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MIXING PROCESSES IN THE NOCTURNAL ATMOSPHERIC BOUNDARY LAYER AND THEIR IMPACTS ON URBAN OZONE CONCENTRATIONS AND HEAT ISLAND INTENSITY

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INTRODUCTION

Photochemical pollutants, such as ground-level ozone (O_3), are known to peak primarily in summer during high-pressure stagnation periods. During such episodes, ozone air quality standards are often exceeded in and downwind of major urban areas. Although air pollution control strategies over the past decades have been widely successful, recent years have shown negligible or only small improvements in air quality in many areas. Thus, the current paradigm for O_3 formation focused on (a) the emission and accumulation of ozone precursors during the morning rush hours and throughout the day, (b) followed by photochemical O_3-formation, as well as (c) the role of surface inversions and advection of the urban plumes into rural areas must be expanded. More recent studies have shown, for example, that the chemistry and transport of polluted air at night by accelerated winds above the surface and the subsequent downward mixing (fumigation) of the pollutants during the next morning (Banta et al., 1998, Zhang and Rao, 1999, Solomon et al., 2000), are equally or even more important than daytime processes. Spikes in nocturnal O_3 (~20-30 ppbv) observed downwind of Philadelphia, PA during NARSTO NEOPS were also found to be associated with low-level jets (LLJs) that form along the Appalachian Piedmont and serve as conveyors for O_3 and aerosol in this region (Philbrick et al. 2000). As O_3 is not formed photochemically at night, these peaks are most likely due to downward mixing of O_3 transported in the ABL aloft.

Investigating the physics and chemistry of these processes at night is particularly challenging because the structure and dynamics of the nocturnal boundary layer (NBL) strongly affect atmospheric chemistry (Banta et al., 2007, Stutz et al., 2004, Geyer and Stutz, 2004), making it spatially heterogeneous. Recent studies with remote sensing instruments (Stutz et al., 2009) also clearly show pronounced vertical gradients of O_3 and NO_2 at night. In polluted and semi-polluted areas the causes of this inhomogeneous behavior are often surface emissions of NO, which then titrate O_3 close to the ground. At higher altitudes ozone concentrations depend on the magnitude of vertical mixing and advection in the NBL but typically remain much higher throughout the night. During the morning transition of the NBL, air from different altitudes with different spatial and chemical histories is then mixed together to provide the starting point for daytime O_3 formation.

In addition to the implications for urban air quality, mixing processes at night are also known to affect nocturnal temperature distributions. It has been shown that the urban heat island (UHI), the difference between temperatures measured in an urban area compared to the temperatures in its rural environment, tends to be strongest at night. Typically, a strong UHI signature can be observed during clear-sky conditions with low wind speeds (Arnfield, 2003). Because, the combined effect of elevated ozone concentrations and high temperatures at night could pose a significant health risk for urban populations, we were motivated to analyze the impacts of nocturnal boundary layer structure on both urban air quality and temperature distributions.

STUDY AREA AND DATA SETS USED

The study area we selected focused on central Oklahoma and included the Oklahoma City metropolitan area (Fig. 1). In this region, high O_3 concentrations are often observed in the summertime, primarily during stagnant, high-pressure weather systems with clear-sky conditions and daytime temperatures peaking above 35°C (Kastner-Klein et al. 2002)). Typically during these types of weather systems, southerly winds prevail and signatures of strong low-level jets have been observed at night (Lundquist and Mirocha, 2008 and references cited therein). The known climatology of these conditions, together with the flat, homogenous terrain and a wealth of weather data from previous studies such as the Joint Urban 2003 (JU2003) tracer experiment (Allwine et al., 2004), were critical for choosing this domain. From the JU2003 campaign, which took place from 28 June through 31 July 2003, sonic measurements on on two tall towers (Grimmond at al., 2004; Gouveia et al., 2007) and sodar measurements (De Wekker et al., 2004) provide observations that quantify the structure, dynamics and mixing in the NBL, while intensive temperature measurements (Basara, et al., 2008) across the OKC metro area, simultaneously provide information about the UHI signature.

Given the climatologically prevalent southerly winds during the summer, another consideration for choosing OKC as a study area was the possibility to investigate the transport of pollutants from the Dallas-Fort Worth (DFW) metroplex, located 300 km south of OKC. Data recorded during O_3 episodes indicate a strong correlation between pollution levels in the DFW-metro area and near OKC (Kastner-Klein et al., 2002). To assess the air quality in the OKC metro area during July 2003, ozone and NOx time series measured at six

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Corresponding author address: Petra M. Klein, School of Meteorology, University of Oklahoma, 120 David L. Boren Blvd. Norman, OK 73072-7307, USA, email: pkklein@ou.edu regulatory monitoring sites in the greater OKC area were included in the analysis. The location of the monitoring sites is shown in Fig. 1. Four of the sites are along a 50-km long, north-south oriented transect, beginning at the southern edge of the OKC metro with the Goldsby site in a rural environment, followed by the sub-urban site in Moore, OK, the central OKC site near the urban core, and finishing at the North OKC site which is in suburban terrain. The two other sites, are 23 km west (Yukon) and 17 km east (Choctaw) of the central OKC site. The concentration time series collected at these sites were provided by the Department of Environmental Quality in Oklahoma City and included hourly ozone concentrations at six sites. NOx concentration were only available for the central OKC and North OKC site.

The data from the sodar operated by the Pacific Northwest National Laboratories (PNNL), which was located approximately 2.5 km south of downtown OKC (Allwine at al., 2004, De Wekker et al., 2004), have been used to determine the prevailing wind direction and wind speed, and to assess the vertical wind speed gradient. Data measured at 250-m and 80-m above ground were used in this analysis. Atmospheric stability was determined based on heat and momentum flux measurements with sonic anemometers at 2 levels (37.3 m and 79.6 m) at the Tyler Media (TM) tower. This tower was operated by the University of Indiana and located 5.5 km south of the OKC central business district (Grimmond et al. 2004). Based on the measurements, the stability parameter *z/L* was determined according to

$$\frac{z}{L} = -\frac{g}{T_s}\frac{k\,z\;\overline{w'T_s'}}{u_*^3} \qquad (1)$$

and the flux Richardson Number Ri_{fl} according to:

$$Ri_{fl} = -\frac{g}{T_s}\frac{\overline{w'T_s'}}{du/dz\;u_*^2} \qquad (2)$$

where all data were collected at the 37-m level, *g* is the acceleration due to gravity, T_s is the sonic temperature, *z* is the height above ground, *k* is the von Karman constant (=0.4), u_* is the friction velocity determined from the momentum flux measurements, the $\overline{w'T_s'}$ kinematic heat flux, and *L* is the Monin-Obukhov length. In the calculation of $Ri_{fl,}$ (2) the wind speed gradient was estimated as $du/dz \approx \Delta u/\Delta z = u_{37}/z$.

To assess to what extend stability parameters determined from operationally collected data can serve as an indicator of the nocturnal mixing processes, data from the Norman Mesonet (NRMN) site, located approximately 26 km south of the central OKC monitoring site along the north-south transect of the air quality monitoring sites, was utilized. Information about the typical layout of Oklahoma Mesonet sites and instrumentation used at these sites can be found in McPherson et al. (2007). The Richardson number *Ri* at NRMN is estimated using:

$$Ri = \frac{g\left[\left(T_{9m} - T_{1.5m}\right)/\Delta z_T + \Gamma_d\right]\Delta z_u^2}{T_{1.5m}\left[\left(u_{10m} - u_{2m}\right)^2 + \left(v_{10m} - v_{2m}\right)^2\right]} \qquad (3)$$

where T_{9m} and $T_{1.5m}$ are the air temperatures measured at 9 and 1.5 m above ground, u_{10m}, u_{2m}, v_{10m} and v_{2m} are the wind velocity components at the 2 m and 10 m levels, which are computed using the wind speed measured at the respective level and the wind direction measured 10 m above ground. The height differences between the NRMN measurement levels are given by Δz_T = (9.0 m-1.5 m) = 7.5 m for air temperature and Δz_u = (10.0 m- 2.0 m) = 8.0 m for wind speed.

The urban heat island strength was determined following the approach used in Basara et al. (2008). The mean urban temperature T_{urban} for OKC was calculated using temperature data collected at 13 Portable Weather and Information Display Systems (PWIDS) stations deployed at 9 m above ground in and around the Oklahoma City central business district on traffic poles. The mean rural temperature T_{rural} was calculated using the 9 m temperature observations from six Oklahoma Mesonet sites surrounding the OKC metro area (ELRE, GUTH, KING, MINC, NRMN, and SPEN). The UHI strength was then defined as

$$\Delta T = T_{urban} - T_{rural}\,. \qquad (4)$$

The LLJ properties during JU2003 were investigated by Lundquist and Mirocha (2008) using data from a boundary-layer wind profiler which was operated and maintained by Pacific Northwest National Lab and located approximately 2 km SSW of the OKC downtown area. Lundquist and Mirocha also analyzed the microscale variability of the LLJ and its effect on turbulent mixing events using wind and turbulence data from a crane pseudo-tower, which was located approximately 750 m NNW of the urban core and often in the urban wake region (Lundquist et al., 2004). Eight sonic anemometers were mounted along this pseudo-tower, from 8-84 m above the surface. It was found that a LLJ was regularly observed during July 2003. The presence of a LLJ was defined if (i) the wind speed profile in the lowest 1000 m accelerates after sunset, attaining a maximum wind speed typically between 700 and 1000 UTC (200 and 500 LT), and (ii) that the maximum wind speed in a profile surpass a threshold of 10 m/s (category LLJ-0 in Whiteman et al. 1997 and Song et al. 2005, for example), with a decrease above the wind speed maximum of at least 5 m/s. Using these criteria, of the twenty-seven nights examined, only four nights (JDs 182, 192, 193, and 204) did not show LLJ signatures in the observed wind profiles. In our current analysis, we used the information about the time of the LLJ, the LLJ height, and the LLJ wind speed maximum and direction that was determined by Lundquist and Mirocha (2008) to investigate if nocturnal urban air quality and UHI strength are affected by these LLJ characteristics.

RESULTS

The diurnal cycles of O_3 and NO_x concentrations, UHI strengths as well as rural and urban cooling/heating rates, prevailing wind direction, wind sheer, and turbulent mixing and stability parameters are shown in Figures 2-4 for 3 weeks during July 2003. The observed O_3 concentrations, with respect to both magnitude and temporal variability are quite similar at all 6 monitoring sites and clear differences between rural, suburban and urban sites cannot be noted. Further, no clear, marked differences exist between weekend and work days. As expected, the highest O_3 concentrations are typically observed in the afternoon with peak values getting close to 8 ppb. After sunset, O_3 concentrations start to decline but often secondary ozone peaks are observed around local midnight (see e.g. during the nights 193/194 and 206/207) and/or the nocturnal concentrations remain above 2 ppb. At the same time, the nocturnal UHI strength, defined according to Eq. (4) is limited to approximately 2 K during several nights while a tendency of lower nocturnal ozone concentrations can be noted during nights with a stronger UHI signature (i.e., greater than 2 K).

To further investigate this trend and to identify the role of turbulent mixing processes in both nocturnal UHI development and ozone pollution levels two 3-day time periods, highlighted in yellow in Figure 3 and 4, were selected for a more detailed analysis (Fig. 5). To simplify the plots, mean ozone concentrations computed as averages of the observations at the sites in Moore, central OKC, and OKC North are shown in Figure 5. Period 1 includes days 197-199 (July 16-18) and represents nights with low ozone concentrations but marked UHI signatures ($\Delta T > 2$ K). During period 2, which runs from day 206-208 (July 25-27), ozone concentrations remained close to or greater than 2 ppb at night while the UHI strength was less than 2 K.

The prevailing wind directions were quite similar during both periods with primarily southwesterly flow during period 1, while during period 2 the winds were initially from SSE but then shifted to the SSW. For all six nights considered, LLJ conditions were present (Lundquist and Mirocha, 2008) and strong wind shear was observed each night. Strength and duration of the shear varied, but a clear relationship between these variations and the O_3 patterns is not obvious (Fig. 5d). However, the trends seen in Figure 5 suggest that O_3 levels at night and in the early morning are correlated with atmospheric stability, here documented by the flux Richardson number Ri_{fl} (Fig. 5b) and nocturnal turbulent mixing as illustrated by the friction velocity u_* values (Fig. 5c). As seen in Figs. 2-3, the turbulent vertical velocities σ_w show generally the same trends as the friction velocities and could also have been chosen as parameter to characterize turbulent mixing. Similarly, the other stability parameters z/L and Ri show the same trends as Ri_{fl}; however, differences in the magnitudes of the various stability parameters exist as can be expected. Figure 5 illustrates that on more stable nights (larger Ri_{fl}), such as during DOY 197-199 (July 16-18), lower O_3-concentrations are observed which coincide with less vertical mixing as suggested by the lower u_*- values measured. During the second period, DOY 206-208 (July 25-27), larger concentrations of O_3 at night coincide with less stable conditions (lower values for Ri_{fl}), during which higher u_*- values and thus stronger vertical mixing persisted.

These trends are further confirmed by Figure 6 in which the early morning (0 – 6 am local time) minimum O_3 concentrations for all southerly-wind nights during JU2003 are plotted against minimum nighttime (6 pm-6 am) friction velocities and against the maximum nighttime Flux Richardson Number Ri_{fl} and Richardson Number at the Norman Mesonet site Ri_{NRMN}. Early-morning minimum O_3 values are strongly influenced by local emissions and must thus be interpreted carefully. However, the tendency for increasing O_3 concentrations with decreasing atmospheric stability, which promotes more ABL mixing at night and in the early morning, can clearly be noted. It further appears that data from the Norman Mesonet site can successfully be used to characterize prevailing stability conditions and as an indicator for the strength of nocturnal mixing. These results are important for future analysis of air quality measurements as the Joint Urban data sets span a very limited time span of only 1 month while Mesonet data are continuously collected year round.

The influence of atmospheric stability on the maximum nocturnal urban heat island strength ΔT_{max}, as well as on the urban and rural cooling rates, are further summarized in Figure 7. These plots also include all cases with southerly approach flow. As noted above, an ΔT_{max} increases as stability increases. Again, the Richardson number at the Norman Mesonet site Ri_{NRMN} provides very similar results as the other stability parameters which will allow us, in the future, to expand the analysis beyond the JU2003 time frame. An interesting question in the heat island formation stems from the fact that temperature is known to drop off very quickly in rural areas on nights that are very stable, primarily due to the lack of vertical mixing and strong radiative cooling of the surface (see e.g. Hunt et al. 2007, LeMone et al., 2003). As such, it is important to investigate the urban and rural cooling rates in more detail to identify whether more pronounced cooling in rural areas may partially trigger the stronger urban heat island signature on strongly stable nights, as opposed to a decline of the urban cooling rates as stability increases. As Figure 7b and 7c illustrate, both the minimum evening (6 pm – 12 am) and the average nighttime (6 pm – 6 am) cooling rates are quite similar at the rural and urban sites for low stabilities but start to deviate as stability increases. While at the rural sites the absolute values of the cooling rates increase, particularly in the evening, as stability increases ($Ri_{NRMN}>0.1$) they start to decline at the urban sites. The largest differences between cases with $Ri_{NRMN}<0.1$ compared to cases with $Ri_{NRMN}>0.1$, can actually be noted for the rural evening cooling rates (Fig. 7c) and it should be further determined as to what extend stronger urban heat island signatures are triggered by stronger cooling at rural sites. This is important as it would indicate that urban areas cool off less than rural sites, in part, simply due to the stronger vertical mixing in cities which would have implications for urban planning.

CONCLUSIONS

The known prevalence of southerly winds and low-level jet formations in the central Great Plains during summer, make this region an ideal site to investigate the structure of the nocturnal boundary layer (NBL) and its impacts on NBL mixing processes. Data sets collected during the Joint Urban 2003 (JU2003) campaign were used to classify the boundary-layer structure and dynamics. Additionally, ozone concentrations measured at regulatory monitoring sites in and near the OKC metro area were used as quasi tracers to study possible mixing and transport regimes for various atmospheric conditions. Ozone time series measured at the regulatory monitoring sites in OKC during six exemplarily chosen days of the JU2003 campaign in general show the expected behavior with lower O_3 mixing ratios at night than during the day, most likely due to the NO titration reaction. However, high O_3 values and secondary peaks are often seen at night. Because O_3 is not formed photochemically at night these peaks are most likely due to downward mixing of O_3 transported in the ABL aloft. Low-level jets developed on most nights during JU2003; associated with strong wind shear. Wind shear strength and duration varied, but a clear relationship between these variations and the O_3 patterns is not obvious. However, some trends suggest that O_3 levels at night and in the early morning are correlated with the flux Richardson number Ri_{fl} and friction velocity u_*. On more stable nights (larger Ri_{fl}), lower O_3-concentrations are observed at night, which could indicate less vertical mixing as also suggested by the lower u_* values measured. During a second period, larger concentrations of O_3 at night coincide with less stable conditions (lower values for Ri_{fl}), during which higher u_* values and thus stronger vertical mixing persisted. Despite the variability of atmospheric stability in the early morning hours, the tendency for increasing O_3 concentrations with decreasing atmospheric stability, which promotes more mixing in the ABL at night and in the early morning, can clearly be noted. The NBL mixing processes also impact the urban heat island intensity. During nights with stronger vertical mixing (indicated by higher O_3-values and lower values for Ri_{fl}) the heat island intensity tends to be lower than during more stable nights with limited vertical mixing. Our analysis demonstrates that detailed meteorological information can provide new insights into nocturnal mixing processes and related air-quality problems, but the lack of vertical concentration profiles still make it difficult to further study the interplay between the BL structure and air chemistry.

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REFRENCES

Allwine K.J., 2004: Overview of JOINT URBAN 2003 - an atmospheric dispersion study in Oklahoma City, Preprints*, Symp. on Planning, Nowcasting, and Forecasting in the Urban Zone,* Seattle, WA, Amer. Meteor. Soc.

Arnfield, A.J., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatology*., **23**, 1-26.

Banta, R.M., L. Mahrt, D. Vickers, J. Sun, B. Balsley, Y. Pichugina, and E. Williams, 2007. The very stable boundary layer on nights with weak low-level jets, *J. Atmos. Sci*. 64, 3068-3090.

Banta, R.M., C.J. Senff, A.B. White, M. Trainer, R.T. McNider, R.J. Valente, S.D. Mayor, R.J. Alvarez, R.M. Hardesty, D.D. Parish, and F.C. Fehsenfeld, 1998. Daytime buildup and nighttime transport of urban ozone in the boundary layer during a stagnation episode, *J. Geophys. Res*., 103, 22,519-22,544.

Basara, J.B., P.K. Hall, Jr., A.J. Schroeder, B.G. Illston, and K.L. Nemunaitis, 2008: Diurnal Cycle of the Oklahoma City Urban Heat Island. *J. Geophys. Res.*, **113.**

De Wekker, S. F. J, L. K. Berg, K. J. Allwine, J. C. Doran, and W. J. Shaw, 2004: Boundary-layer structure upwind and downwind of Oklahoma City during the Joint Urban 2003 field study. Preprints*, 5th Symp. on the Urban Environment,* Vancouver, BC, Amer. Meteor. Soc.

Geyer, A., and J. Stutz, The vertical structure of OH-HO_2-RO_2 chemistry in the nocturnal boundary layer: a one-dimensional model study, 2004: *J. Geophys. Res.*, *109*, doi:10.1029/2003JD004425.

Gouveia, F. J., M. J. Leach, J. H. Shinn, W. E. Ralph, 2007: Use of a Large Crane for Wind and Tracer Profiles in an Urban Setting. J. Atmos. Oceanic Technol., 24, 1750-1756

Grimmond, C.S.B., H.-B. Su, B. Offerle, B. Crawford, S.Scott, S. Zhong, and C. Clements, 2004: Variability of sensible heat fluxes in a suburban area of Oklahoma City. Preprints*, Symp. on Planning, Nowcasting, and Forecasting in the Urban Zone,* Seattle, WA, Amer. Meteor. Soc.

Hunt, E. D., J. B. Basara, and C. R. Morgan, 2007: Significant inversions and rapid in situ cooling at a well-sited Oklahoma Mesonet station. *J Appl. Meteor. Clim.*, **46,** 353-367.

Kastner-Klein P., D. Williams, F. Hall, 2002. Impact of long-range transport on ozone pollution in the Oklahoma City metro area. *Proceedings of the 12th Joint Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Association,* May 20-24, Norfolk, Virginia, USA.

Lundquist, J.K., and J.D. Mirocha. Interaction of nocturnal low-level jets with urban geometries as seen in Joint Urban 2003 data. Paper J5.10.

LeMone, M. A., K. I. Ikeda, R. L. Grossman, and M. W. Rotach, 2003: Horizontal variability of 2-m temperature at night during CASES-97. *J. Atmos. Sci.*, **60,** 2431-2449.

Lundquist, J.K., F. Gouveia, and J. Shinn, 2004: Observations of turbulent kinetic energy dissipation rate in the urban environment. Preprints*, Symp. on Planning, Nowcasting, and Forecasting in the Urban Zone,* Seattle, WA, Amer. Meteor. Soc., available at http://ams.confex.com/ams/pdfpapers/71468.pdf

Lundquist, J.K. and J. D. Mirocha, 2008: Interaction of Nocturnal Low-Level Jets with Urban Geometries as Seen in Joint Urban 2003 Data. J. Appl. Meteor. Climatol., 47, 44-58 doi: 10.1175/2007JAMC1581.1

McPherson, R. A., and Coauthors, 2007: Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet, J. Atmos. Oceanic Technol., 24, 301– 321.

Philbrick, C. R., and Coauthors, 2000. Investigations of Ozone and Particulate Matter Air Pollution in the Northeast (NE-OPS 98). *PM2000: Particulate Matter and Health*. *Air and Waste Management Association,* 24-28 January 2000, Charleston, SC.

Solomon, P., Cowling, E., Hidy, G., Furiness, C., 2000. Comparison of scientific findings from major ozone field studies in North America and Europe. *Atmospheric Environment,* 34, 1885-1920.

Stutz, J., B. Alicke, R. Ackermann, A. Geyer, A. White, and E. Williams, 2004: Vertical profiles of NO_3, N_2O_5, O_3, and NO_x in the nocturnal boundary layer: 1. Observations during the Texas Air Quality Study 2000, *J. Geophys. Res., 109*, doi:10.1029/2003JD004209.

Stutz, J., Wong, K.W., Lawrence, L., Ziemba, L., Flynn, J.H., Rappenglück, B., Lefer, B. (2009), Nocturnal NO_3 radical chemistry in Houston, TX, *Atmos. Environ.*, doi: 10.1016/j.atmosenv.2009.03.004

Whiteman, C.D., X. Bian, and S. Zhong, 1997: Low-level jet climatology from enhanced rawindsonde observations at a site in the southern Great Plains, *J. Appl. Meteorol.*, 36, 1363-1376.

Zhang, J., and Rao, S.T., 1999. The role of vertical mixing in the temporal evolution of ground-level ozone concentrations. *J. Appl. Met.*, 38, 1674-1691.

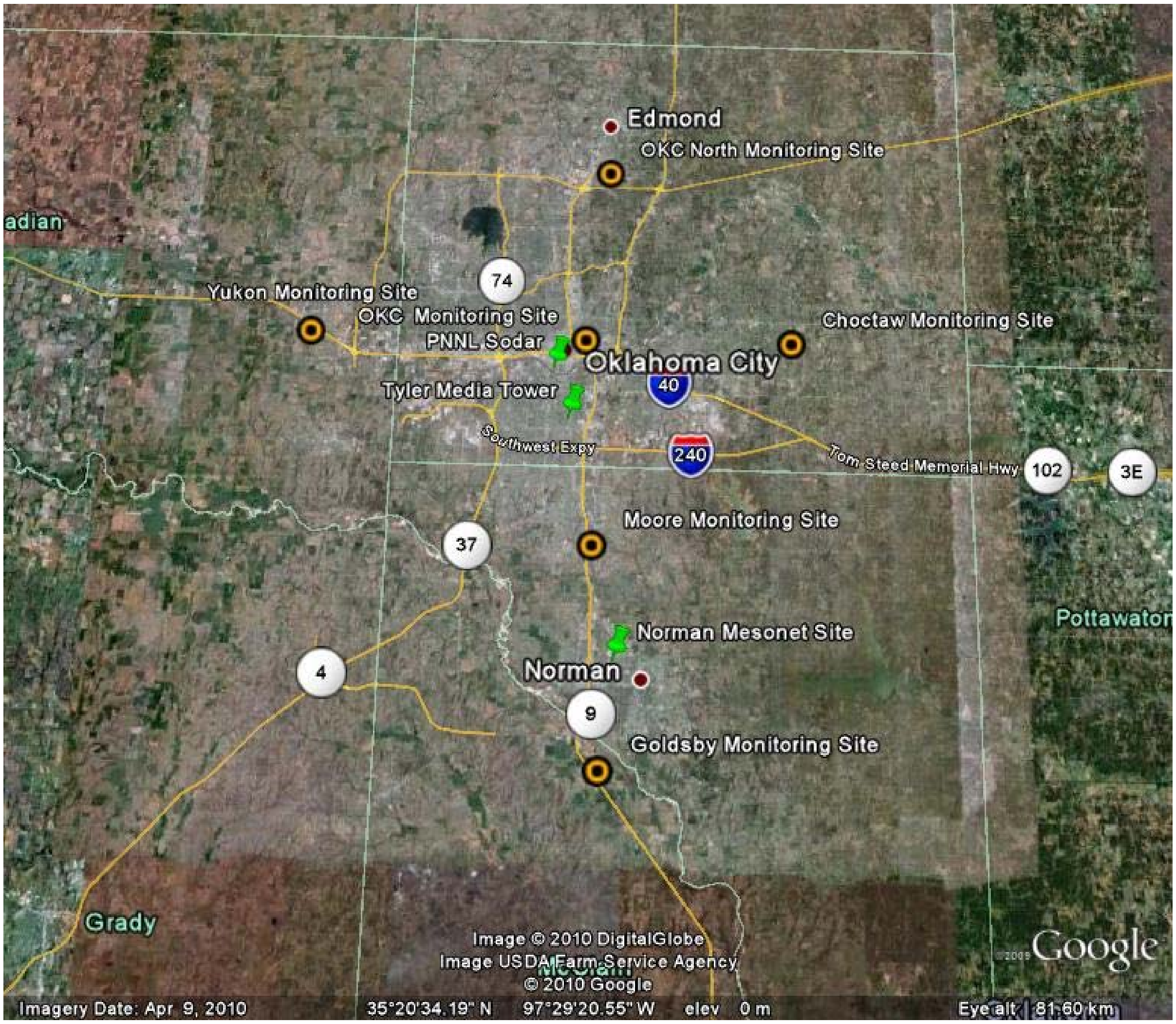

Fig. 1: Map of the study area showing the location of the air quality monitoring sites (orange circles) and meteorological observation sites (green pins) used in the data analysis.

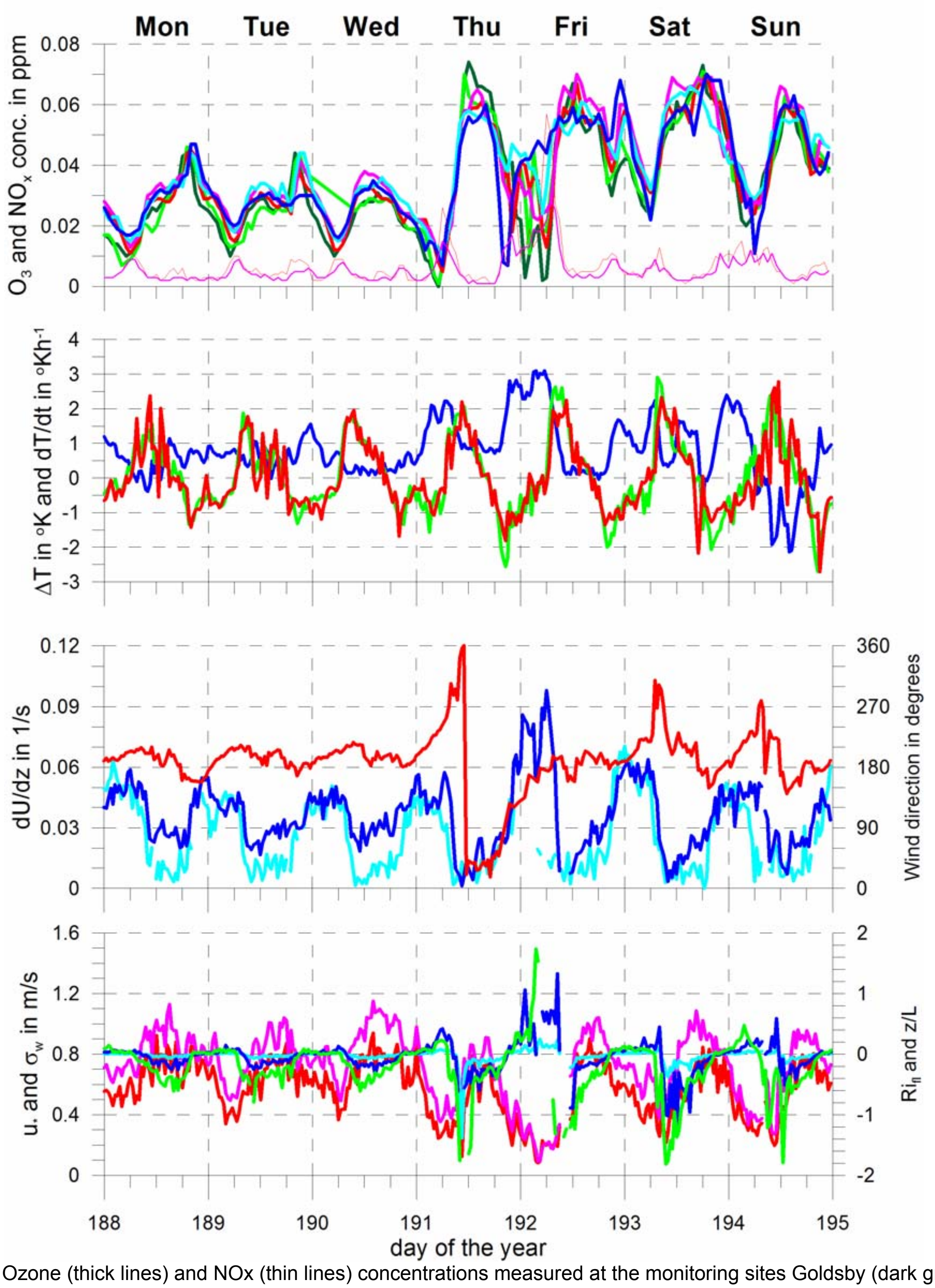

Fig. 2: Ozone (thick lines) and NOx (thin lines) concentrations measured at the monitoring sites Goldsby (dark green), Moore (light green), OKC (red), OKC North (pink), Choctaw (cyan) and Yukon (blue) during the week July 7-13, 2003 (top plot). The second plot shows the UHI strength (blue) and rural (green) and urban (red) cooling/heating rates during the same time period. Wind direction (red, right axis) and wind sheer calculated between the 250-m and 80-m PNNL sodar level (cyan, left axis) and 37-m and 80-m TM sonics (blue, left axis) are shown in the 3. plot. The bottom plot shows the average shear stress velocity u_* (red, left axis) and vertical turbulent velocity σ_w (pink, left axis), computed from the 37-m and 80-m TM sonic data, and stability parameters z/L (blue, right axis), Ri_{fl} (cyan, right axis) and Ri (green, right axis) computed according to Eqs. (1-3).

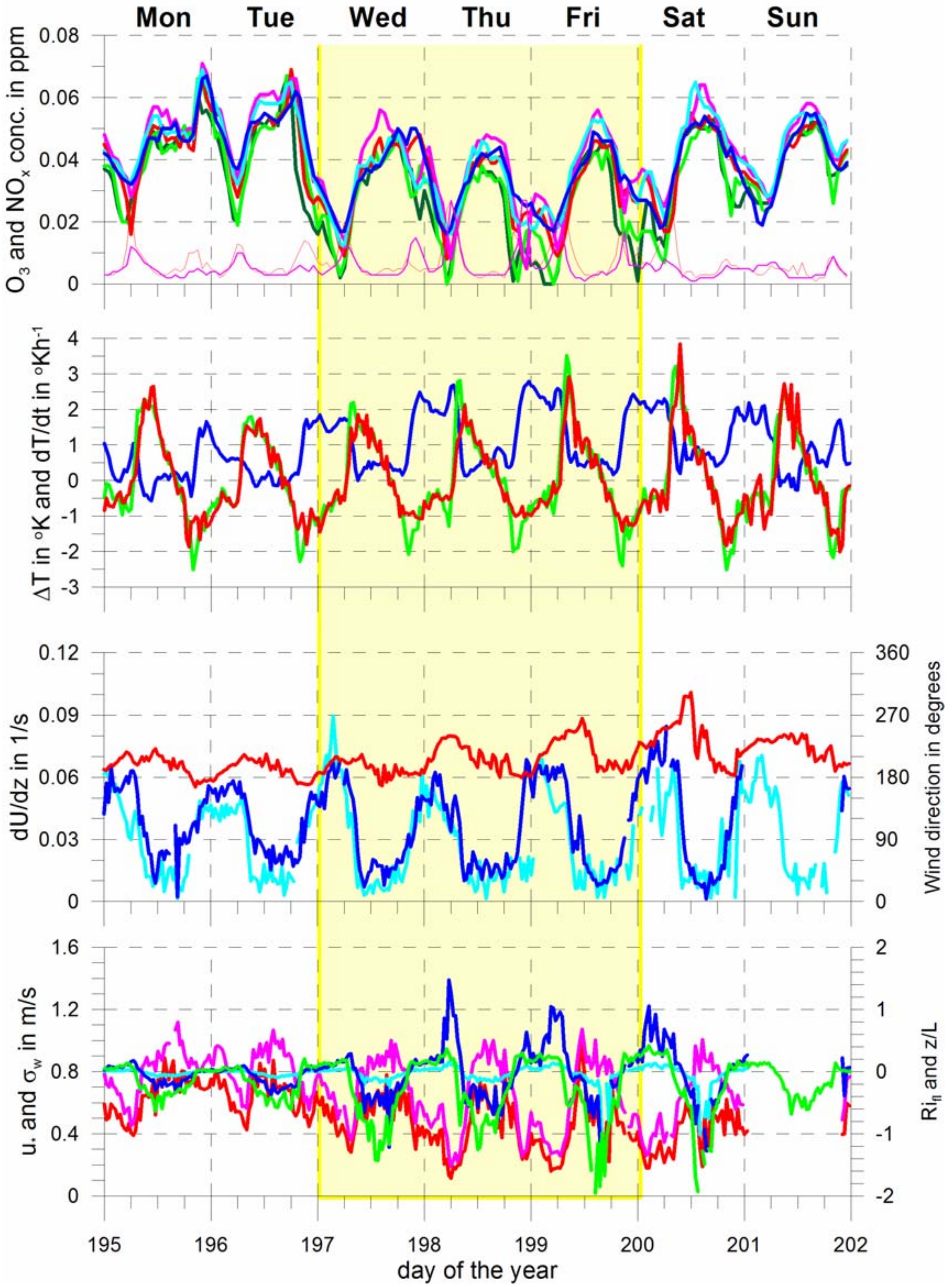

Fig. 3: Same as Fig. 2 but for the week July 14-20, 2003.

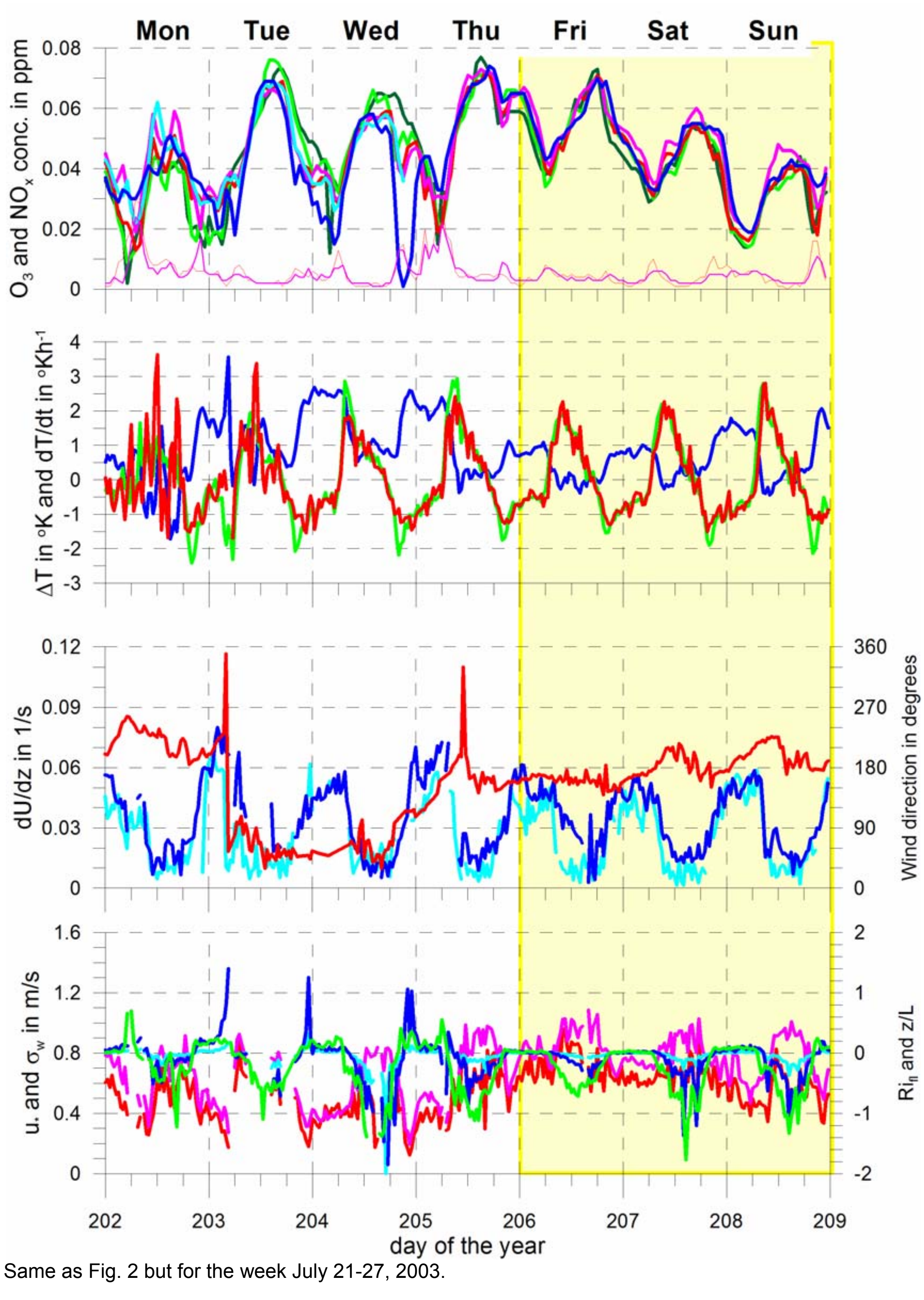

Fig. 4: Same as Fig. 2 but for the week July 21-27, 2003.

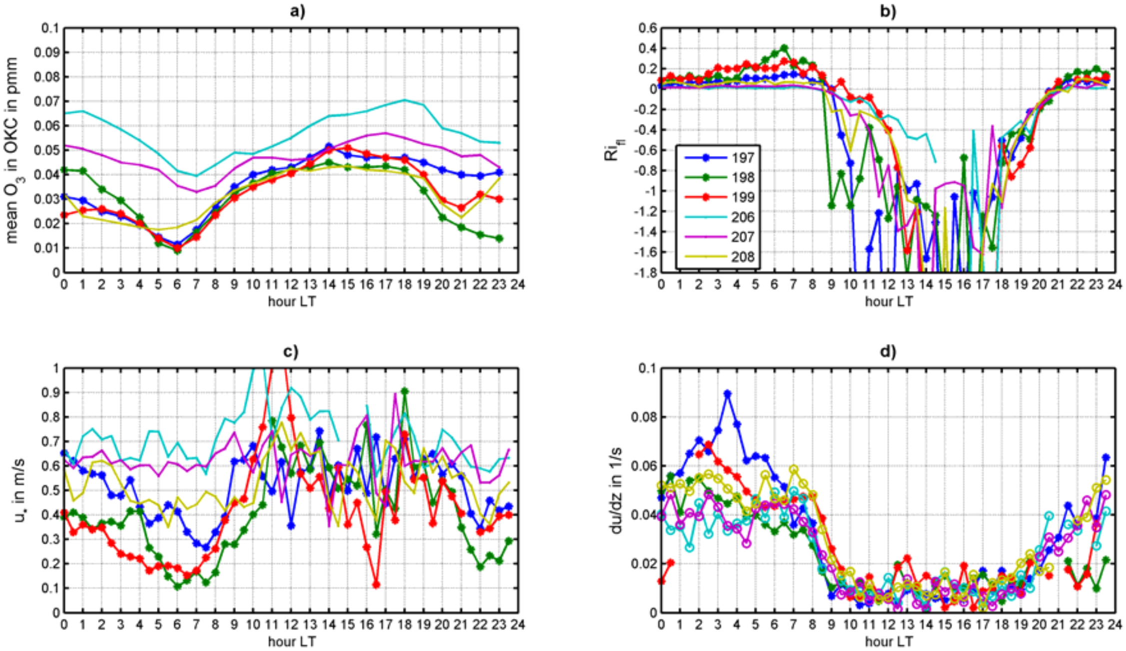

Fig. 5: Hourly near-ground O3 concentrations in OKC (a) for six days in July 2003 (legend shows Days of the Year, DOY). The flux Richardson Number Rifl (b) and shear stress velocity u* (c), both determined from sonic anemometer data measured at 37 m and 80 m height on the TM tower (Grimmond et al. 2004) are also shown, as well as wind speed gradients (d) evaluated using data from the PNNL sodar (Allwine et al. 2004) at z=80 m and z=250 m.

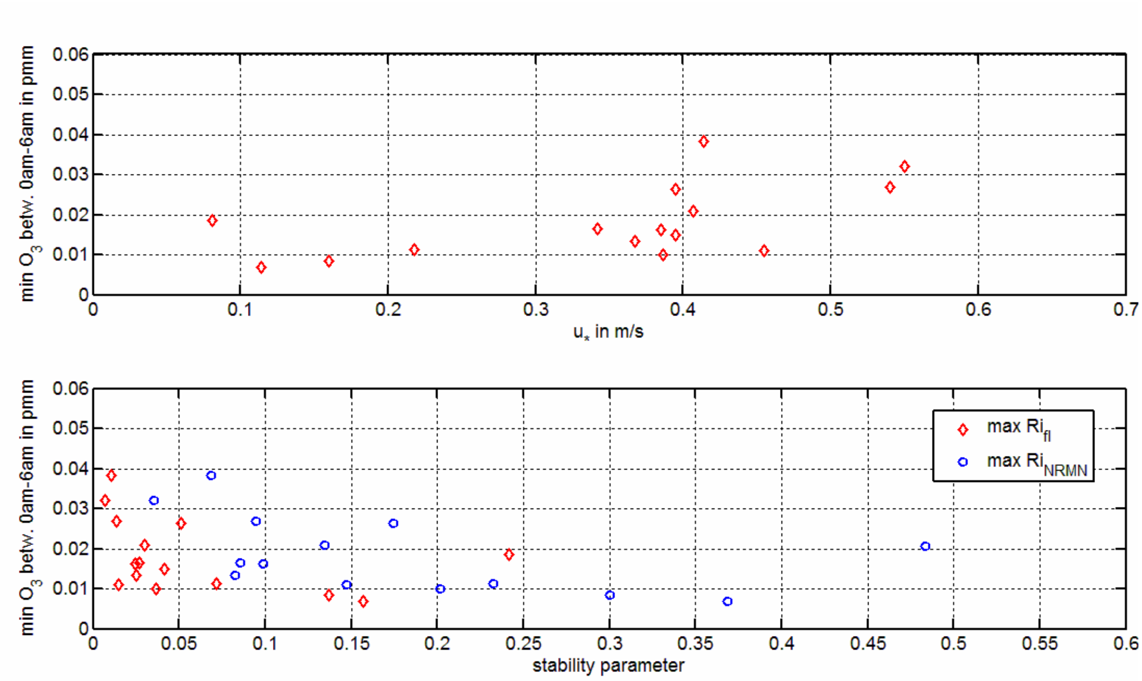

Fig. 6: Early morning (0am-6am) minimum O_3 concentrations plotted as function of the minimum nighttime (6pm-6am) friction velocity u_* (top) and as function of the nighttime maximum flux Richardson Number Ri_{fl} (bottom, red) and Richardson Number Ri_{NRMN} at the Norman (NRMN) Mesonet site (bottom, blue).

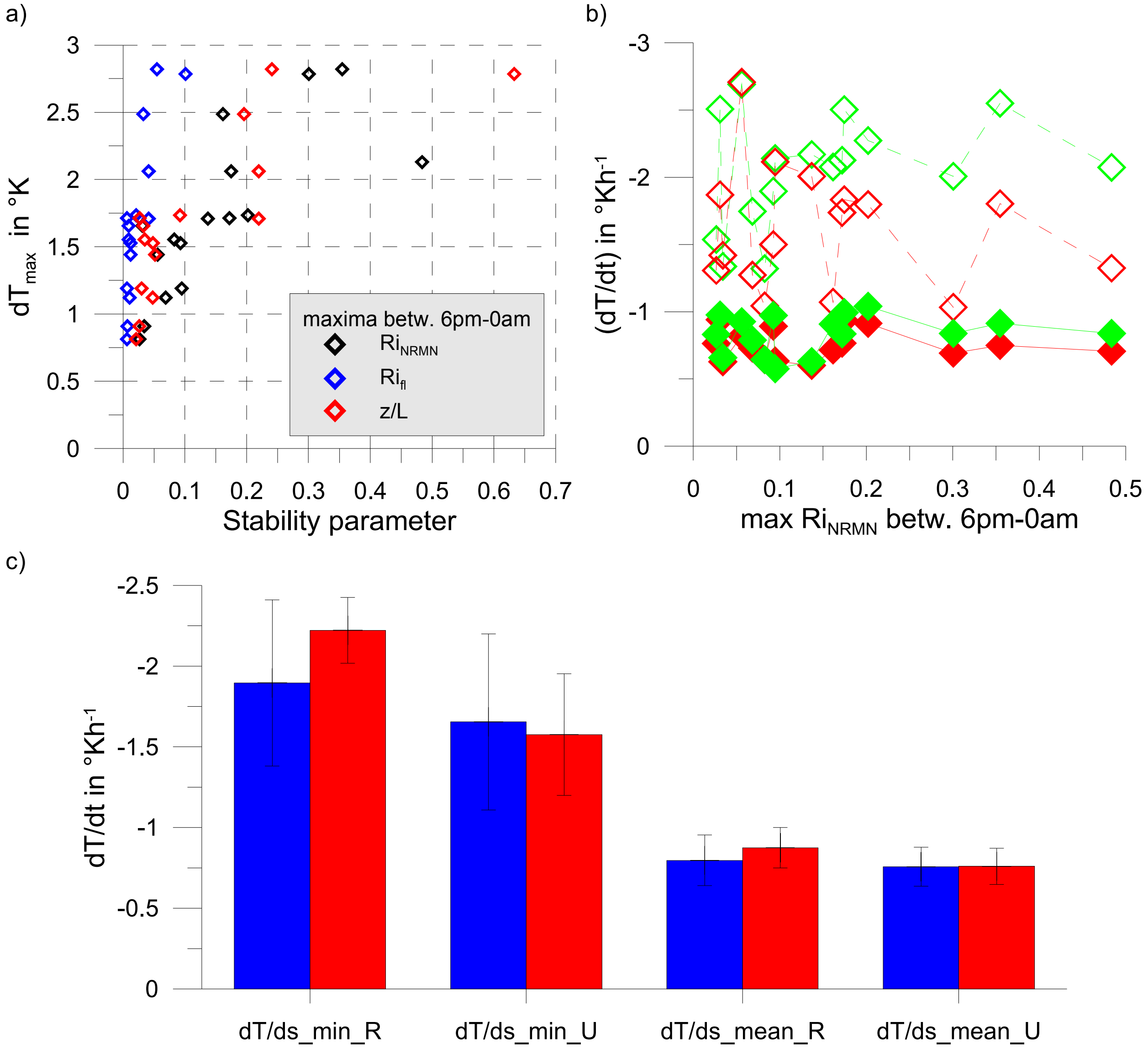

Fig. 7: Maximum UHI strength between 6pm and 0am as function of three different stability parameters (a), as well as average (solid lines) nighttime (6pm-6am) cooling rates and minimum (dashed lines) evening (6pm-0am) cooling rates at the rural (green) and urban (red) sites as function of the maximum evening Richardson number Ri_{NRMN} at the Norman Mesonet site (b). The bar diagram (c) illustrates the differences in these cooling rates for cases with $Ri_{NRMN}<0.1$ (blue) and $Ri_{NRMN}>0.1$ (red).