Improving simulations of the convective boundary layer in and around Oklahoma City using the coupled WRF-LIS system

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ABSTRACT

Joint Urban 2003 was the largest urban dispersion experiment ever conducted in North America. Between the dates of 28 June to 31 July 2003, a vast array of instrument systems collected high-resolution observations of meteorological variables in and around Oklahoma City. The data collected from the field instrumentation, combined with data collected from existing atmospheric observing systems in central Oklahoma, provide a unique opportunity to investigate various processes related to the impact of urban areas on the planetary boundary layer. The impacts of the urban canopy on the boundary layer are poorly represented in numerical weather prediction models. Thus, during the 10-week period of the 2006 NASA Graduate Student Summer Program, simulations were performed using the uncoupled Land Information System for the Oklahoma City and surrounding areas. A spin-up experiment was conducted to investigate the behavior of the Noah land surface model for a domain over Oklahoma. The simulation results were then compared with in situ observations from the Oklahoma Mesonet and Joint Urban 2003 field experiment.

1. INTRODUCTION

A recent study by the United Nations found that by 2025, 80% of the world's population will live in cities (Shepherd et al. 2002) while currently in the United States, 64% of the population lives within less than 2% of the U.S. land area (Dabberdt et al. 2000). Thus, the weather observed within urban environments significantly impacts the majority of people worldwide. In addition, the significant land-use differences between the rural and urban areas, as well as increased atmospheric pollution, have considerable impacts on the climate from local to regional scales. Urban-induced weather phenomena directly impact society through more intense heat waves, increased flooding, and reduced visibility, which in turn lead to more direct and indirect weather-related accidents and deaths and significant economic loss (Changnon 1992).

To date, much of the current understanding of the impacts of urban areas on atmospheric processes results from a number of field programs including those conducted in a number of North American cities: St. Louis (Lowry 1974), Chicago, Los Angeles, Vancouver, Montreal, Mexico City, Tucson, Salt Lake City (Allwine et al. 2002), and Phoenix (Grimmond and Oke 1995). During June and July 2003, the largest urban dispersion field experiment of its kind, Joint Urban 2003, was conducted in Oklahoma City (OKC). Between 28 June and 31 July 2003, a vast array of instrument systems collected high-resolution observations of meteorological variables in and around OKC. The data collected from the field instrumentation, combined with data collected from existing atmospheric observing systems in central Oklahoma represents perhaps the largest conglomeration of instruments ever assembled designed to quantify the impact of urban areas on atmospheric process within the planetary boundary layer.

Urban areas constitute a very small fraction of the earth's surface. However, urban

sprawl continues to expand the structure of cities and numerical weather prediction (NWP) models are being developed at increasingly greater resolutions. As such, it is vital to begin the integration of urban areas into regional weather prediction models. Perhaps the greatest near-future impact of urban areas on NWP at regional scales will be linked to how land surface models (LSMs) simulate the energy balance in urban areas. The results of the study will improve the parameterizations of land surface states within urban regions. In turn, the simulation of boundary layer conditions will be improved within NWP models, which can further impact the forecast of temperature and precipitation in and around urban areas.

2. JOINT URBAN 2003

The Department of Homeland Security and the Defense Threat Reduction Agency sponsored an urban dispersion experiment in OKC during July 2003. The goal of Joint Urban 2003 (JU03) was to "collect meteorological tracer data resolving atmospheric dispersion at scales-of-motion ranging from flows in and around a single city block, in and around several blocks in the downtown Central Business District (CBD), and into the suburban OKC area several km from the CBD" (Clawson et al. 2005).

OKC was selected for JU03 for several reasons, which included a consolidated and well defined CBD of tall buildings, relatively flat terrain without large bodies of water bordering the city, predictable wind conditions for the study period, the gridded nature of the city streets (Fig. 1), and the support of city officials for the project. In addition, an extensive weather-observing infrastructure was in place in central Oklahoma that included the Oklahoma Mesonet (Brock et al. 1995), the KOUN dual polarization radar, the OUN upper air station, and four NEXRAD Doppler radars.

The instruments employed during JU03 consisted of over 140 3-D sonic anemometers for surface-based and tower-based measurements, 13 2-D sonic anemometers, over 30 surface meteorological stations, seven surface energy budget stations, two CTI wind tracer lidars, three radiosonde systems, three wind profiler/RASS systems, one FM-CW radar, three ceilometers, a NOAA Twin Otter aircraft, and nine sodars (including midi- and mini-sodars).

Given the extensive dataset collected during JU03, a unique opportunity existed to quantify atmospheric processes within the planetary boundary layer in unmatched detail in and around OKC. As such, uncoupled land surface simulations were conducted for OKC and surrounding areas.

3. MOTIVATION

Urbanization produces radical changes in the surface and atmospheric properties of a region (Oke 1987). Thermal, radiative, moisture, and aerodynamic characteristics of a region are modified by the urban landscape, thus having profound impacts on the radiative, energy, momentum, and water balances. For example, human activity in urban areas, such as fossil fuel burning, releases significant amounts of water vapor and heat into the atmosphere, which impact the surface energy and water budgets. The impervious materials used for buildings, sidewalks, and roads limit the amount of precipitation infiltrated at the land surface. As a result, urban areas are characterized by large volumes of runoff during high precipitation events (Oke 1987). The amount of solar radiation received at the surface can be reduced during its passage through a polluted atmosphere (Jáuregui and Luyando 1999). On the other hand, the albedo of urban surfaces is lower than that of rural surfaces, which results in increased absorption of solar radiation (Aida 1982). Pollution and urban geometry act to increase the amount of downward

longwave radiation and decrease upward longwave radiation within the urban environment (Johnson et al. 1991). The construction materials used and lack of vegetation cover in urban areas limit evapotranspiration, increase sensible heat transport, and increase heat storage, thus warming the atmosphere (Nunez and Oke 1977; Hildebrand and Ackerman 1984). Within the urban street canyon, reduced wind speeds decrease the total turbulent transport of heat away from the surface (Oke 1987). Several of these impacts combine to produce the urban heat island effect, where nighttime air temperature within urban environments is warmer than surrounding rural temperatures. Finally, the anthropogenic release of water vapor and pollution into the atmosphere increase summer precipitation downwind of large cities (Dettwiller and Changnon 1976; Shepherd et al. 2002; Rozoff et al. 2003).

Despite these impacts, surface and atmospheric conditions within the urban boundary layer are not routinely observed. As a result, much of the current understanding of the impacts of urban areas on atmospheric processes results from a number of field programs including those conducted in a number of North American cities: St. Louis (Lowry 1974), Chicago, Los Angeles, Vancouver, Montreal, Mexico City, Tucson, Salt Lake City (Allwine et al. 2002), and Phoenix (Grimmond and Oke 1995). Results from these urban field programs have served as the foundation for modeling the urban boundary layer.

The complex structure of the urban boundary layer has made it difficult to simulate the effects of the urban canopy on the lower atmosphere in mesoscale models. In the past, urban areas represented small fractions of grid boxes in NWP models. Thus, it was believed that any effects of the urban canopy on the atmosphere were lost when averaged over the coarse model grid. Due to restrictions on the model resolution, limits on available computing resources, and required timeliness of forecasts, cities are poorly resolved in operational NWP models (Best

2005). The complex interactions between the urban canopy and the atmosphere are not treated explicitly in mesoscale models. Instead, because they are subgrid-scale processes, they are parameterized. As a result, urban areas are typically represented in a vegetation-atmosphere-transfer model as bare soil or concrete with modified parameters such as increased surface roughness, reduced soil moisture availability, and reduced albedo. In addition, the parameterization assumes buildings and roads are at the same temperature and treats building height and coverage ratio implicitly in the surface layer. While simple models are interesting for comparison, they are not useful if key physics are disregarded (Betts 2004). As a result, the current approach fails to reproduce the vertical structure of turbulent fluxes and urban heat island effects due to the neglect of the impacts of building geometry (Martilli et al. 2002).

"As mesoscale model resolution increases, it will be increasingly important to properly represent urban influences on the radiation budget, surface moisture, sensible heat exchange processes, and anthropogenic heat and moisture fluxes" (Dabberdt et al. 2000). To bridge the gap between subgrid-scale and grid-scale processes in mesoscale models, efforts have focused on improving the representation of urban areas in mesoscale models by concentrating on either thermal or dynamical parameterizations (Martilli et al. 2002). Thermal parameterizations have focused on how the urban canopy impacts the radiative and surface energy balances (Tso et al. 1991; Johnson et al. 1991; Grimmond et al. 1991; Best 1998; Taha 1999; Voogt and Grimmond 2000; Masson 2000; Kusaka et al. 2001; Grimmond and Oke 2002; Masson et al. 2002; Offerle et al. 2003 Kanda et al. 2005b, c; Jin and Peters-Lidard 2006). On the other hand, dynamical parameterizations focused on impacts on winds and the generation of turbulent kinetic energy (Delage and Taylor 1970; Bornstein 1975; Uno et al. 1989; Liu et al. 1996; Maruyama 1999). While most urban canopy parameterizations have focused on either thermal or dynamical

parameterizations for mesoscale models, a third class of urban canopy models, referred to here as hybrid models, has incorporated both urban thermal and dynamical improvements (Ca et al. 1999; Urano et al. 1999; Martilli et al. 2002; Otte et al. 2004).

4. SCIENCE QUESTIONS

Extreme weather events in urban areas result in thousands of deaths each year, many of which could be avoided by more specific or accurate forecasts, advisories, and warnings. Flash flooding and severe storms can disrupt transportation systems and cause power failures. In addition, urban areas can worsen flash flooding by increasing runoff and shortening the time for water to reach collection areas. Increased runoff and heavy water flow can then overwhelm sewer systems and cause sewer overflow, degrading water quality. For example, the Washington, D.C. area received 10-15" of rain in late June 2006. The rainfall resulted in five fatalities, numerous swift water rescues, washed out roads and train lines, power outages, and damaged buildings and homes (NWS 2006).

Excessive heat is problematic in urban areas due to the urban heat island effect. As a result, city residents experience sustained heat stress both day and night, while rural areas often receive relief at night. During July 13-15, 1995, Chicago experienced unusually high maximum and minimum temperatures, as well as high relative humidity, which resulted in 465 heat-related deaths. The U.S. Department of Commerce (1995) concluded that the July 1995 heat wave was exacerbated by urbanization, particularly in Chicago.

Recent national and international events have heightened attention to acts of terrorism in heavily populated urban areas. Characteristics of the urban boundary layer impact the dispersion of toxic fallout and harmful chemicals and ultimately, the number of lives at risk. Finally,

industrial plants and automobiles in cities pollute the air, which is then transported to other locations, impacting the health of humans, plants, and animals, building materials, and fabrics.

Due to severe weather, homeland security threats, air and water quality risks, and climate variations, decision makers need rapid access to high-resolution, meteorological data and more accurate weather predictions. As higher resolution forecast models are implemented operationally, it becomes increasingly important to correctly represent the physical processes occurring in urban environments.

Can we understand the impacts of the urban canopy on the boundary layer above and downwind of OKC? Understanding the impacts of the OKC area on the boundary layer requires analysis of JU03, Oklahoma Mesonet, and upper air data, as well recognizing the shortcomings of how OKC is currently represented in land surface and NWP models. Can we improve the parameterization of urban canopy-atmosphere interactions for OKC in a LSM and in a coupled land-atmosphere system, without sacrificing the computational efficiency of the modeling system? Currently, NWP models fail to correctly capture the effects of the urban canopy on the boundary layer. These effects include the conversion of mean kinetic energy into turbulent kinetic energy at the top of the urban canopy, drag induced by buildings, the trapping of radiation, and differential heating due to building geometry. Improving the urban canopy parameterizations in land surface and NWP models includes utilizing thermal and dynamical improvements and determining the relative importance of each.

If we are successful and improve the parameterization of urban canopy-atmosphere interactions, then we may consider the following: The State of Oklahoma provided the funding to develop and deploy an urban micronet in OKC. Can we further improve urban representation in NWP models if we utilize the observational data from the OKC Urban Micronet in

simulations of the urban boundary layer? What are the implications for public policy and emergency management in OKC? Can useful decision-making tools be derived from the results of this study?

5. METHODOLOGY

This study investigates the representation of the OKC area in mesoscale models and its impact on the boundary layer using uncoupled land and coupled land-atmosphere systems. In order to improve current land surface and boundary layer parameterizations, it is important to first identify their limitations with respect to the urban environment.

5.1 LIS

NASA's Goddard Space Flight Center (GSFC) developed the Land Information System (LIS), a high performance land surface modeling and data assimilation system that simulates global land surface conditions at spatial resolutions of 1-5 km (Peters-Lidard et al. 2004, 2005; Tian et al. 2004; Kumar et al. 2005). LIS consists of uncoupled LSMs forced with observed precipitation, radiation, meteorological variables, and surface parameters, and was developed to update LSMs to represent the impacts of engineered surfaces on mesoscale land-atmosphere interactions (Peters-Lidard et al. 2004). The LSMs currently implemented in LIS are: the Noah LSM (Ek et al. 2003), the NCAR Common Land Model (CLM; Dai et al. 2003), the Variable Infiltration Capacity model (VIC; Liang et al. 1994), and the Mosaic LSM (Koster and Suarez 1996).

The Noah LSM is a soil-vegetation-atmosphere transfer model initially developed at Oregon State University (Pan and Mahrt 1987). Since then, it has been continuously extended

by the National Centers for Environmental Prediction (NCEP) and collaborators for use in the NCEP's regional and global prediction models and data assimilation systems (Chen et al. 1996, 1997; Betts et al. 1997; Koren et al. 1999; Ek et al. 2003). Noah has four soil layers of thicknesses of 10, 30, 60, and 100 cm, constant rooting depth of 40 cm, and constant total column depth of 200 cm. Urban areas are represented in the Noah LSM as bare soil with an increased roughness length and reduced albedo.

The CLM is a state-of-the-art LSM developed by a grass-roots collaboration of scientists interested in making a land model available for public use (Dai et al. 2003). The CLM represents soil temperature and moisture through unevenly spaced soil layers and uses a tiled or mosaic approach to represent subgrid variability in the surface energy and water balances. The CLM is the LSM for the National Center for Atmospheric Research (NCAR) Community Climate System Model, which has been tested extensively in both coupled and uncoupled modes. Urban land cover is included in the CLM so future versions can study urbanization. As a result, the urban cover is currently set to zero.

5.2 WRF

The Weather Research and Forecasting (WRF) model (Skamarock et al. 2005) is a next-generation mesocale NWP model designed to serve operational forecasting and atmospheric research needs. The collaborative partners that developed WRF include NCAR, NCEP, Forecast Systems Laboratory (FSL), Air Force Weather Agency (AFWA), Naval Research Laboratory, University of Oklahoma, and Federal Aviation Administration (FAA).

NASA's LIS has been successfully coupled with the WRF model and results suggested that LIS improved the coupled system estimates (Peters-Lidard et al. 2005). The proposed work

of this study will use the LIS-WRF coupled system with an urban canopy model and data from JU03 to improve the simulation of the boundary layer over the various land surfaces within OKC. In turn, the simulation of boundary layer conditions will be improved within NWP models, which can further impact the forecast of temperature precipitation in and around urban areas.

5.3 Land Surface Spin-up

Each LSM has a unique land surface climatology. In addition, the reliability of a LSM is limited by the accuracy of the forcing data and initial conditions (Rodell et al. 2005). If the initial conditions deviate from the land surface climatology, the model must be allowed to reach an equilibrium state, otherwise known as spin-up. If the model is not adequately spun up, the initial conditions may produce erroneous trends as the land surface states drift toward the model climatology.

To determine the length of spin-up time required for LIS simulations over Oklahoma, a spin-up experiment was conducted. The spin-up experiment consisted of the Noah LSM at a 1-km resolution and a domain over Oklahoma, excluding the panhandle. The atmospheric forcing data was that of the North American Land Data Assimilation System (NLDAS) and soil data was from the State Soil Geographic (STATSGO) database. The prescribed initial soil temperature was 290 K and initial soil moisture was volumetric water content of 0.325. 1-, 12-, 24-, and 36-month spin-ups were conducted, with the simulations ending on 3 July 2003. Soil moisture and temperature for all four soil layers were examined to determine if the land surface had reached an equilibrium state.

6. PRELIMINARY RESULTS

The percent differences of soil moisture and soil temperature for 3 July 2003 between successive spin-up runs were calculated to determine whether the land surface states had reached equilibrium. For example, the percent difference between the land surface states for 3 July 2003 after 1- and 12-month spin-ups were calculated from the following equation:

$$\text{Percent Difference} = \frac{\left(\text{Value after 12-mo spin-up} - \text{Value after 1-mo spin-up}\right)}{\frac{1}{2}\left(\text{Value after 12-mo spin-up} + \text{Value after 1-mo spin-up}\right)} \times 100\%$$

This metric indicated the improvement of the variable with each additional year of spin-up.

The largest changes in soil moisture occurred during the first year of spin-up (Fig. 2), where percent differences were as large as -90%. The percent differences significantly decreased with 24 months of spin-up. In addition, the lower soil layers had larger values of percent difference between successive spin-ups and took longer to reach an equilibrium state. Percent differences between the 36- and 24-month spin-up runs exceeded ± 1% in the lowest soil layer. Thus, a spin-up simulation of 48 months should be performed to determine whether the Noah LSM reached equilibrium in regards to soil moisture for all layers within 36 months.

Examination of a time series graph of volumetric water content for the latitude and longitude of OKC revealed discrepancies between initial soil moisture conditions and those after one or more years of spin-up (Fig. 3). The initial volumetric water content was, in many cases, too moist for the soil conditions of Oklahoma due to persistent dry periods. Lower soil layers take longer to spin up due to the memory of the soil. Thus, while the initial soil moisture was appropriate for the upper two soil layers on 3 July 2002, the conditions were too moist for the lower two soil layers and resulted in the need for a longer spin-up. The same was true for the 3 July 2001 initialization. In the case of the 1-month spin-up, Figure 3 illustrates how a lack of

spin-up and erroneous initial conditions can impact the land surface states for the date of interest. Future spin-up experiments will include the use of more realistic initial conditions based on observations from the Oklahoma Mesonet to assess if and how it shortens the time required to reach equilibrium.

Soil temperatures reached equilibrium more quickly than soil moisture (Fig. 4). The percent differences of soil temperature exceeded ± 0.1% for the 12- and 24-month spin-ups where the soils were classified as fine sandy loam. The percent differences for the 24- and 36-month spin-up simulations indicated that the Noah LSM had reached equilibrium in regards to soil temperature within 24 months.

After the LSM reaches equilibrium, it is important to verify that the model land surface states are representative of the actual land surface conditions. Thus, 24-hour simulations for 3 July 2003 were performed after each spin-up and the hourly model output were compared with data from the Oklahoma Mesonet and JU03. It should be noted that the observations, which are point measurements, are not expected to be identical to the area averages output by Noah. However, point measurements can provide useful information about model behavior and biases.

Skin temperature observations from the Norman Mesonet site and JU03 were compared with values modeled by Noah at the corresponding grid points (Figs. 5a-b). The observed skin temperatures implied an urban heat island effect in OKC whereas the modeled values did not. However, the urban heat island effect was not apparent in the observations of sensible heat flux (Figs. 5c-d). The lower sensible heat flux values in OKC were due to intermittent afternoon clouds over OKC. Examination of the site location revealed that shading from buildings did not play a factor as the site was placed sufficiently far from buildings. Finally, observed values of latent heat flux were compared with modeled values. The observed and modeled values were

consistent with those from previous field experiments in which urban areas are characterized by lower latent heat flux values due to less vegetation cover and impervious construction surfaces.

7. CONCLUSIONS

Urbanization produces radical changes in the surface and atmospheric properties of a region. However, these urban canopy-atmosphere interactions are poorly represented in NWP models. This study investigates the representation of the OKC area in mesoscale models and its impact on the boundary layer using NASA GSFC's LIS.

To assess the current representation of the OKC area in the LSMs available within the LIS framework, the land surface states had to be appropriately spun up. A spin-up experiment was conducted to determine the length of spin-up time required for LIS simulations over Oklahoma. The spin-up experiment consisted of the Noah LSM at a 1-km resolution and a domain over Oklahoma. Results revealed that soil temperatures for all soil layers reached equilibrium within 24 months, much faster than soil moisture. However, the initial soil moisture conditions were too moist for the deeper soil layers. As a result, the two lower soil layers had not reached equilibrium within 24 months of initialization. Thus, a 48-month spin-up must be performed to determine whether 36 months is sufficient for spinning up the Noah LSM for Oklahoma.

Preliminary verification efforts revealed that Noah correctly captured urban-rural trends of latent heat fluxes. However, when compared with point measurements from JU03 for 3 July 2003, significant differences were noted between modeled and observed skin temperatures. Further verification with additional data is required to fully assess Noah's urban parameterization

scheme. The spin-up experiment and verification with observations will be duplicated with CLM in the near future.

Once the limitations of Noah and CLM are identified, an urban canopy model will be developed for use within the LIS-WRF coupled system to predict the components of the surface energy balance and profiles of winds, temperature, and moisture in OKC. The model will be validated using observations from JU03 and the future OKC Urban Micronet (to be completed by 1 January 2007). The model may then be used for other urban locations, provided validation data is available. In turn, the simulation of boundary layer conditions will be improved within NWP models, which can further impact the forecast of temperature and precipitation in and around urban areas.

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FIGURES

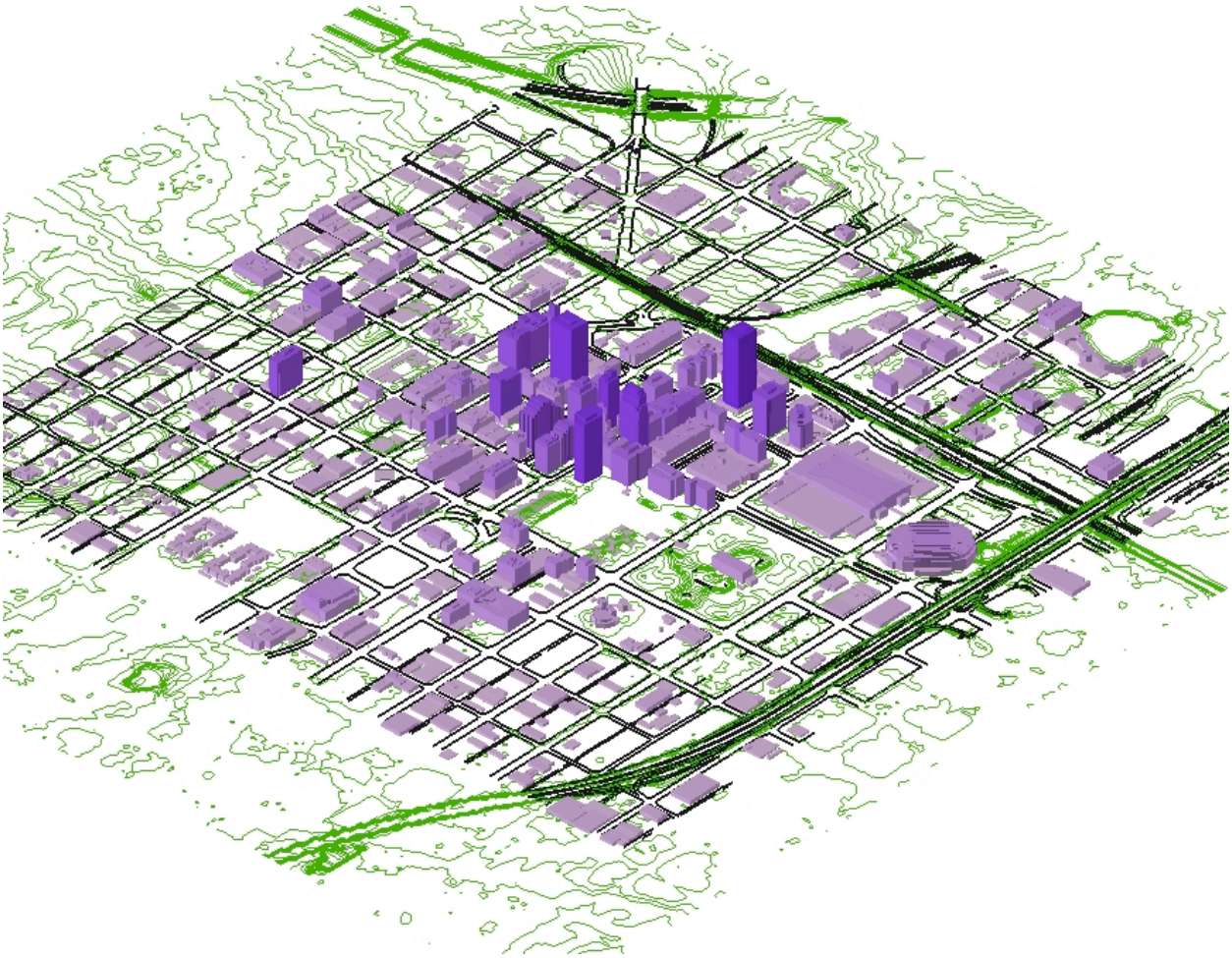

Figure 1. A three-dimensional display of downtown OKC created using the JU03 GIS database**.**

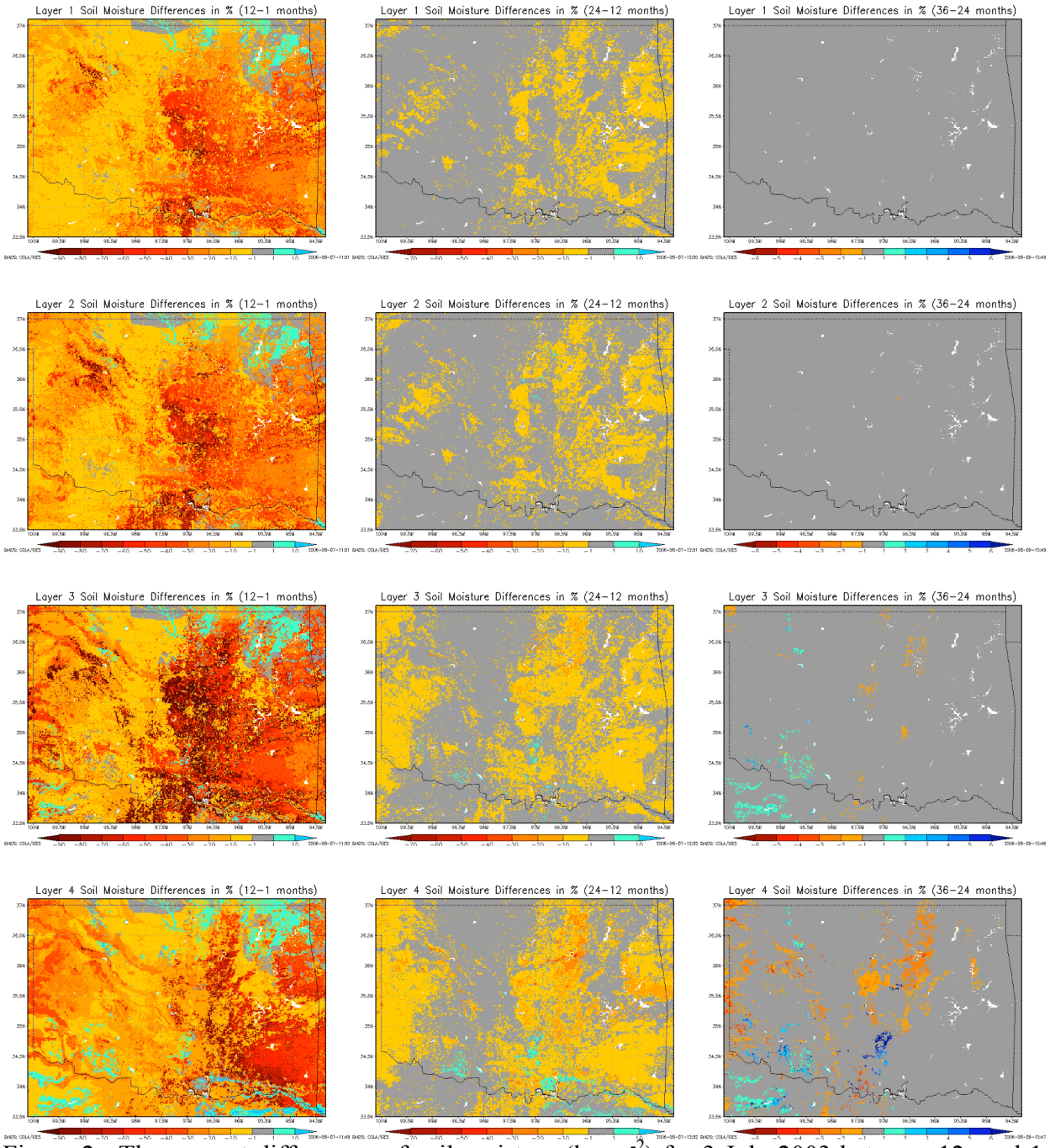

Figure 2. The percent differences of soil moisture (kg m^{-2}) for 3 July 2003 between 12- and 1-month spin-up periods (left column), 24- and 12-month spin-up periods (middle column), and 36- and 24-month spin-up periods (right column) for soil layers 1 (top row), 2 (second row), 3 (third row) and 4 (fourth row) of the Noah land surface model. The gray color indicates percent differences of ± 1%.

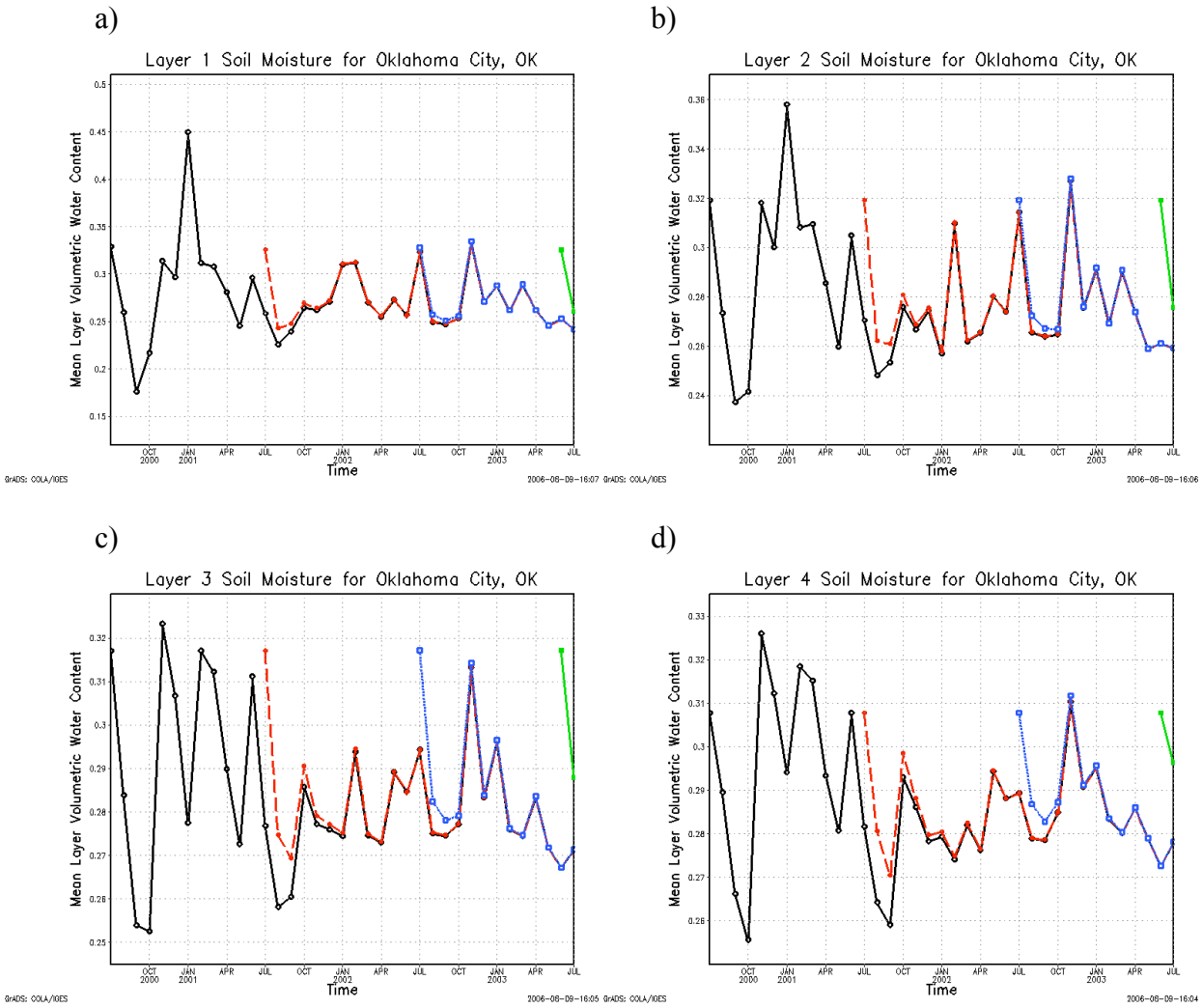

Figure 3. Time series of volumetric water content (%) for soil layers a) 1, b) 2, c) 3, and d) 4 of the Noah land surface model at the latitude and longitude of OKC during spin-up simulations of 1 (green), 12 (blue dashed), 24 (red dashed), and 36 (black) months.

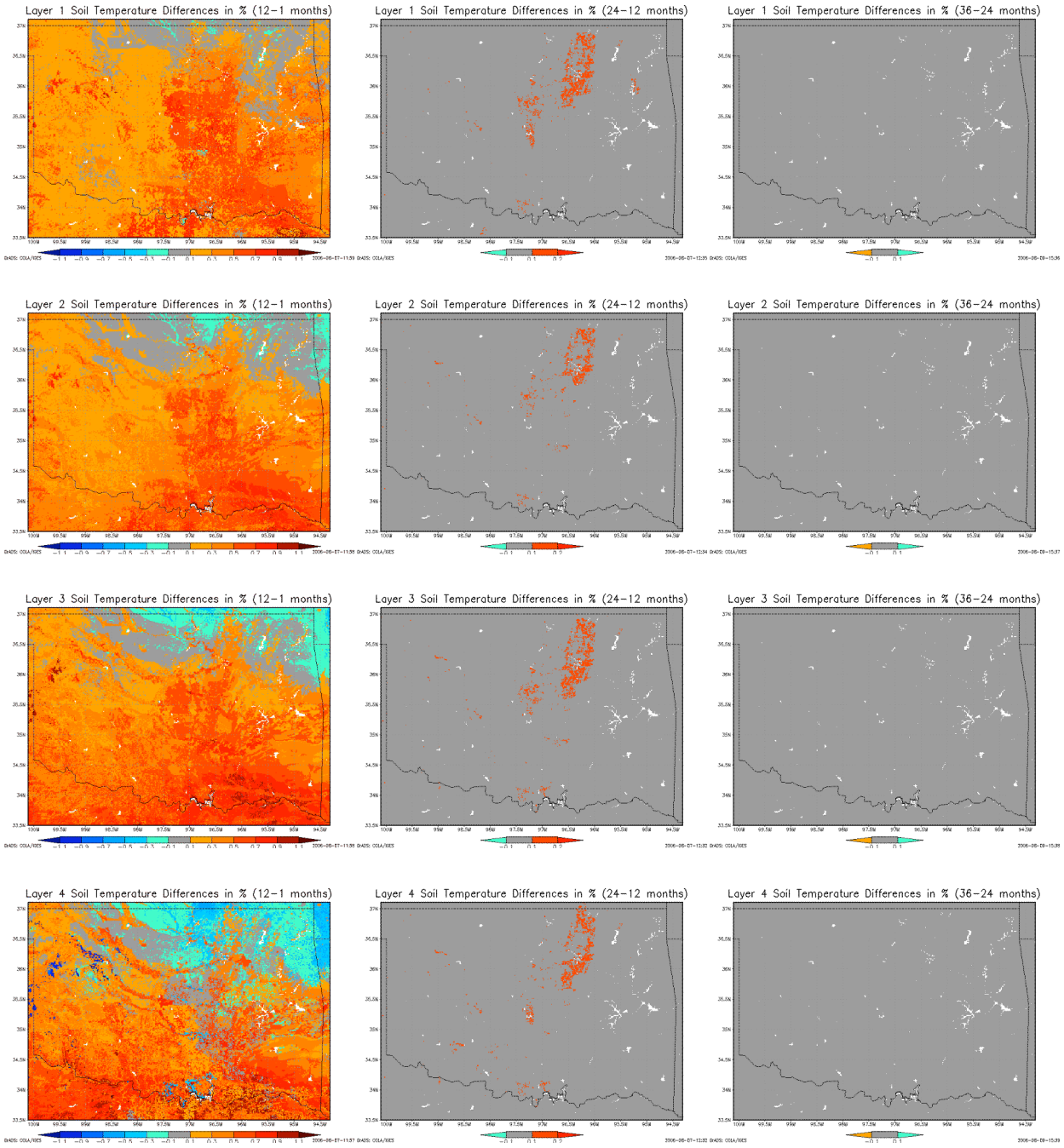

Figure 4. The percent differences of soil temperature (K) for 3 July 2003 between 12- and 1-month spin-up periods (left column), 24- and 12-month spin-up periods (middle column), and 36- and 24-month spin-up periods (right column) for soil layers 1 (top row), 2 (second row), 3 (third row) and 4 (fourth row) of the Noah land surface model. The gray color indicates percent differences of ± 0.1%.

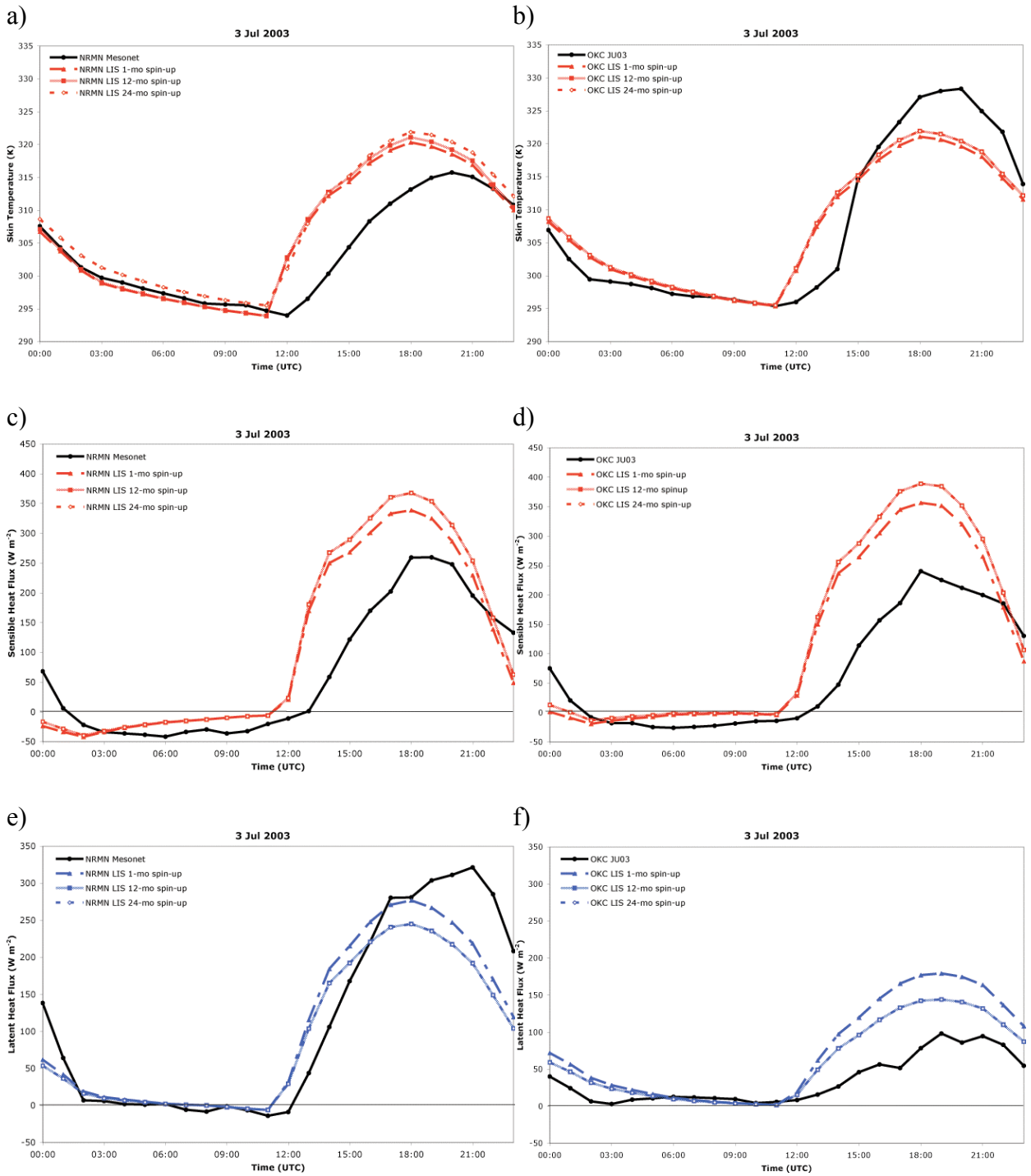

Figure 5. Time series of skin temperature (a-b), sensible heat fluxes (c-d), and latent heat fluxes (e-f) observed (black line) at the Oklahoma Mesonet site (left column) and during JU03 (right column), and modeled by Noah (dashed) at the corresponding grid points.