wind Eng. Ind. Aerodyn.*, **81**, 197-210.
- Vukovich, F. M., 1971: Theoretical analysis of the effect of mean wind and stability on a heat island circulation characteristic of an urban complex. *Mon. Wea. Rev.*, **99**, 919-926.
- Vukovich, F. M., 1973: A study of the atmospheric response due to a diurnal heating function characteristic of an urban complex. *Mon. Wea. Rev.*, **101**, 467-474.
- Vukovich, F. M., 1975: Study of the effect of wind shear on a heat island circulation characteristic of an urban complex. *Mon. Wea. Rev.*, **103**, 27-33.
- Vukovich, F., and J. Dunn, 1978: A theoretical study of the St. Louis heat island: some parameter variations. *J. Appl. Meteor.*, **17**, 1585-1594.
- Vukovich, F., and W. J. King, 1980: Comparisons between observed data and simulated results on the urban heat island circulation. *J. Appl. Meteor.*, **19**, 764-770.
- Vukovich, F., J. Dunn, and B. Crissman, 1976: A theoretical study of the St. Louis heat island: the wind and temperature distribution. *J. Appl. Meteor.*, **15**, 417-440.
- Vukovich, F., W. J. King, J. W. Dunn, and J. J. B. Worth, 1979: Observations and simulations of the diurnal variation of the urban heat island circulation and associated variations of the ozone distribution: A case study. *J. Appl. Meteor.*, **18**, 836-854.
- Wang, W., and N. L. Seaman, 1997: A comparison study of convective parameterization schemes in a mesoscale model. *Mon. Wea. Rev.*, **125**, 252-278.
- Weisman, M. L., and J. B. Klemp, 1986: Characteristics of isolated convective storms. *Mesoscale Meteorology and Forecasting*, Ed., P. Ray, Amer. Meteor. Soc., 331-358.
- Welch, R. M., J. Paegle, and W. G. Zdunkowski, 1978: Two-dimensional numerical simulation of the effects of air pollution upon the urban-rural complex. *Tellus*, **30**, 136-150.
- Wilson, N., and R. Shaw, 1977: A higher order closure model for canopy flow. *J. Appl. Meteor.*, **16**, 1197-1205.
- Yamada, T., 1972: Urban heat island effects on air pollution. Preprints, *Conference on Urban Environment*, Amer. Meteor. Soc., Philadelphia, PA, 99-105.

- Yamada, T., 1982: A numerical study of turbulent airflow in and above a forest canopy. *J. Meteor. Soc. Japan*, **60**, 439-454.
- Yoshikado, H., 1992: Numerical study of the daytime urban effect and its interaction with the sea breeze. *J. Appl. Meteor.*, **31**, 1146-1164.
- Yu, T. -W., and N. K. Wagner, 1975: Numerical study of the nocturnal urban boundary layer. *Bound.-Layer Meteor.*, **9**, 143-162.
- Zilitinkevich, S., V. M. Gryanik, V. N. Lykossov, and D. V. Mironov, 1999: Third-order transport and nonlocal turbulence closures for convective boundary layers. *J. Atmos. Sci.*, **56**, 3463-3477.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

SIGMA =1.000 LAND USE (category) 1996-07-26_15.00.00 = 1996-27-26_00 = 15.00H SMOOTH= 0

LANDUSE July 26 NO-URBAN 3-km DOMAIN

Fig. 5

Fig. 6

Fig.7

Fig. 8

Fig. 9

Fig. 10

Fig. 13

Fig. 14

Fig. 15

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

26 JUL 96, 1500 EDT

T (K)

Fig. 24

Fig. 25

26 JUL 96, 1600 EDT

T (K)

Fig. 26

Fig. 28

Fig. 29

Fig. 30

Fig. 31

Fig. 32

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Fig. 57

Fig. 58

Fig. 59

Fig. 60

SIGMA = 0.997 T (C) 1996-07-26_18.00.00 = 1996-07-26_00 + 18.00H SMOOTH= 0

23m TEMPERATURE July 26 BASE CASE 3-km DOMAIN
 CONTOUR FROM 24.000 TO 31.000 CONTOUR INTERVAL OF 0.50000 PT(3,3)= 29.420

Fig. 61

Fig. 62

Fig. 63

Fig. 64

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