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THE STRUCTURE OF THE CONVECTIVE BOUNDARY LAYER IN AND AROUND OKLAHOMA CITY

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1. INTRODUCTION

Joint Urban 2003 (JU2003) was the largest urban dispersion experiment ever conducted in North America. Between the dates of 28 June and 31 July 2003, a vast array of instrument systems collected high-resolution observations of meteorological variables in and around Oklahoma City (OKC). The data collected from the field instrumentation, combined with data collected from existing atmospheric observing systems in central Oklahoma, provided a unique opportunity to investigate various processes related to the impact of urban areas on atmospheric process within the convective boundary layer (CBL).

While observational studies have long shown that urban areas significantly impact local weather and climate, the simulation of urban effects is a weakness of current land surface models (LSMs) (Sailor and Fan 2002; Best 2005; Jin et al. 2007). NASA 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 (Kumar et al. 2006; Peters-Lidard et al. 2007). 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 land-atmosphere interactions (Peters-Lidard et al. 2004).

For this study, the vertical profiles of temperature and specific humidity are reconstructed and the structure of the CBL is quantified immediately upwind and downwind of the central business district (CBD) of OKC. In addition, preliminary results from spin-up simulations are presented, which use the Noah LSM within the LIS framework.

2. OBSERVATIONAL DATA

2.1 Joint Urban 2003 (JU2003)

The Department of Energy, the Department of Defense, and the Department of Homeland Security sponsored an urban dispersion experiment in OKC from 28 June through 31 July 2003. The goal of JU2003 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 CBD, and into the suburban OKC area several kilometers from the CBD" (Clawson et al. 2005).

OKC was selected for JU2003 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, 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, the KOUN dual polarization radar, the OUN upper air station, and four NEXRAD Doppler radars.

Ten intensive observation periods (IOPs) that spanned eight hours in duration were completed during the 34-day study period. During the IOPs detailed meteorological, turbulence, and tracer measurements were recorded.

2.1.2 Radiosonde Data

To quantify the structure of the CBL in and around OKC during JU2003, data were collected by radiosondes launched at regular time intervals by experiment participants, as well as those launched by the National Weather Service (NWS) in Norman at 0000 and 1200 UTC. The Argonne National Laboratory (ANL) launched radiosondes during IOPs from First Christian Church, approximately five kilometers north of the OKC CBD (Fig. 2.1). The Pacific Northwest National Laboratory (PNNL) launched radiosondes during IOPs two kilometers south of the OKC CBD at the OKC Traffic Maintenance Yard on the south edge of Wheeler Park. To supplement the vigorous sampling during IOPs, the Army Research Laboratory (ARL) launched soundings each day from the same location as ANL, typically at 0600 and 1800 UTC. The ARL launch interval was designed to offset the launch times by the NWS at

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0000 and 1200 UTC. The variables measured by the radiosondes include height, pressure, temperature, potential temperature, relative humidity, mixing ratio, and occasionally wind speed and direction.

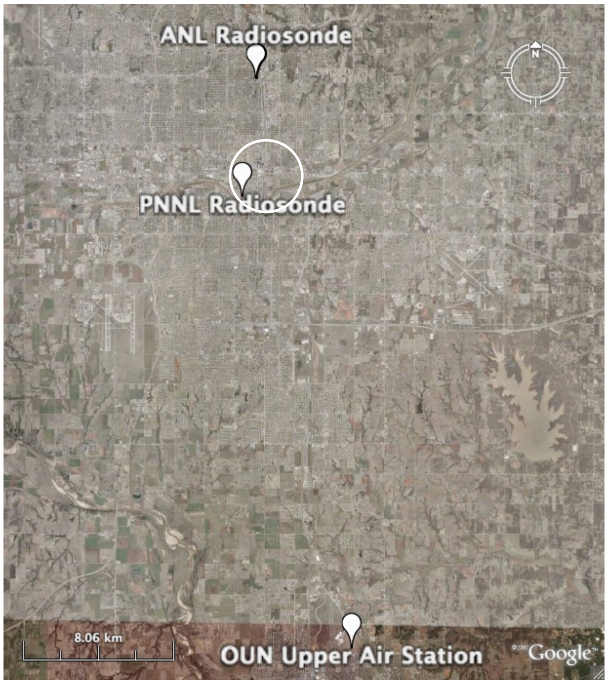

Figure 2.1. Locations of the radiosondes launched by the Argonne National Laboratory (ANL), Army Research Laboratory (ARL), Pacific Northwest National Laboratory (PNNL), and the National Weather Service in Norman (OUN) during Joint Urban 2003 with respect to Oklahoma City's Central Business District, circled in white. Source of imagery: Google Earth.

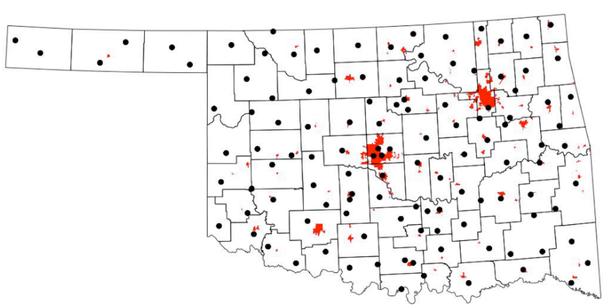

Figure 2.2. Current locations of the Oklahoma Mesonet sites. Mesonet sites are indicated by solid black circles. Urban areas are shaded in red.

2.2 The Oklahoma Mesonet

The Oklahoma Mesonet is an automated network of over 100 remote, hydrometeorological stations across Oklahoma (Fig. 2.2; McPherson et al. 2007). Each station measures 10 core variables which include: air temperature and relative humidity at 1.5 m, wind speed and direction at 10 m, barometric pressure, precipitation, incoming solar radiation, bare and vegetated soil temperatures (10 cm BGL), and soil moisture (5, 25, 60, and 75 cm BGL). Observations from the Oklahoma Mesonet are collected every five minutes, with the exception of soil temperature (15 minutes) and soil moisture (30 minutes). The Mesonet was installed in 1993 and became operational on 1 January 1994.

3. MODELING SYSTEMS

Of the different types of boundaries in atmospheric models, the lower boundary, the land surface, is the only one with physical significance (Pielke 2002). As a result, varying characteristics of this boundary significantly impact the properties of the overlying CBL. Primarily, the CBL is modified by the land surface through the exchange of water and energy at the land surface-atmosphere interface. In additional, modifications to the CBL by the land surface further impact mesoscale and synoptic scale processes. Thus, because of the critical importance of the land surface in mesoscale atmospheric systems, the interactions between the land surface and the atmosphere must be represented as accurately as possible (Pielke 2002).

3.1 The Noah Land Surface Model

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 modified 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.

3.2 The Land Information System (LIS)

NASA GSFC developed the 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, 2007; Kumar et al. 2006). LIS consists of uncoupled LSMs forced with observation-based precipitation and radiation as well as model-based meteorological variables and surface parameters. Further, LIS 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, the NCAR Common Land Model Version 2 (CLM2; Dai et al. 2003), the Variable Infiltration Capacity model (VIC; Liang et al. 1994, 1996), the Mosaic LSM (Koster and Suarez 1996), and the Simple Biosphere model with Hydrology (Sellers et al. 1986; Sud and Mocko 1999).

3.3 LIS-WRF Coupled System

Typically, LIS is operated uncoupled to an atmospheric model. However, recently, LIS has been successfully coupled with the Weather Research and Forecasting (WRF; Skamarock et al. 2005) model by following the Earth System Modeling Framework, which allows users to run LIS within the Advanced Research WRF (ARW) dynamical core (Kumar et al. 2005). The LIS-WRF coupled system offers several advantages over the ARW alone. The coupled system allows the user to optimize the initialization of surface and soil variables by tuning the spin-up time according to the domain and specifying atmospheric forcing (Case et al. 2007). In addition, the LIS-WRF system provides access to all of the LSMs implemented in LIS, as opposed to the three LSM options currently in WRF. The coupled system also allows the user to introduce high-resolution datasets of land surface parameters and surface observations through the data assimilation tools implemented in LIS. Currently, two LSMs in LIS, Noah and CLM2, have been implemented for use in the LIS-WRF coupled system. Preliminary results demonstrated that the LIS-WRF system improved estimates over WRF alone (Peters-Lidard et al. 2005).

4. PRELIMINARY RESULTS

4.1 Radiosonde Comparisons

Several radiosondes were launched during JU2003. As mentioned previously, the launch sites were arranged such that the CBL far upwind, immediately upwind, and far downwind of OKC were sampled. To ensure that the radiosondes launched downwind of the CBD of OKC (ARL and ANL) were sampling the urban boundary layer (UBL) and the radiosondes launched far upwind of OKC (OUN) were sampling the rural boundary layer, cases were limited to days with southerly winds. Data from the Norman and Spencer Mesonet sites and the OUN radiosondes were inspected from 1 July through 31 July 2003 for cases with winds between 150° and 210°, clear to partly cloudy skies, and no measurable precipitation. Figure 4.1 illustrates vertical profiles of potential temperature and specific humidity immediately upwind (PNNL), and far downwind (ANL) of the CBD of OKC for 7 July and 9 July 2003.

The vertical profiles of temperature and humidity illustrate that initially the CBL immediately upwind of the CBD of OKC developed more quickly than that far downwind of the CBD (Fig. 4.1). This faster initial development immediately upwind of the CBD was likely due to proximity to the urban core. However, as the day progressed and the CBL heights increased from approximately 700 m at 1500 UTC to 1800 m at 2200 UTC, the downwind CBL became deeper than the upwind CBL. The deeper CBL downwind of the CBD of OKC was supported by southerly upper level winds, which advected the air modified by the urban landscape to north of the CBD. It should also be noted that the CBL far downwind of the CBD was slightly warmer and drier than the upwind CBL on 7 July (Fig. 4.1).

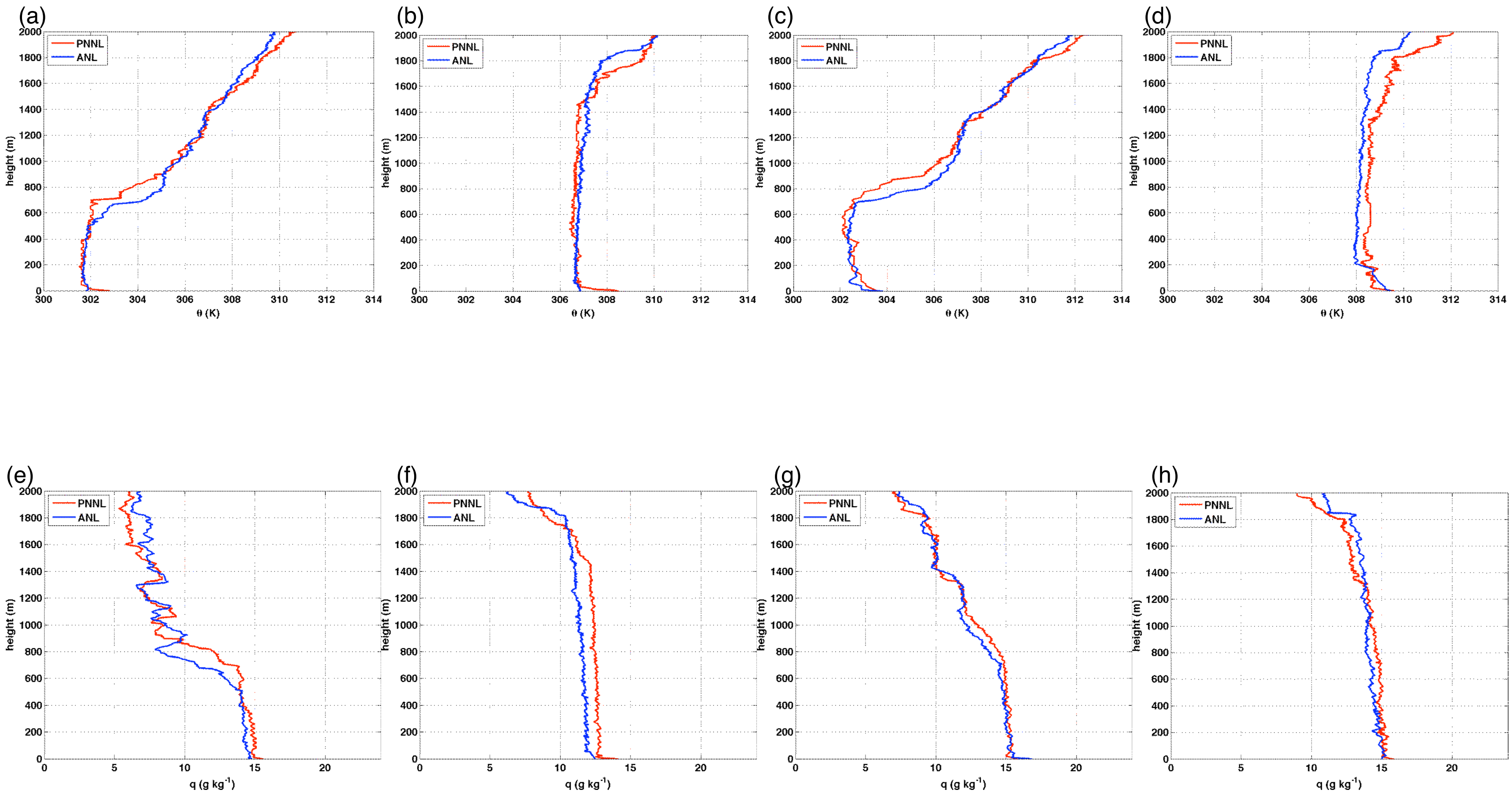

Figure 4.1. Vertical profiles of temperature (a-d) and specific humidity (e-h) recorded by radiosondes launched by PNNL (red) and ANL (blue) at 1500 UTC (a, c, e, g) and 2200 UTC (b, d, f, h) on 7 July 2003 (a, b, e, f) and 9 July 2003 (c, d, g, h).

4.2 Offline LIS Spin-up Experiment

Each LSM has a unique land surface climatology that is determined primarily by the model physics (Cosgrove et al. 2003; Rodell et al 2005). 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. Consequently, if the model spin-up process is not properly executed, the initial conditions may produce errors whereby the land surface state drifts toward the model climatology.

To determine the length of spin-up required for simulations over Oklahoma, an experiment was conducted which consisted of the Noah LSM at 1-km resolution and a domain that covered the majority of Oklahoma with the exception of the panhandle. The atmospheric forcing data used North American Land Data Assimilation System (NLDAS; Mitchell et al. 2004) variables, the State Soil Geographic (STATSGO; Miller and White 1998) database was used for the soil information, and land use information was provided by the US Geological Survey's (USGS) Global Land Cover Characterization (GLCC; Loveland et al. 2000). As suggested by Rodell et al. (2005), the spin-up started from middling to wet initial states whereby the prescribed initial soil temperature was 290 K and initial soil moisture was volumetric water content of 0.325 across the domain. The spin-up simulations were conducted for the following periods, each ending on 1 July 2003: 1, 3, 6, 9, 12, 15, 18, 21, 24, 30, 36, 42, 48, 54, 60 and 66 months. Once completed, soil moisture and soil temperature for all four soil layers as well as total column soil moisture were examined to determine whether the land surface had reached an equilibrium state.

The metric used to determine whether the land surface states reached equilibrium was the percent difference where the 66-month simulation was used as the "control" simulation. Thus, the percent difference values of soil moisture, soil temperature, and total column soil moisture were calculated with respect to the 66-month spin-up run. Thus, positive values of percent difference indicate that the initial soil moisture (temperature) was too wet (warm), while negative values indicate that the initial soil moisture (temperature) was too dry (cool) compared to the control. Two specific values of percent difference were used as threshold values to quantify whether the values of percent difference had reached equilibrium: 1% and 0.01%. The 1% difference represents the level where the LSM ceases to exhibit model output changes on a "practical" scale and represents the error in many observation systems (Cosgrove et al. 2003). The 0.01% difference represents the fine scale model equilibrium, which satisfies the Goddard Institute for Space Studies (GISS) group requirements and exceeds the Simplified Simple Biosphere (SSiB) modeling group requirements (0.1%) used during the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS; Henderson-Sellers et al. 1993) experiment (Yang et al. 1995; Cosgrove et al. 2003).

4.2.1 Soil Temperature

Soil temperature values reached model equilibrium rapidly for the 0-10 cm soil layer (Fig. 4.2a) and practical scale equilibrium (1%) was reached within the first month of spin-up. Further, several simulations approached fine scale model equilibrium (Tables 4.1-4.2). The entire domain reached fine scale model equilibrium after 36, 42, and 60 months of spin-up.

As with the 0-10 cm layer, the soil temperature values for the 10-40 cm layer reached practical equilibrium within the first month of spin-up. Further, fine scale model equilibrium was attained after 42 and 60 months of spin-up (Fig. 4.2b; Tables 4.1-4.2).

Practical equilibrium with respect to soil temperature was reached for the 40-100 cm layer within one month of simulation time (Fig. 4.2c). While fine scale equilibrium was not reached within 60-months of simulation time, values of percent difference that exceeded ± 0.01% for the 36-, 42-, 48-, 54-, and 60-month simulations were small in magnitude (Tables 4.1-4.2).

Practical scale model equilibrium was attained within six months of spin-up for 100-200 cm soil temperature values. However, due to the thickness of the soil layer, fine scale equilibrium was never reached (Fig. 4.2d) even though several simulations approached fine scale equilibrium (Tables 4.1-4.2). When the percent difference values of soil temperature between 60- and 66-months of spin-up were compared with soil texture, it was determined that the regions in southwest Oklahoma that did not reach fine scale equilibrium were soils consisting of clay.

	1	3	6	9	12	15	18	21	24	30	36	42	48	54	60
ST 1	-0.801	-0.396	-0.268	-0.265	-0.164	-0.087	-0.067	-0.053	-0.078	-0.022	-0.005	-0.003	-0.009	-0.010	-0.003
ST 2	-0.733	-0.419	-0.309	-0.291	-0.197	-0.094	-0.072	-0.059	0.043	0.042	-0.012	-0.008	-0.003	-0.022	-0.004
ST 3	-0.908	-0.545	-0.414	-0.365	-0.274	-0.133	-0.103	-0.086	-0.062	-0.027	-0.020	-0.017	-0.010	-0.038	-0.006
ST 4	-1.112	-0.519	-0.433	-0.400	-0.327	-0.187	-0.178	-0.161	-0.187	-0.125	-0.073	-0.065	-0.075	-0.022	-0.020
SM 1	-5.325	-1.833	-1.793	-1.626	-0.881	-0.719	-0.639	-0.581	-15.733	-13.276	-0.256	-0.109	-1.005	-0.082	-0.277
SM 2	-2.441	-2.632	-3.807	-3.595	-1.955	-1.563	-1.419	-1.298	-20.282	-15.774	-0.502	-0.430	-1.352	-0.178	-0.310
SM 3	-3.780	-4.691	-6.204	-4.028	-2.790	-2.314	-1.989	-1.465	-21.267	-11.243	-0.955	-1.927	-3.966	-0.173	-1.055
SM 4	-8.127	-8.169	-6.839	-1.238	-5.794	-4.491	-5.428	-6.386	-5.222	-2.550	-1.805	-2.776	-4.039	-3.401	-3.025
TCSM	-32.817	-15.384	-9.078	-2.176	-8.362	-6.466	-6.707	-8.088	-9.133	-4.811	-2.465	-3.802	-3.117	-4.606	-4.042

Table 4.1. Minimum values of percent difference for soil temperature (ST), soil moisture (SM), and total column soil moisture (TCSM) relative to the 66-month spin-up simulation.

	1	3	6	9	12	15	18	21	24	30	36	42	48	54	60
ST 1	0.688	0.415	0.095	0.049	0.026	0.018	0.005	0.005	0.323	0.313	0.003	0.003	0.018	0.007	0.003
ST 2	0.571	0.571	0.080	0.015	0.010	0.018	0.007	0.008	0.268	0.232	0.004	0.004	0.023	0.003	0.005
ST 3	0.730	0.727	0.115	0.048	0.015	0.019	0.016	0.020	0.299	0.240	0.007	0.011	0.040	0.009	0.012
ST 4	1.371	1.268	0.580	0.428	0.223	0.071	0.062	0.054	0.103	0.076	0.016	0.025	0.025	0.083	0.027
SM 1	89.320	28.274	18.508	14.729	12.846	6.445	4.024	2.920	-0.721	-0.593	0.217	0.218	0.043	0.877	0.140
SM 2	124.712	37.982	20.473	15.089	12.966	7.043	4.440	3.302	0.294	0.511	0.249	0.246	0.169	0.965	0.250
SM 3	154.875	91.557	60.734	48.259	28.790	13.908	10.498	8.924	0.016	2.482	3.370	2.772	0.670	3.807	1.225
SM 4	148.718	122.822	96.246	88.029	71.470	41.360	38.210	33.936	22.416	18.562	15.124	13.318	8.449	6.359	2.708
TCSM	114.626	82.452	60.414	53.361	38.973	32.588	30.778	27.194	15.642	12.955	11.853	10.415	6.550	4.976	2.098

Table 4.2. Maximum values of percent difference for soil temperature (ST), soil moisture (SM), and total column soil moisture (TCSM) relative to the 66-month spin-up simulation.

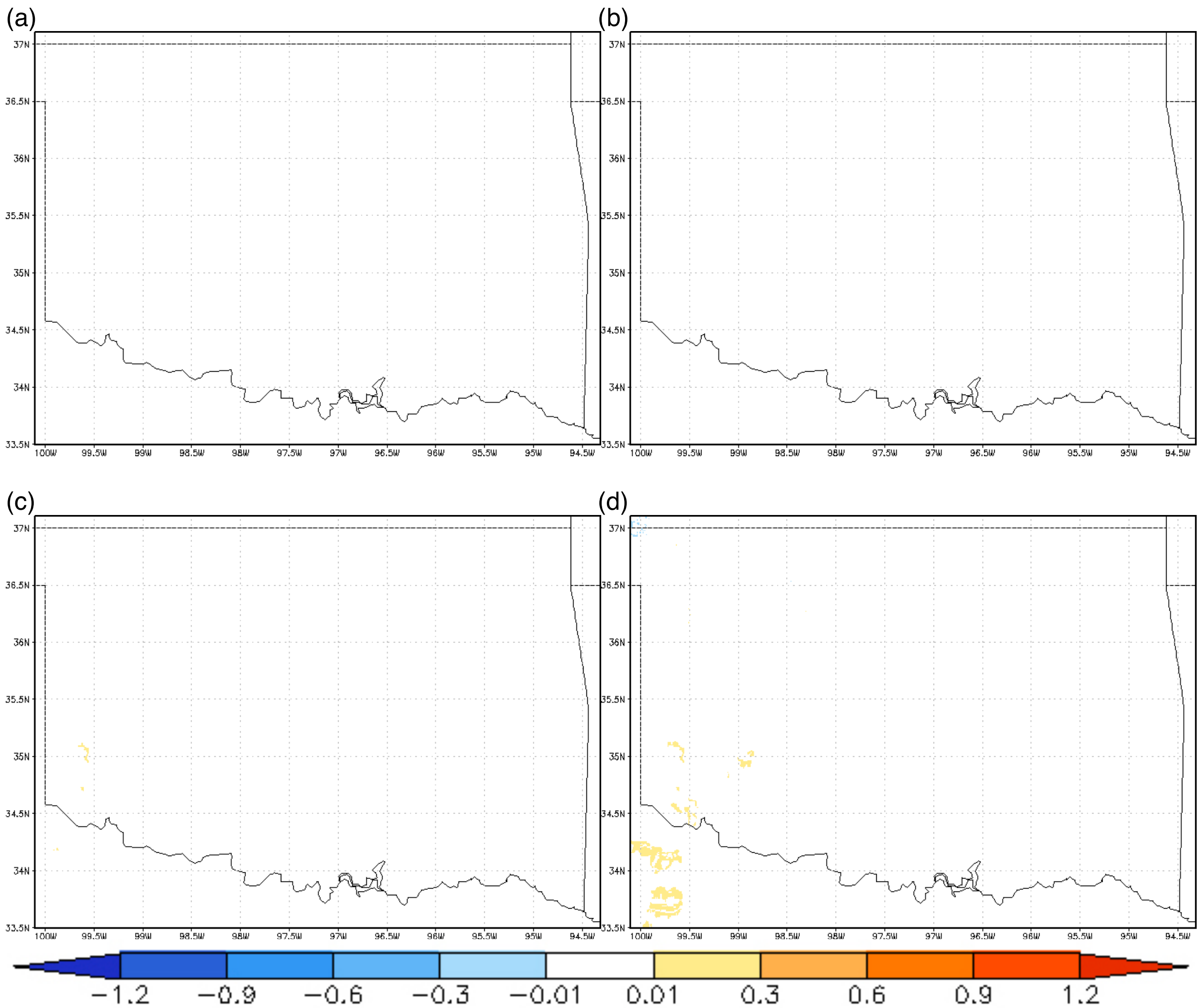

Figure 4.2. Percent difference values of soil temperature for 60-month spin-up with respect to the 66-month spin-up simulation for (a) 0-10 cm, (b) 10-40 cm, (c) 40-100 cm, and (d) 100-200 cm soil layers. White shading represents values of percent difference less than 0.01%.

4.2.2 Soil Moisture

Soil temperature has less interannual variability and variational inertia than soil moisture (Houser et al. 1999; Cosgrove et al. 2003). As a result, soil moisture required more spin-up time to reach equilibrium than soil temperature. The 0-10 cm soil layer reached practical equilibrium after 36-months of spin-up (Fig. 4.3a). However, fine scale equilibrium was not reached (Tables 4.1-4.2). The soil texture in north central Oklahoma where fine scale equilibrium was not attained is silt loam.

The results for the 10-40 cm soil layer were similar to those of the 0-10 cm layer (Fig 4.3b). Practical equilibrium was attained after 36 months of simulation time and fine scale equilibrium for the 10-40 cm layer soil moisture was not reached; the minimum value of percent difference for the 60-month simulation was -0.3101% (Tables 4.1-4.2). As with the 0-10 cm soil layer, the large areas of Oklahoma that did not reach fine scale equilibrium were characterized by silt loam soil texture.

As the depth and thickness of the soil layers increased, it required increased time to reach practical equilibrium. Thus, the 40-100 cm soil layer did not reach practical equilibrium across the domain (Fig. 4.3c); the maximum value of percent difference for the 60-month simulation was 1.2251% (Tables 4.1-4.2). Upon inspection of the data, it was determined that only two grid point values exceeded the ±1% threshold for practical scale model equilibrium.

Soil moisture for the 100-200 cm soil layer never reached practical scale model equilibrium (Fig. 4.3d). The regions in southwestern Oklahoma with negative values of percent difference were characterized by clay soil texture.

The spin-up trends for total column soil moisture were similar to those for soil moisture of the individual soil layers (Fig. 4.4). The initial soil moisture conditions were primarily wetter than the model climatology and as the simulation time increased, the soil column and individual soil layers dried from southeast to northwest. The urban areas, such as OKC and Tulsa, reached practical equilibrium significantly faster than the other land use classes (Figs. 4.4a-c). Conversely, the soils classified as clay and silt loam required longer simulation periods to reach practical scale equilibrium. Further, the maximum values of percent difference of total column soil moisture were never less than 2% for all of the simulations (Tables 4.1-4.2). As such, practical equilibrium was never attained for the entire domain.

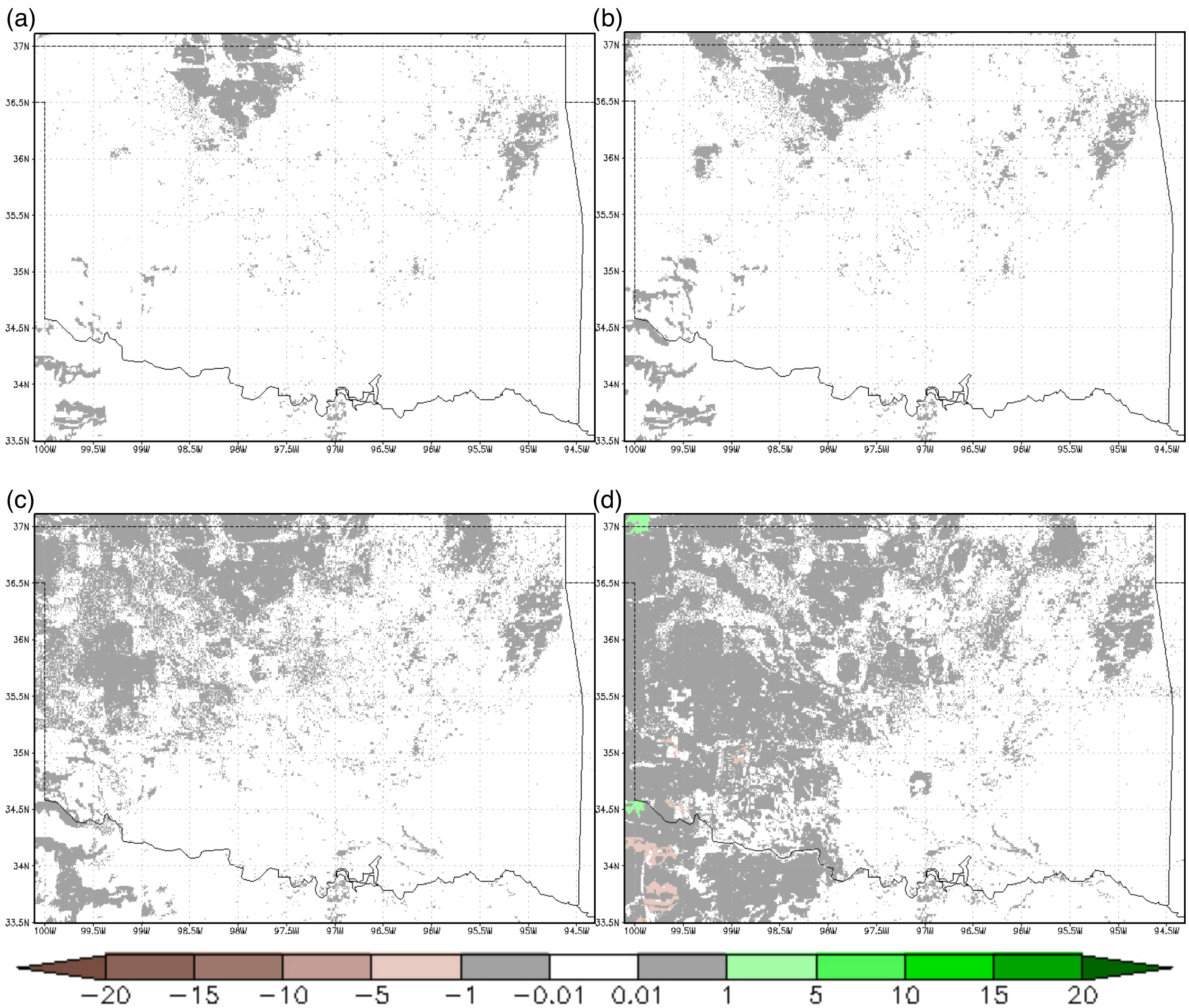

Figure 4.3. Percent difference values of soil moisture for 60-month spin-up with respect to the 66-month spin-up simulation for soil layer (a) 0-10 cm, (b) 10-40 cm, (c) 40-100 cm, and (d) 100-200 cm soil layers. White shading represents values of percent difference less than 0.01%.

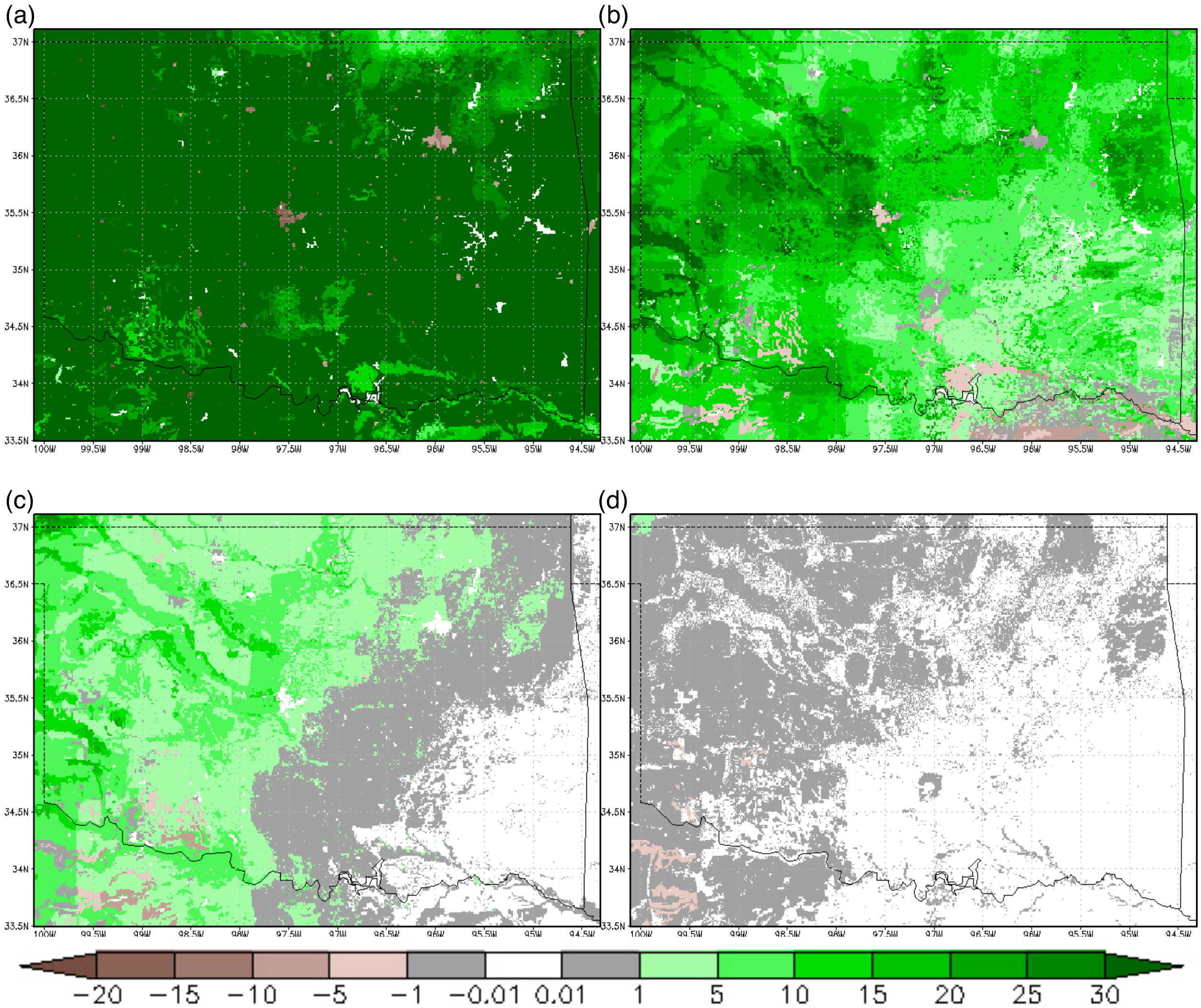

Figure 4.4. Percent difference values of total column soil moisture for (a) 1-month, (b) 6-month, (c) 18-month, and (d) 60-month spin-up with respect to the 66-month spin-up simulation. Gray shading represents values of percent difference less than or equal to 1%. White shading represents values of percent differences less than or equal to 0.01%.

4.2.3 Winter Initialization

Because the initial soil moisture and soil temperature values used for this spin-up experiment were chosen based on set time intervals with respect to July 2003 (i.e., not based on specific observations), the initial soil moisture was often too wet. As a result, significant drying was required to reach model equilibrium. However, the 30-month spin-up run displayed the opposite trend and anomalous soil conditions yielded a noticeable impact on the spin-up of soil moisture.

The 2000-2001 winter in Oklahoma was dominated by several winter storms that produced unusual snow and ice totals as well as below normal temperatures (Johnson 2000). In addition, Oklahoma experienced above average precipitation in December 2000, January 2001, and February 2001 and ice and snow that fell during January continued to melt through the first week of February (Johnson 2001).

As stated previously, the initial soil temperature prescribed for the spin-up experiment was 290 K. However, Mesonet observations from 28 December 2000 – 1 January 2001 indicated that soil temperature values in Oklahoma were significantly cooler. For example, at the 5 and 10 cm depths, soil temperature values were approximately 273 K, while those at 30 cm were approximately 275 K. Thus, the soil conditions prescribed for Noah were too warm. As a result, ice and snow melted quickly within the model and entered the water balance. The rapid ice and snow melt in the model compensated for low values of initial soil moisture for much of Oklahoma (Fig. 4.5). As a result, areas initially subject to a significant dry anomaly, such as the eastern half of Oklahoma, approached practical equilibrium within four months of simulation time (Fig. 4.5d). However, if the simulation had been coupled to an atmospheric model, the land surface would not have recovered so quickly.

5. CONCLUSIONS

Vertical profiles of temperature and specific humidity were reconstructed from radiosonde data recorded during JU2003. For cases with southerly winds throughout the CBL, profiles from radiosondes launched two kilometers upwind of the CBD of OKC were compared with those launched five kilometers downwind of the CBD. Results revealed that initial CBL development was faster immediately upwind of the CBD. However, observations indicated that the CBL heights were greater downwind of the CBD in the late afternoon due to thermal advection.

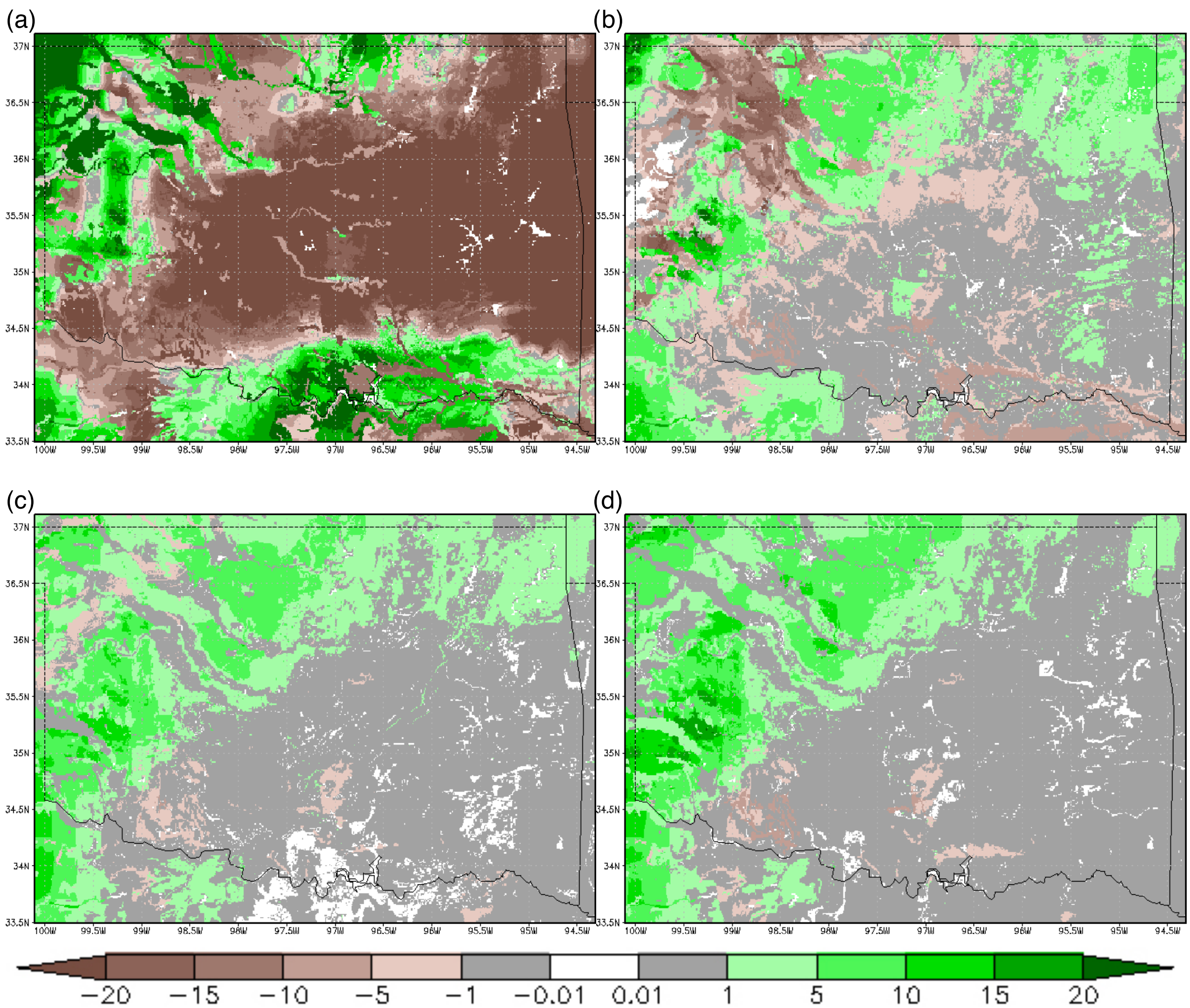

Figure 4.7. Percent difference values of soil moisture for the 0-10 cm soil layer after (a) 1 month, (b) two months, (c) three months, and (d) four months of simulation time for the 30-month spin-up with respect to the 66-month spin-up simulation. Gray shading represents values of percent difference less than or equal to 1%. White shading represents values of percent differences less than or equal to 0.01%.

In addition, preliminary results from a spin-up experiment were presented, which was conducted to determine how long of a simulation was required for the Noah LSM to reach practical and fine scale equilibrium. Simulations of various lengths were conducted out to 66 months, with the 66-month simulation treated as the control simulation.

The results of the spin-up experiment were as expected. The deeper soil layers and the soil moisture variables required more simulation time to reach equilibrium than the shallow, thinner soil layers and the soil temperature variables. Fine scale equilibrium was only reached with respect to soil temperature for the 0-10 and 10-40 cm soil layers. Practical scale equilibrium was attained with respect to soil temperature for all soil layers. With respect to soil moisture, practical equilibrium was reached for the 0-10 and 10-40 cm soil layers. With respect to total column soil moisture, equilibrium was not reached. As such, either additional forcing data must be obtained to allow for a longer spin-up time or more optimal initial conditions must be determined. Once the spin-up time for the Noah LSM is identified, a similar but less extensive experiment will be conducted for CLM2.

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