Impacts of Land Use and Land Cover Change on Urban Hydroclimate of Colorado River Basin

by

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ABSTRACT

Rapid urbanization and population growth occurring in the cities of South Western United States have led to significant modifications in its environment at local and regional scales. Both local and regional climate changes are expected to have massive impacts on the hydrology of Colorado River Basin (CRB), thereby accentuating the need of study of hydro-climatic impacts on water resource management in this region. This thesis is devoted to understanding the impact of land use and land cover (LULC) changes on the local and regional hydroclimate, with the goal to address urban planning issues and provide guidance for sustainable development.

In this study, three densely populated urban areas, viz. Phoenix, Las Vegas and Denver in the CRB are selected to capture the various dimensions of the impacts of land use changes on the regional hydroclimate in the entire CRB. Weather Research and Forecast (WRF) model, incorporating the latest urban modeling system, is adopted for regional climate modeling. Two major types of urban LULC changes are studied in this Thesis: (1) incorporation of urban trees with their radiative cooling effect, tested in Phoenix metropolitan, and (2) projected urban expansion in 2100 obtained from Integrated Climate and Land Use Scenarios (ICLUS) developed by the US Environmental Protection Agency for all three cities.

The results demonstrated prominent nocturnal cooling effect of due to radiative shading effect of the urban trees for Phoenix reducing urban surface and air temperature by about 2~9 $^{\circ}$C and 1~5 $^{\circ}$C respectively and increasing relative humidity by 10~20% during an mean diurnal cycle. The simulations of urban growth in CRB demonstrated

nocturnal warming of about 0.36 ˚C, 1.07 ˚C, and 0.94 ˚C 2m-air temperature and comparatively insignificant change in daytime temperature, with the thermal environment of Denver being the most sensitive the urban growth. The urban hydroclimatic study carried out in the thesis assists in identifying both context specific and generalizable relationships, patterns among the cities, and is expected to facilitate urban planning and management in local (cities) and regional scales.

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TABLE OF CONTENTS

Page

LIST OF TABLES……vii

LIST OF FIGURES……...……...viii

CHAPTER

1 INTRODUCTION……...1

Literature Review….....1

Study Objective……2

Organization of this Thesis……..……..…...3

2 RADIATIVE SHADING EFFECT OF URBAN TREES ON COOLING THE REGIONAL BUILT ENVIRONMENT……..……..…….....4

Introduction……..4

Methodology……9

Model Evaluation and Discussion……..….13

Concluding Remarks……..….21

3 INTER-CITY COMPARISON OF IMPACT OF URBAN GROWTH ON REGIONAL HYDROCLIMATE IN COLORADO RIVER BASIN...…….23

Introduction……23

Materials and Method……....26

Numerical Experiments…….28

Results……....30

4 CONCLUSIONS AND PERSPECTIVES…….46

CHAPTER Page

Conclusions and Recommendations……..……..…….....46

Future Work...…….....47

REFERENCES……..……..50

APPENDIX…….....57

A SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF 2-M AIR TEMPERATURE FOR ALL SEASONS IN PHOENIX…….57

B SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF 2-M AIR TEMPERATURE FOR ALL SEASONS IN DENVER……. 59

C SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF 2-M AIR TEMPERATURE FOR ALL SEASONS IN LAS VEGAS……61

D SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SURFACE TEMPERATURE FOR ALL SEASONS IN PHOENIX……..60

E SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SURFACE TEMPERATURE FOR ALL SEASONS IN DENVER……...61

F SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SURFACE TEMPERATURE FOR ALL SEASONS IN LAS VEGAS…….67

G SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SENSIBLE HEAT FOR ALL SEASONS IN PHOENIX……...69

H SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SENSIBLE HEAT FOR ALL SEASONS IN DENVER…….70

I SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SENSIBLE HEAT FOR ALL SEASONS IN LAS VEGAS……...65

APPENDIX Page

J SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF GROUND HEAT FOR ALL SEASONS IN PHOENIX…….75

K SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF GROUND HEAT FOR ALL SEASONS IN DENVER……..77

L SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF GROUND HEAT FOR ALL SEASONS IN LAS VEGAS……....77

M SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF LATENT HEAT FOR ALL SEASONS IN PHOENIX……..81

N SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF LATENT HEAT FOR ALL SEASONS IN DENVER……70

O SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF LATENT HEAT FOR ALL SEASONS IN LAS VEGAS……...71

LIST OF TABLES

Table Page

2.1. Modified Urban Parameters Used in Three Urban Categories in WRF 12

2.2. Physical Parameterizations Schemes Adopted in WRF..... 13

3.1. Classification of Urban Categories According to Impervious Cover Percentage..... 28

LIST OF FIGURES

Figure Page

2.1. Schematic Diagram of Thermal Energy Exchange in Urban Canopy With Radiative Shading by Trees. R, H, and D Denote the Tree Crown Radius, Height, and Distance from Wall, Respectively, with Subscript 'T' Standing for Trees. 9

2.2. Geographical Representation of the Domain Extent with Overlaid Topography (in Meters) 14

2.3. Comparison of Time Series of Simulated and Observed (a) 2-M Air Temperature, and (b) 2-M Relative Humidity Averaged over Urban Stations for June, 2012 16

2.4. Simulated Impact of Trees on Surface Temperature for Phoenix During June-August, 2012 at (a) 0200 LT, and (b) 1400 LT 18

2.5. Simulated Impact of Trees on 2-M Air Temperature for Phoenix During June-August, 2012 at (a) 0200 LT, and (b) 1400 LT 19

2.6. Simulated Impact of Trees on 2-M Relative Humidity for Phoenix During June-August, 2012 at (a) 0200 LT, and (b) 1400 LT. 20

2.7. Diurnal Variation of the Average Impact of Trees on (a) Surface Temperature, (b) 2-M Air Temperature, (c) Ground Heat Flux, and (d) 2-M Relative Humidity for Phoenix During June-August, 2012. 21

3.1. Representation of the Five Domains of the Study with Delineation of the CRB 29

3.2. Land Use Categories for the Two Scenarios, WRF_Control (a,c,e) and WRF_2100 (b,d,f) for Three Cities; Phoenix (a,b), Denver (c,d) and Las Vegas (e,f) 30

Figure Page

3.3. Land Surface Temperature Comparison between MODIS Data (a,c) and WRF Simulation (b,d) Results, Averaged from January 01-08, 2010 for Nightime over Phoenix (a,b) and Las Vegas (c,d) 32

3.4. Land Surface Temperature Comparison between MODIS Data (a,c) and WRF (b,d) Results, Averaged from January 01-08, 2010 for Daytime over Denver (a,b) and Las Vegas (C,D) 33

3.5. 2-M Air Temperature Daytime Difference between 2100 and 2010 during Spring Season for (a) Phoenix, (b) Denver, and (c) Las Vegas 34

3.6. 2-M Air Temperature Nighttime Difference between 2100 and 2010 during Spring Season for (a) Phoenix, (b) Denver, and (c) Las Vegas 35

3.7. Annual 2-M Air Temperature Daytime and Nighttime Difference between 2100 and 2010 for Phoenix, Denver, and Las Vegas 36

3.8. Diurnal Difference of 2m Air Temperature (T_2) between 2100 and 2010 in Three Cities for (a) Winter, (b) Spring, (c) Summer, And (d) Fall 37

3.9. Diurnal Difference of Surface Temperature between 2100 and 2010 in Three Cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall 38

3.10. Diurnal Difference of Sensible Heat Flux Between 2100 and 2010 in Three Cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall 39

3.11. Diurnal Difference of Ground Heat Flux Between 2100 and 2010 in Three Cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall 41

3.12. Diurnal Difference of Latent Heat Flux Between 2100 and 2010 in Three Cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall 42

Figure Page

3.13. Impact of Urban Expansion on the Energy Balance of Urban Surface over Daytime for (a) Phoenix, (b) Denver, and (c) Las Vegas. Rn is the Net Radiation (Positive Downwards); H is Sensible Heat (Positive Upwards); LE is Latent Heat (Positive Upwards); G is the Ground Heat (Negative Downwards). All Values are in W/M^2..... 44

3.14. Impact of Urban Expansion on the Energy Balance of Urban Surface over Daytime for (a) Phoenix, (b) Denver, and (c) Las Vegas. Rn is the Net Radiation (Positive Downwards); H is Sensible Heat (Positive Upwards); LE is Latent Heat (Positive Upwards); G is the Ground Heat (Negative Downwards). All Values are in W/M^2..... 45

CHAPTER 1 INTRODUCTION

1.1. Literature Review

The hydrologic effects of climate change in the Western region of United States have been reported to be negative and significant by Intergovernmental Panel on Climate Change (IPCC) (Jiménez Cisneros et al. 2014). Reduction of the availability of surface water is expected in the coming century with the region becoming drier and warmer (National Research Council 2010). In particular, Colorado River Basin (CRB), known as the life blood of the American Southwest, is vulnerable due to its sensitivity of discharge to precipitation and temperature changes, that are further exacerbated by semi-arid nature of the basin (Loaiciga et al. 1996). CRB has a critical role in the socioeconomic and ecosystem well-being of the south western region, contributing water supplies to nearly 40 million people of seven states (Arizona, Denver, Nevada, New Mexico, Utah, California), generating 10 billion of kilowatt-hours of electricity annually for the region, irrigating nearly 4 million acres of cropland in U.S. and Mexico and supporting wide diversity of wildlife including endangered species (Bruce 2012). Increase in temperature in CRB will result in increased rain and snow ratio, increased evapotranspiration, and decreased annual streamflow (Christensen et al. 2004) directly affecting water resources available to humans and to ecosystems.

Along with the impacts of climate change, CRB region is also experiencing rapid population growth and urbanization (Barnett and Pierce 2009) that has contributed to contentious and uncertain future of the region (Boepple 2012). The land use and land cover (LULC) change due to urbanization is also responsible for local and regional

climate change thereby aggravating the impacts of global climate change (Bates et al. 2008) on the CRB region and the major cities within it. Many studies have been carried out to determine the impact of climate change on hydrology of CRB (Christensen et al. 2004; Christensen and Lettenmaier 2007; Gao et al. 2011; Rasmussen et al. 2011; Wi et al. 2012; Milly et al. 2005). These studies predicted rise in temperature (3 -5 ^{0}F) with decrease in precipitation (0 – 6 %) and fluctuating water runoff (6 – 45 %) in CRB by 2100 with applications of General Circulation Models (GCMs) and Regional Circulation Models (RCMs). However, urbanization induced local and regional climate changes are largely missing in these studies leading to inadequate representation of holistic climate change impacts (global and regional) in the CRB region.

Recording the fastest population growth for 2000-2010, Arizona (24.6%) and Nevada (35.1 %), Phoenix and Las Vegas, along with Denver, are among the major cities that rely on the water supply in CRB (Boepple 2012; United Nations 2015). Nevada and Arizona are the top two states with 114.3 % and 108.8 % increase in projected population for 2030 with Colorado at top 15 with 34.7 % increase (United Nations 2015). The change in surface energy and hydrological processes due to urbanization (Kalnay and Cai 2003) leads to significant change in urban microclimate (Arnfield 2003). This concatenates to directly or indirectly influence the global climate change (Deng et al. 2013), emphasizing the importance of understanding the impacts of urbanization on local and regional hydroclimate and corresponding adaptation/mitigation strategies.

Many studies have been carried out to further the understanding of the hydroclimatic implications of urbanization on local and regional climate (Arnfield 2003; Brazel et al. 2000; Christensen et al. 2004; Imhoff et al. 2010; Oke 1982) . These studies provided in-

depth understanding of urban heat island mechanism (Oke 1982; Arnfield 2003; Collier 2006), variation in precipitation (Shepherd 2005), and related sustainability implications (increased water and energy consumption) (Gober et al. 2009; Guhathakurta and Gober 2007; Song and Wang 2015a). However, there have been relatively less studies concerning environmental consequences from rapidly growing urban areas (Trusilova et al. 2009). Addressing the hydroclimatic implications of urban expansion is necessary to provide guidance for planning and heading the cities towards sustainable development with least consequences on environment.

Along with understanding the hydroclimatic impacts, it is imperative to comprehend the adaptation/mitigation strategies for the urban cities, which are susceptible to changing environmental variables. During past decades, various mitigation strategies have been proposed and implemented to alleviate excessive urban heat, including urban trees (Akbari et al. 2001; Roy et al. 2012), reflective pavements (Yang et al. 2015b), and green roof systems (Yang et al. 2016). In particular, urban trees present a feasible form of urban green infrastructures for heat mitigation. The participatory role of urban trees with its shading effects and evapotranspiration in urban land-atmosphere interaction also assists in improving the building energy efficiency by declining cooling demand (Akbari et al. 2001). Recent years have seen increasing number of studies on urban trees with incorporation of trees in urban canopy model (UCMs) (Lee et al. 2008; Krayenhoff et al. 2014; Wang 2014; Ryu et al. 2016; Song et al. 2015a). These studies have shown the significant implications of inclusion of trees on predicting the overall cooling effect for the local environment. However, all these studies were offline in the sense that the urban land surface processes with trees included are not fully interactive with the driving

environmental forcing, resulting in potential errors in quantifying the actual effect of trees in an integrated land-atmosphere system.

Given the impacts of urbanization on the CRB region, researchers and planners must pay attention to sustainably built urban forms (Seto et al. 2010). Cities are the fundamental units of climate change adaptation and mitigation. The impacts of global changes thus highly depend on the pathway cities choose to develop, necessitating the study of hydroclimatic impacts and mitigation strategies. In addition, due to great difference in the physical, chemical and biological characteristics of landscapes of different regions, it is necessary to carry out and make comparison among different regions for analysis of spatiotemporal and climatic impacts variation within the regions (Deng et al. 2013).

1.2. Study Objectives

This study is intended to further the understanding of the impacts of LULC change in the continuously expanding cities of CRB region with the attempt to bridge the existing research gaps, as discussed in Chapter 1.1. The urban hydroclimatic impacts are determined through simulations of different land use scenarios. Numerical simulations are conducted using the state-of-the-art urban modeling system in a mesoscale numerical weather prediction model, viz. the Weather Research and Forecasting (WRF) platform; the latter serves as the backbone of everyday weather service of the United States. The thesis will address the following two key forms of LULC changes and assess their impact on urban hydroclimate:

1) Radiative shading effect of urban trees at the city scale, and
2) Inter comparison of hydroclimatic impacts of urbanization between cities with seasonal variation.

1.3. Organization of this Thesis

This thesis is organized as follows. Chapter 2 describes the incorporation of urban trees into mesoscale atmospheric model and its impact on urban hydroclimate, based on the study of Upreti et al. (2017). Chapter 3 explores the hydroclimatic impacts of LULC change in different cities with seasonal variation. Chapter 4 summarizes the entire study and concludes the key findings on impacts of LULC change on urban hydroclimate. Recommendations for future research directions are also presented in Chapter 4.

CHAPTER 2 RADIATIVE SHADING EFFECT OF URBAN TREES ON COOLING THE REGIONAL BUILT ENVIRONMENT

2.1. Introduction

Global population is undergoing rapid urbanization; more than half (54%) of the world's population is living in cities, and the proportion is projected to increase to 66% by 2050 (United Nations 2014). The conversion from natural landscapes to the built environment, concomitant with the rapid urbanization, induces modifications of surface energy and hydrologic balance, leading to changes of urban microclimate (Arnfield 2003). Specifically, the change in amount of radiative energy absorption and its repartitioning into latent and sensible heat due to landscape modification modulate heat and moisture cycles at the surface as well as in near-surface air (Oke 1988). The local signals of urban land surface changes then penetrate into the overlying atmospheric boundary layer, participate into the synoptic circulations, and thus manifest in the regional hydroclimate, via a cascade of land-atmosphere interactions (Song and Wang 2015a). These urbanization-induced changes challenge both environmental (regional urban climate change, air quality degradation, urban heat island effect, etc.) and energy sustainability, thus accentuating the importance of adaptation/mitigation strategies in the cities (Oke 1982; Song and Wang 2015a). During past decades, various mitigation strategies have been proposed and implemented to alleviate excessive urban heat, including urban trees (Akbari et al. 2001), reflective pavements (Yang et al. 2015b), and green roof systems (Yang et al. 2016).

Urban trees present a feasible form of urban green infrastructures for heat mitigation. The shading effect of urban trees reduces the net energy absorption thus modifying the urban energy balance (Roy et al. 2012) and cooling the urban canopy and boundary layers by reducing the sensible heat (Armson et al. 2012; Rahman et al. 2015). The participatory role of urban trees with its shading effects and evapotranspiration in urban land-atmosphere interactions also assists in improving the building energy efficiency by declining cooling demand (Akbari et al. 2001). The houses with shade trees have shown decrease in peak cooling demand of over 30% in previous studies (Akbari et al. 1997) . Similarly, shade trees also contribute to human thermal comfort by reducing surface and air temperatures and reducing direct and diffusive shortwave (solar) radiation from reaching canyon facets (Wang et al. 2015; Hedquist et al. 2014).

The effects of shading and evapotranspiration of trees on the built environment have triggered various research efforts to incorporate trees in urban modeling systems. (Lee and Park 2008) included trees in the vegetated urban canopy model (VUCM) by including the hydrological processes of trees via evapotranspiration, but without taking into account the effect of radiative shading. (Krayenhoff et al. 2014) included the radiative effects of tall trees in multi-layer urban canopy model (UCM) based on Monte Carlo ray-tracing method. Wang (2014) integrated urban trees into a single-layer UCM, enabling heat exchange between trees and urban facets via modifications of the radiative view factors. This modified view factors was later adopted by (Ryu et al. 2016), together with other biophysical processes of urban trees such as ET. Song and Wang (Song and Wang 2015a) integrated urban trees into a single column atmospheric model, and used this new modeling framework to investigate the impact of urban trees on urban boundary-

layer dynamics. These studies using offline (stand-alone) UCMs have shown that the inclusion of trees has significant impacts on predicting the overall cooling effect by urban green infrastructures for the local environment at the suburban (neighborhood to city) scales (Song et al. 2016; Wang et al. 2016). However, these studies are offline in the sense that the urban land surface processes with trees included are not fully interactive with the driving environmental forcings, resulting in potential errors in quantifying the actual effect of trees in an integrated land-atmosphere system.

For online platforms with fully coupled land-atmospheric dynamic modules, such as the Weather Research and Forecasting (WRF) model, the incorporation of the shading effect of urban trees not only allows an enhanced accuracy in predicting regional climate, but also has significant implications to sustainable urban planning in, e.g. building energy efficiency (Akbari et al. 1997, 2001). Among the developed systems, the single-layer UCM (Masson 2000; Kusaka et al. 2001) integrated into the WRF platform (Chen et al. 2011) has undergone continuous improvements and been widely used (Wang et al. 2013; Yang et al. 2015a) for accounting the land-atmosphere feedback and predicting urban hydroclimate. Nevertheless, modelling of water and energy budgets related to urban trees remains largely inadequate and presents as an open challenge hitherto in WRF-UCMs (Krayenhoff et al. 2014, 2015; Ryu et al. 2016). Numerical difficulty still persists in resolving the participatory role of trees in the exchange of radiative energy in built terrains (viz. shading by blockage of direct solar radiation, and trapping of terrestrial radiation) (Krayenhoff et al. 2014; Wang 2014).

The purpose of the present study is to incorporate urban trees to be participatory into the fully coupled WRF-UCM system, by including the shading/trapping effect (Fig. 2.1) in radiative heat exchange in street canyons. This study applied the Monte Carlo algorithm method for radiative exchange in 2D street canyons, integrating urban trees and their shading effect derived by a previous study (Wang 2014). With the integrated model, a fully coupled regional scale simulation was carried out for the Phoenix Metropolitan area.

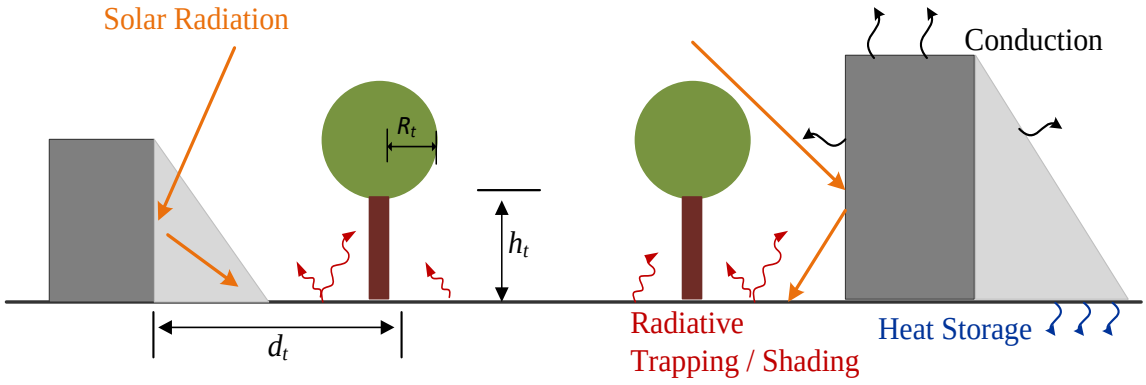

Figure 2.1. Schematic diagram of thermal energy exchange in urban canopy with radiative shading by trees. R, h, and d denote the tree crown radius, height, and distance from wall, respectively, with subscript ‘t’ standing for trees.

2.2. Methodology

2.2.1. Representation of urban trees in WRF

The presence of trees in a canyon interrupts the radiative rays transmitted between the canyon facets and modifies the view factors between them. A stochastic ray-tracing method based on the Monte Carlo algorithm was adopted for capturing the radiative exchange processes inside the street canyon with trees (Wang 2014). This method has

been widely used in previous studies with urban trees (Krayenhoff et al. 2014; Ryu et al. 2016; Wang 2014) because of its simplicity, flexibility, and robustness of implementation.

For the application of the Monte Carlo ray-tracing method and its subsequent incorporation into WRF-UCM, following assumptions were made: (a) Two symmetric rows of trees are present in the street canyon, with the cylindrical crown size of radius R_t (see Fig. 2.1); (b) The ray blocking effect of tree trunks is negligible considering their small size relative to the tree crown; (c) Radiative thermal energy is diffusive and decomposed of bundles of rays, each with separately generated and traced trajectory; and the emitting direction for each ray is generated by random numbers; (d) All facets (roads, walls, and trees) involved in the radiative exchange are Lambertian and gray. In the street canyon, vertical perpendicular distance from the tree crown center to the ground (h_t) and horizontal perpendicular distance from the tree crown center to the nearest wall (d_t) are used to determine the spatial location of the trees inside the street canyon, as shown in Fig. 1.

Radiative ray emitted from a canyon facet is traced by the direction of the ray from a generic *i*-th surface, which is determined by the azimuth angle η_i and the polar angle θ_i:

$$h_i = \arcsin\left(\sqrt{R_h}\right), \quad (1)$$

$$q_i = 2pR_q, \quad (2)$$

where R_η and R_θ are independent random numbers. The Monte Carlo algorithm is applied to trace along the randomly generated direction for the emitted ray. If this emitted ray is

absorbed by a surface *j*, it is taken into account of the view factor F_{ij}. Indices *i* and *j* range from 1 to 6, representing the six canyon facets presented in the radiative exchange processes, i.e. the sky, the ground, two facing walls, and two symmetric tree crowns. The shading effect of trees is then determined by the modified sky view factors with the presence of trees in the canyon.

For more realistic representation of urban trees in the study area, the Survey 200 dataset of urban trees retrieved from the Central Arizona-Phoenix Long Term Ecological Research (CAP-LTER) project was analyzed to obtain information of tree in Phoenix region. Height and crown radius required for the parameterization of trees in the urban canopy model was acquired from the tree dataset for all urban categories (commercial, high-density residential, and low-density residential) presented in WRF, with different canyon aspect ratios (building height/road width). The obtained information was then applied for estimating the sky view factors using aforementioned Monte Carlo algorithm, as a function of urban geometry and tree sizes and locations.

2.2.2. WRF-UCM System

Enabled by the stochastic simulation of radiative heat exchange in urban canyons with the presence of shade trees, we implement the modified single layer UCM into the WRF platform. The information of trees and the modified urban parameters in the study area, to be used for subsequent regional hydroclimate simulations by WRF, is detailed in Table 2.1. WRF is a mesoscale model for numerical weather predictions and atmospheric simulations (Skamarock et al. 2008), with applications in both research and operational fields. The single-layer UCM adopted in WRF is considered to be computationally

efficient for studying mesoscale climate system mainly because of its simplicity of parameterization and the realistic representation of urban land surface processes (Kusaka et al. 2001). The model capacity and predictive skills of the integrated WRF-UCM have been tested in studying regional urban climate and air quality for a number of major cities worldwide (Chen et al. 2011; Kusaka and Kimura 2004; Tewari et al. 2010).

Table 2.1. Modified urban parameters used in three urban categories in WRF

WRF urban category	Building height (m)	Road width (m)	Roof width (m)	Tree radius(m)	Sky view factors without trees	Modified sky view factors with trees
Low Residential	5.0	10	7.0	2.0	0.6180	0.3344
High Residential	10	12.5	15	1.5	0.4806	0.3241
Commercial	24	20	20	1.0	0.3620	0.3086

In this study, numerical simulations were initialized with meteorological conditions obtained from the National Centers for Environmental Prediction Final Operational Global Analysis data (consisting of geopotential, humidity, soil moisture and temperature, and winds), which were available on a $1^o \times 1^o$ resolution with a 6-h temporal frequency. All simulations utilized 35 vertical levels on a terrain-following coordinate system. Land surface processes were simulated using the Noah land surface model, coupled with the single-layer urban canopy model. Other major physical parameterization schemes used in this study are presented in Table 2.2.

Table 2.2. Physical parameterizations schemes adopted in WRF

Physics in WRF	Physical Parameterization Schemes	Reference
Planetary boundary layer dynamics	Yonsei University scheme	(Hong, Noh, and Dudhia 2006)
Microphysics	Thompson scheme	(Thompson et al. 2008)
Shortwave radiation	Dudhia scheme	(Dudhia 1989)
Longwave radiation	Rapid radiative transfer model	(Mlawer et al. 1997)
Surface layer dynamics	MM5 similarity scheme	(Fairall et al. 2003)

2.2.3. Case Study

To quantify the impact of urban trees on regional hydroclimate, the Phoenix metropolitan area was selected as our study site. Phoenix is one of the fastest growing cities of United States with an increase in population growth rate of 4% per year in the past 4 decades (Frey 2012). The hot and dry desert climate of Phoenix has worsened over time with rapid urbanization and the city is in a dire need of mitigation strategies for the sustainable development in the future.

A two-way nested grid configuration with all three domains centered at Phoenix (Fig. 2.2) was applied for the study. Spatial resolution was 32, 8, and 2 km for the outer, middle, and inner domains, respectively. The outermost domain had a size of

1824 km × 1824 km, the middle domain covered a surface area of 616 km × 616 km, and the innermost domain covered 210 km × 210 km.

The MODIS global land-cover data was used (Friedl et al. 2002) for outer and middle domains since they covered portions of Mexico. For the inner domain, the National Land Cover Database (NLCD) 2006 (Fry et al. 2011) was used to represent the variety of urban land use (i.e., commercial, high-density residential, and low-

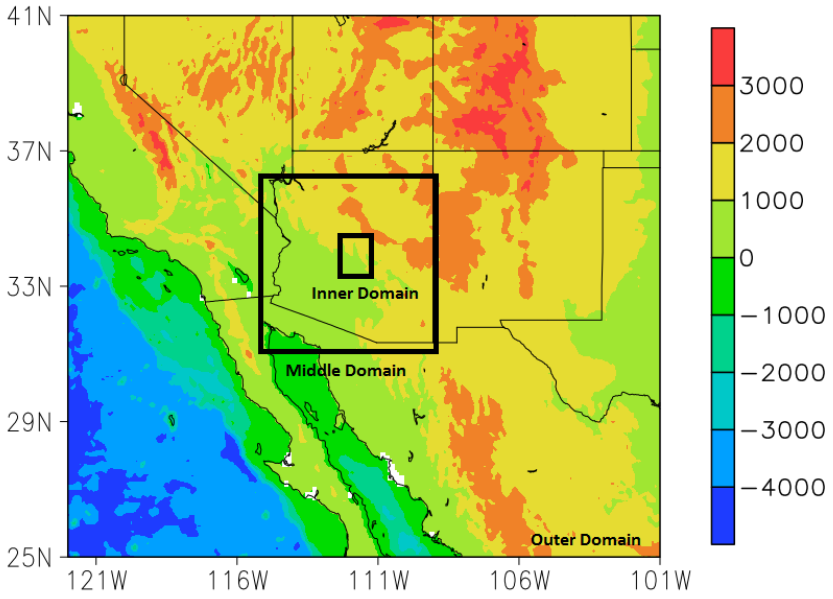

Figure 2.2. Geographical representation of the domain extent with overlaid topography (in meters)

density residential). Our analysis focused only on the high-resolution innermost domain covering the metropolitan Phoenix. Simulations were carried out for three months (June-August, 2012) including the last week of May as a spin-up period, which was not considered in subsequent analysis. These three months represent the summer

time in Phoenix when maximum temperature and heat stress on residents are observed, which makes them optimum months for urban heat mitigation strategies study.

Two sets of simulations were carried out: the first case was a control run with the default single-layer UCM (hereafter "WRF-Control") and the second case used the modified single-layer UCM including urban trees (hereafter "WRF-tree"). Comparison of results from the first and second cases will reveal the impact of trees on urban hydroclimate for the Phoenix metropolitan area.

2.3.Model Evaluation and Discussion

The evaluation of WRF simulations was carried out by comparing simulation results with observed data from ground-based weather stations. 2-m air temperature (T_2) and 2-m relative humidity (RH_2) are selected as model performance indicators, which are measured at 2 m height from the top of street canyons. T_2 and RH_2 measurements from three urban Arizona Meteorological Network (AZMET) stations: Encanto (33.479^o N, 112.096^o W), Greenway (33.621^o N, 112.108^o W), and Mesa (33.387^o N, 111.867^o W) were collected for the comparison. These three urban stations represented the urban area with appropriate urban fraction defined by the WRF modeling framework.

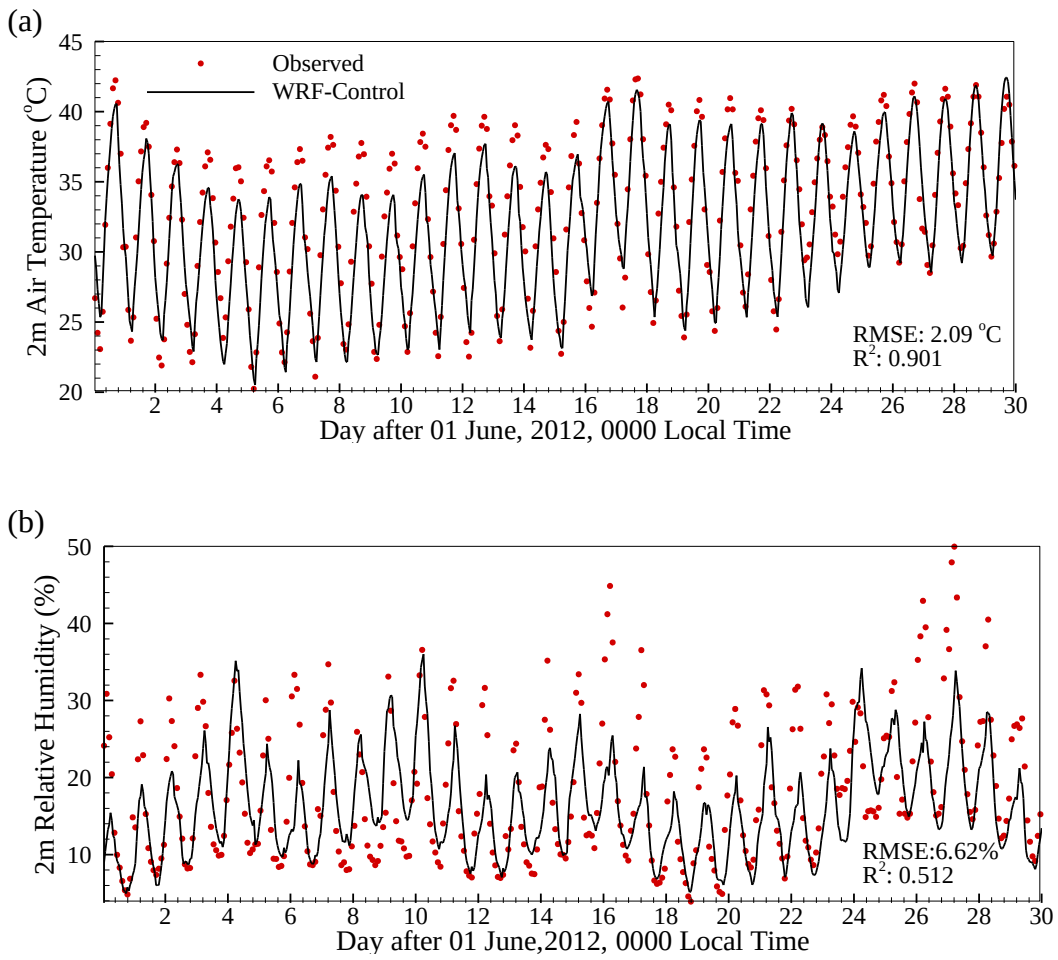

Figure 2.3. Comparison of time series of simulated and observed (a) 2-m air temperature, and (b) 2-m relative humidity averaged over urban stations for June, 2012

Time series of observed T_2 and RH_2 in June, 2012 are compared against the simulated results from the WRF-UCM in Fig. 2.3. Average of measurements from three urban ground-based stations was used for the comparison.

The statistical goodness-of-fit coefficients (R2) are 0.901 and 0.512, while root mean square errors (RMSEs) are 2.09 ºC and 6.16% for T2 and RH2, respectively. Fig.

2.3 shows that predicted 2-m air temperature and 2-m relative humidity capture the evolution of observation reasonably well. Maximum error is about 2 ^{o}C and 15% for T2 and RH2 in the simulation period.

After evaluating the model performance with in-situ measurements, the numerical simulation was carried out with modified sky view factors (Table 1) to reflect the presence of urban trees in the study area, while the rest of parameter space remains the same. The spatial patterns of environmental change with and without trees are shown in Figs. 2.4.-2.7. taken as the difference in simulation results between the WRF-control and WRF-tree cases and averaged over the entire simulation period of 3 months. Fig. 2.4 shows the impact of shade trees on surface temperature for Phoenix at 0200 LT and 1400 LT; the time instants are selected to represent the nighttime and daytime responses, respectively. It is found that tree shading is able to reduce urban surface (skin) temperature by a maximum of 10 ^{o}C averaged through the summer months (June-August). The maximum reduction of temperature at 0200 LT (~ 10 ^{o}C) is larger than that at 1400 LT (~ 8 ^{o}C), which is in agreement with the previous study (Z.-H. Wang 2014). As a desert city, Phoenix features a more prominent urban heat island (UHI) effect during nighttime than that in daytime (Brazel et al. 2000). Without trees in the urban canyon, the built environment (roads and walls with large heat capacities) absorbs and stores a significant amount of thermal energy in pavements during the day and releases it slowly at night. The existence of nighttime UHI has been observed for most U.S. cities (Imhoff et al. 2010). Shading from trees reduces the amount of heat absorbed by roads and walls during the day significantly, which in turn leads to the

significant nocturnal cooling of UHI. It is noteworthy that with the evapotranspiration effect of trees not included in the proposed modeling framework, the actual degree of cooling, particularly for nighttime, may not be accurate, which necessitates further model development in more realistic representation of functionality of urban trees in urban climate models.

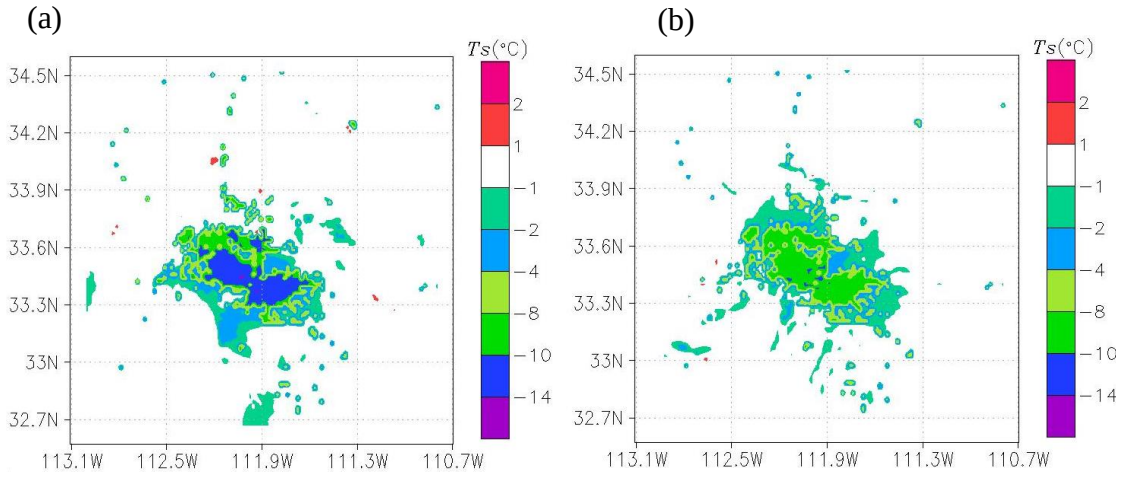

Figure 2.4. Simulated impact of trees on surface temperature for Phoenix during June-August, 2012 at (a) 0200 LT, and (b) 1400 LT

The impact of trees on 2-m air temperature is shown in Fig. 2.5. The cooling effect on 2-m air temperature by trees is about 6 °C maximum at 0200 LT at the urban core, and ranges 1 to 4 °C for the rest of metropolitan. In contrast, the nocturnal cooling has a smaller magnitude of ~ 1-5 °C at 1400 LT. This finding is consistent with the trend of surface temperature in Fig. 2.4. It is clear that trees have a stronger impact on the surface temperature than that on the air temperature, for surface heating of engineered materials is stronger than atmospheric heating by sensible heat. By modifying the radiative balance of urban facets, trees have a direct impact on urban surface

temperature and subsequently affect air temperature via reducing sensible heat flux.

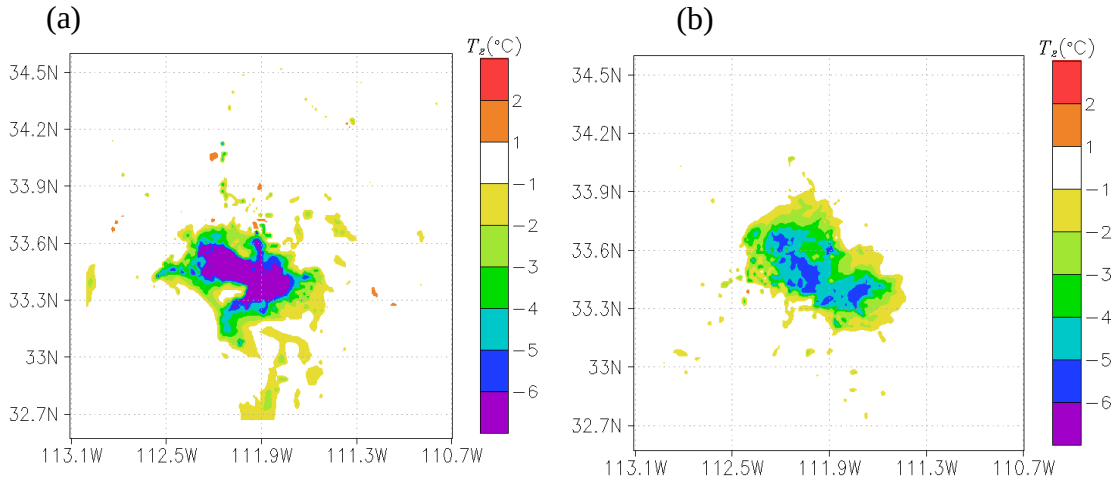

Figure 2.5. Simulated impact of trees on 2-m air temperature for Phoenix during June-August, 2012 at (a) 0200 LT, and (b) 1400 LT

The effect on ambient relative humidity (measured at 2 m) by urban trees is demonstrated in Fig. 2.6. The increase in 2-m relative humidity is attributed to the decrease in 2-m air temperature due to trees (Fig. 2.5). With a lower temperature, air requires less moisture to become saturated, which leads to the increased relative humidity. Increases of up to 16% is observed at 0200 LT (Fig. 2.6a) for small patches of central Phoenix, while the rise in 2-m relative humidity is about 12% at 1400 LT (2.6b).

Fig. 2.7 illustrates the mean diurnal variations of the impact of urban trees averaged over all the urban pixels in the study area. The presence of trees in the urban canyon decreases the daily mean surface temperature (Fig. 2.7a) from 33.96 °C to 25.29 °C, the daily mean 2-m air temperature (Fig. 2.7b) from 31.69 °C to 28.4 °C, and the ground heat flux (Fig. 2.7c) from 8.85 W m^{-2} to -2.03 W m^{-2}.

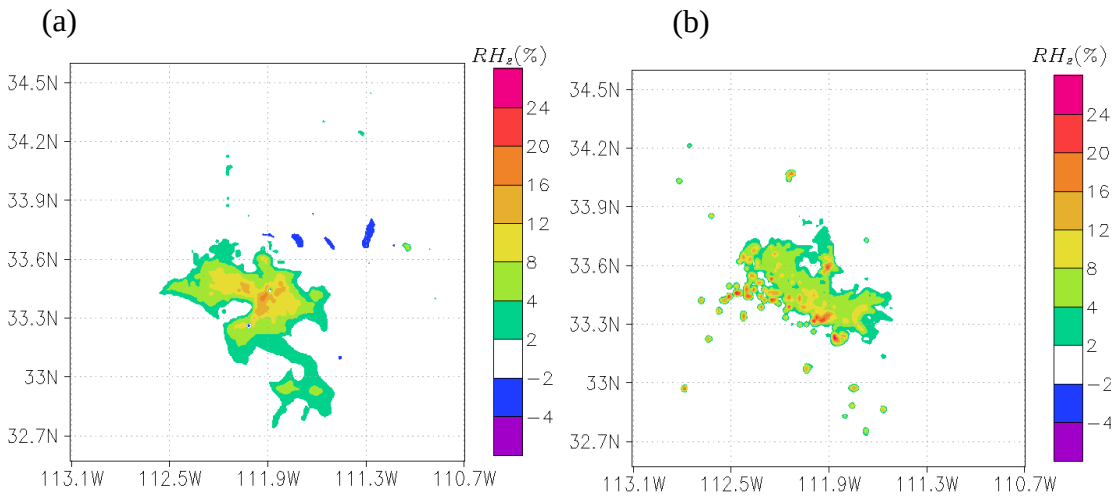

Figure 2.6. Simulated impact of trees on 2-m relative humidity for Phoenix during June-August, 2012 at (a) 0200 LT, and (b) 1400 LT.

The maximum decrease for surface temperature, 2-m air temperature, and ground heat flux is 9.98 °C, 4.17 °C, and 107 W m^{-2}, respectively. Comparing to the spatial patterns illustrated in previous figures, the maximum decrease of surface temperature and 2-m air temperature occurs at night, while the maximum decrease in ground heat flux is observed in daytime. Fig. 2.7d shows that trees increase daily mean 2-m relative humidity from 24.22% to 34.04% for the Phoenix metropolitan area. The maximum increase of about 23% in 2-m relative humidity is observed during the morning time.

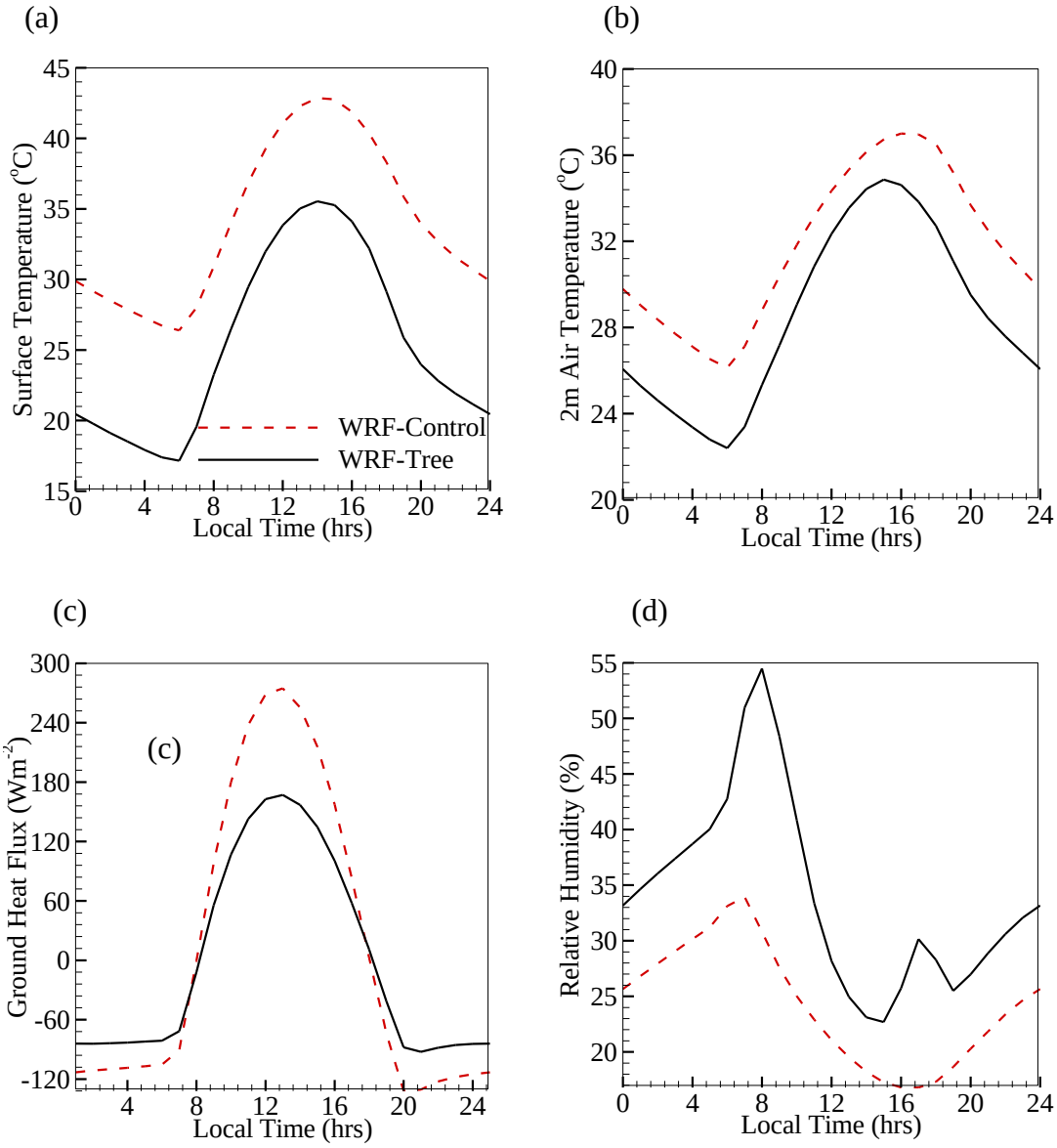

Figure 2.7. Diurnal variation of the average impact of trees on (a) surface temperature, (b) 2-m air temperature, (c) ground heat flux, and (d) 2-m relative humidity for Phoenix during June-August, 2012.

2.3. Concluding Remarks

In this chapter, urban trees were implemented into the single-layer urban canopy

model coupled with the WRF modelling system. With the new modelling framework, the impact of trees on the built environment was investigated for the Phoenix metropolitan area at the regional scale. Results showed that urban trees reduced 2-m air temperature, surface temperature, and ground heat flux considerably throughout the diurnal cycle. Relatively humidity in the built environment was increased as a result of reduced air temperature. The cooling effect of trees on urban environment was found to be greater in nighttime than in daytime, primarily due to the reduced heat storage in engineering materials resulted from the blockage of incoming solar radiation by trees in daytime.

It is noteworthy that urban trees were presented in the street canyon with the primary effect of radiative shading enabled by the stochastic simulation of the sky view factor. Other ecohydrological processes of urban trees, such as the root uptake of energy and water, ET via leafs, plant dynamics, and seasonal variability are not taken into the proposed modeling framework and remain open for future research. Nevertheless, since the current study represents a pioneering research effort that explores the impact of urban trees in a fully integrated land-atmosphere system for regional hydroclimate modeling, the findings are expected to provide insights on using shade trees as one of the potential urban mitigation strategies and a step forward towards the sustainable development of cities.

CHAPTER 3 INTER-CITY COMPARISON OF IMPACT OF URBAN GROWTH ON REGIONAL HYDROCLIMATE IN COLORADO RIVER BASIN

3.1. Introduction

The world is urbanizing rapidly, from one third of world population residing in urban areas in 1950 to more than half of world population in the urban settlements in 2014 (United Nations 2014) . With the global population projection to reach 9.7 billion by 2050 (United Nations 2015) , increase of 2.5 billion more urban population is expected (United Nations 2014). This continuously increasing urban population entails conversion of natural landscapes to urban landforms, leading to modification of surface radiation and moisture balance with significant consequences on air quality, natural resource sustainability and local and regional hydroclimate (Arnfield 2003; Gober and Kirkwood 2010; Collier 2006) and direct impacts on water resources with fluctuations in hydrological cycle (DeFries and Eshleman 2004; Hall et al. 1999; Jayne and Campbell 2011; Liu et al. 2017). In United States where 82% of total population is urban, water-constrained southwestern region is critically affected by the implications of urbanization on the water resources (Gober and Kirkwood 2010).

Colorado River Basin (CRB), also referred to as the life blood of the American southwest contributes to around 40 million people supporting seven states of United States; Arizona, California, Colorado, New Mexico, Nevada, Utah and Wyoming (Boepple 2012). Since the socioeconomic and ecosystem well-being of the Southwestern United States relies critically on health of CRB, assessment of magnitude and effects of climatic and anthropogenic changes affecting water quality and availability in CRB is crucial (Jayne and Campbell 2011; Rasmussen et al. 2011). Many studies have been

carried out to determine the impact of global and regional climate change on hydrological cycle of CRB (Christensen et al. 2004; Christensen and Lettenmaier 2007; Gao et al. 2011; Rasmussen et al. 2011; Wi et al. 2012; Milly, Dunne, and Vecchia 2005). These studies predicted rise in temperature (3 -5 ^{0}F) with decrease in precipitation (0 – 6 %) and fluctuating water runoff (6 – 45 %) in CRB by 2100 with applications of GCMs and RCMs. However, the climate changes depicted in the studies are largely missing the climate impact due to urbanization, leading to inadequate representation of holistic climate change impacts (global and regional) in the CRB region.

Nevada and Arizona are the top two states with over one hundred percent increase in projected population for 2030 with Colorado making the top 15 with 34.7 % increase (United Nations 2015). The increase in population and urban development, coupled with the direct effects of climate change on water resources, have contributed to the uncertain future of CRB (Boepple 2012; Christensen et al. 2004). This has underscored the importance of addressing hydroclimatic implications of an expanding city. There have been numerous studies aiming to understand the hydroclimatic implications of urbanization on local and regional climate (Arnfield 2003; Brazel et al. 2000; Christensen et al. 2004; Imhoff et al. 2010; Oke 1982). Many new lights have been shed on the understanding of urbanization-induced changes such as heat island effect (Oke 1982; Arnfield 2003; Collier 2006), variability in precipitation (Shepherd 2005), and related sustainability implications (increased water and energy consumption) (Gober et al. 2009; Guhathakurta and Gober 2007). However, there have been relatively less studies concerning environmental consequences from rapidly growing urban areas (Trusilova et al. 2009). Proper understanding of hydroclimatic implications of urban expansion is

required for many reasons; one important reason is to provide necessary guidance to carry city development forward with sustainable development.

To address these outstanding challenges, multiscale multiphysics numerical modeling framework holds an important key. Among them, Weather Research and Forecasting (WRF) (Skamarock et al. 2008) integrated with the single-layer urban canopy model (Kusaka et al. 2001; Masson 2000) has been widely adopted. WRF-urban modeling system has undergone continuous improvements and been widely used (Wang et al. 2013; Yang et al. 2015a) for improved predictive skills of urban hydroclimate. This modeling framework has been applied in different study areas like Arizona (Georgescu et al. 2012; Georgescu et al. 2013) , Australia (Argüeso et al. 2014), Europe (Trusilova et al. 2009) and China (Deng, et al. 2013) to incorporate future urban growth simulation and determine the hydroclimatic impacts. However, intercomparison among cities in CRB has not yet been carried out to capture the various dimensions of impacts of LULC change on local and regional hydroclimate.

The purpose of the present chapter is to determine and compare the hydroclimatic response to urbanization of three major growing cities of CRB region, i.e. Phoenix, Denver and Las Vegas, between 2010 and 2100. The latest WRF-Urban modelling system is adopted for regional hydroclimate simulations. In particular, the A2 scenario with maximum rate of urban expansion is adopted here based on Intergovernmental Panel for Climate Change (IPCC) Special Report on Emission Scenarios (SRES) (US EPA 2009). By focusing on three rapidly urbanizing cities, the objective is to understand the impacts of urbanization on the local-regional hydroclimate to individual cities in CRB

and to comprehend the differences in hydroclimatic effects of urbanization between three cities depending on type of urbanization (expansion and intensification) and surrounding environment.

3.2. Materials and Method

3.2.1. WRF Modeling System

The Advanced Research version of WRF (ARW, version 3.4.1) was used for all the numerical simulations in this study. WRF is a mesoscale model for numerical weather predictions and atmospheric simulations (Skamarock et al. 2008), with applications ranging from local to global level. In this study, numerical simulations were initialized with meteorological conditions obtained from the National Centers for Environmental Prediction Final Operational Global Analysis data (consisting of geopotential, humidity, soil moisture and temperature, and winds), which were available on a $1^o \times 1^o$ resolution with a 6-h temporal frequency. All simulations utilized 35 vertical levels on a terrain-following coordinate system. Land surface processes were simulated using the Noah land surface model, coupled with the single-layer urban canopy model.

Other major physical parameterization schemes used in this study included: 1) Dudhia scheme for shortwave radiation (Dudhia 1989), 2) the Rapid Radiative Transfer Model for longwave radiation (Mlawer et al. 1997), 3) Thompson scheme for microphysics (Thompson et al. 2008), 4) the MM5 similarity scheme for surface layer, and 5) the Yonsei University scheme for planetary boundary layer (Hong et al. 2006).

3.2.2. Inclusion of Urban Growth Scenarios in WRF

Urban expansion for 2100 in the three cities is accounted by incorporating the EPA's Integrated Climate and Land Use Scenarios (ICLUS) (US EPA 2009). Standard demographic approaches and a spatial model was used to create the scenarios with national coverage at 1 ha resolution (Bierwagen et al. 2010). These scenarios are consistent with the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) social, economic, and demographic storylines (Nakićenović et al. 2000). The storylines under SRES are described along two major axes, economic versus environmentally driven development (A-B) and global versus regional development (1-2) thus defining four quadrants comprising four storylines; A1, A2, B1 and B2 (US EPA 2009). These storylines can facilitate in future climate and land use assessments since these are applied in GCMs by the climate change science community (Reginster and Rounsevell 2006; Solecki and Oliveri 2004; Bierwagen et al. 2010). Each scenario used rates of population growth from the US Census Bureau as the baseline, which was modified to reflect the four main SRES storylines. The storylines were adapted for US to inform changes to fertility, domestic and international migration, household size, and travel times from the urban core (US EPA 2009). The ICLUS outputs are derived from two models: demographic model to generate population projections using a cohort-component model and a gravity model, and spatial allocation model to distribute projected population into housing units across the country.

In order to consider limiting case of urban growth in this study, the A2 scenario was used in this study, which resulted in largest change in urban and sub urban housing density, increased impervious surface cover and greater conversion of other land cover classes. In this scenario, the increase in impervious surface percentage was 164 % with

population forecast of nearly 690 million compared to the minimum increase in impervious surface of 60% with population forecast of nearly 380 million for B1 scenario by 2100 (Bierwagen et al. 2010). The resolution of the data was converted from 1 ha to 3 km for the innermost domains covering the three cities.

The impervious cover percentage from ICLUS was utilized to classify the urban category into commercial, high residential and low residential classes (Table 3.1). This classification was carried out to represent the urban classes in the study area.

Table 3.1 Classification of urban categories according to impervious cover percentage

Classification	Impervious Surface Percentage
Low Residential	20% - 39%
High Residential	40% - 64%
Commercial	64% - 100%

3.2.3. Numerical Experiments

The grid configuration consisted of 5 domains (Figure 3.1), using a grid spacing of 48 km (outermost domain), 12 km (second domain) and 3 km (each of the three innermost domains). The three innermost domains covered the three cities, Phoenix, Denver and Las Vegas with surface area of 207 km * 207 km and the middle domain covered the entire CRB with the surface area of 1692 km * 1692 km. The baseline simulation was conducted for Year 2010 divided into four seasons, viz. winter (December-February), spring (March-May), summer (June-August) and Fall (September-November), with one month spin-up period for each season. The same climate forcings

for 2010 and 2100 projections are used, so to single out and explicitly determine the impacts of LULC change without global change impacts.

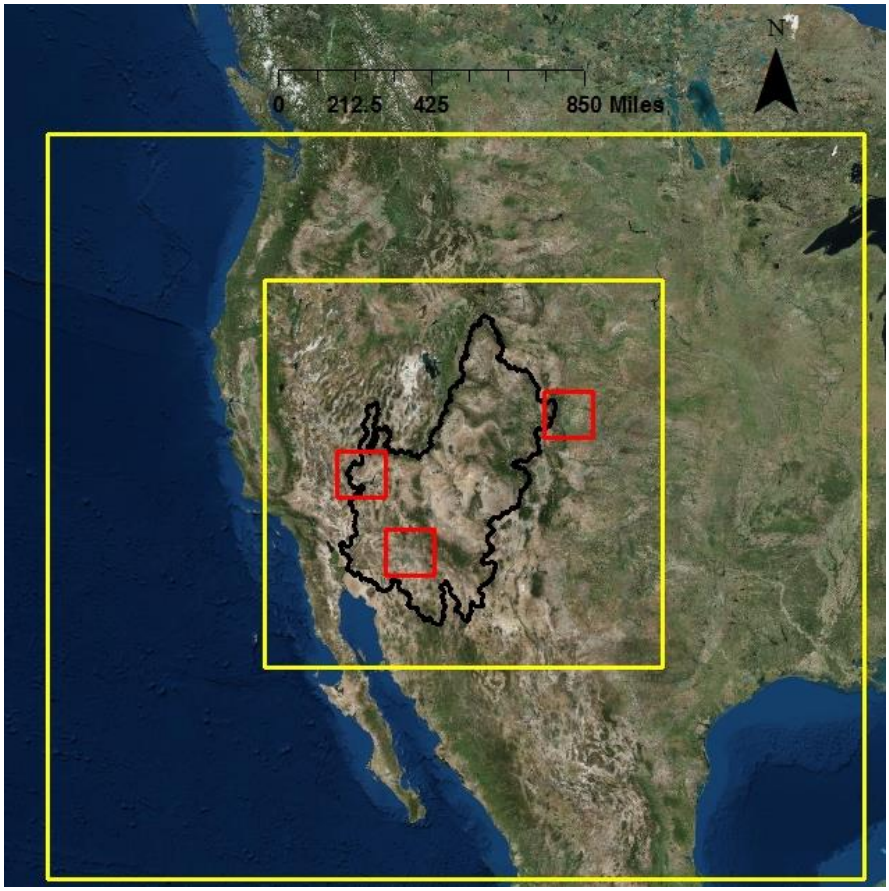

Figure 3.1. Representation of the five domains of the study with delineation of the CRB

For each city, two sets of simulation were conducted. The first case was the control case (hereafter WRF_Control) that utilized the land use data from 2010 base case scenario of ICLUS and the second case was the projected urban expansion for 2100 (hereafter WRF_2100) under the A2 scenario of ICLUS (Fig. 3.2).

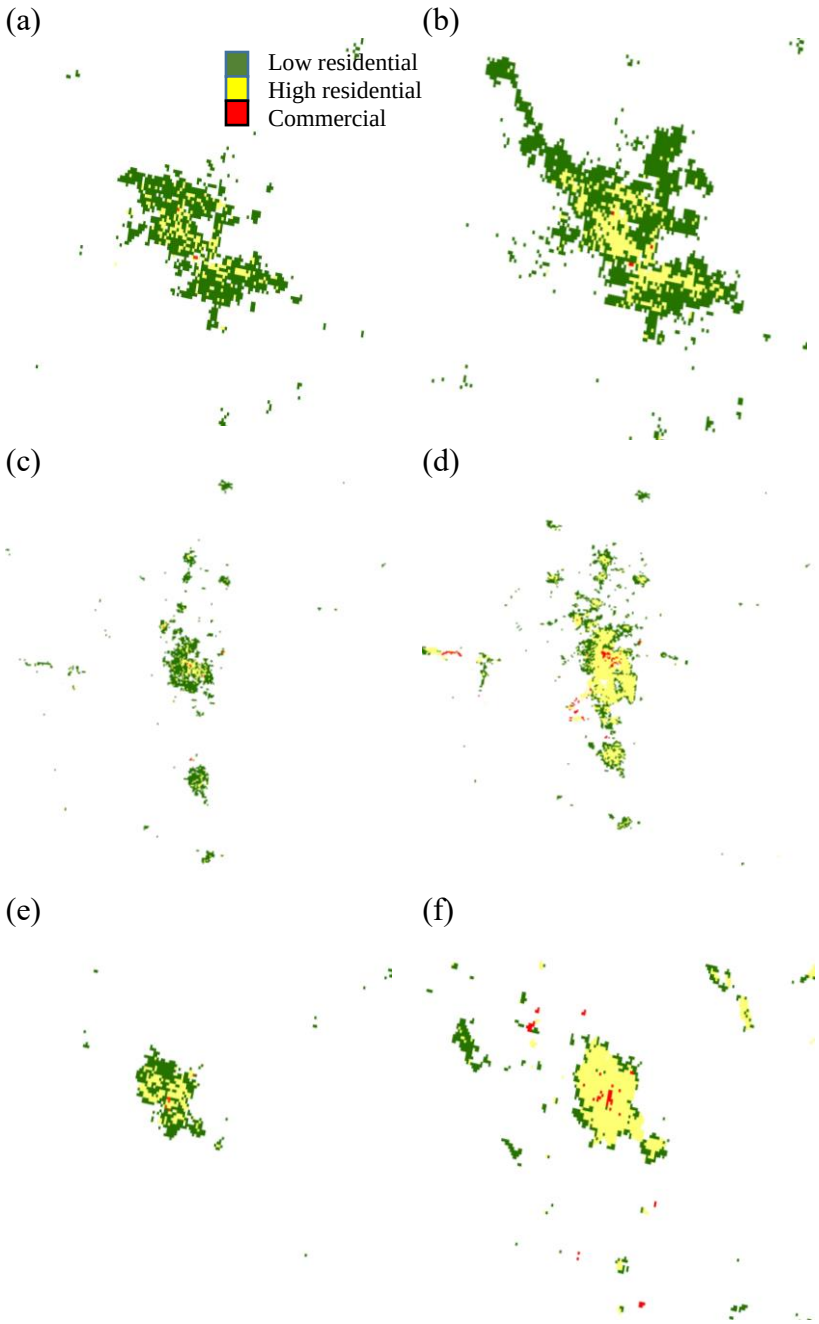

Figure 3.2. Urban categories for the two scenarios, WRF_Control (a,c,e) and WRF_2100 (b,d,f) for three cities; Phoenix (a,b), Denver (c,d) and Las Vegas (e,f)

3.3. Results

3.3.1. Model Evaluation

The model was evaluated by comparing the simulated results with satellite images and weather stations. To compare with the satellite images, WRF model was run for a week for summer (June 02- June 10, 2010) and winter time (Jan 09- Jan 15, 2010) with one-week spin up period for both seasons. MODIS land surface temperature data (averaged over 8 clear days, 1km resolution) was downloaded for segments covering the innermost domains. This data was processed using ArcGIS to obtain final remotely-sensed imagery (Figure 3.3). These satellite images were achieved for both daytime and nighttime. The satellite overpass time for day was around 1800 UTC and for night was around 0500 UTC. This overpass time was used in the generation of WRF results for each domain. Average surface temperature at 1800 UTC was obtained for daytime comparison and similarly, for night time comparison average surface temperature at 0500 UTC was obtained.

In Figures 3.3 & 3.4, reasonably good agreement was observed between the satellite images and model results. The similarity in spatial patterns of temperature distribution was found to be more significant in night time than day time. It is also noteworthy that the model predictions have more markedly warming in the urban cores than their surroundings.

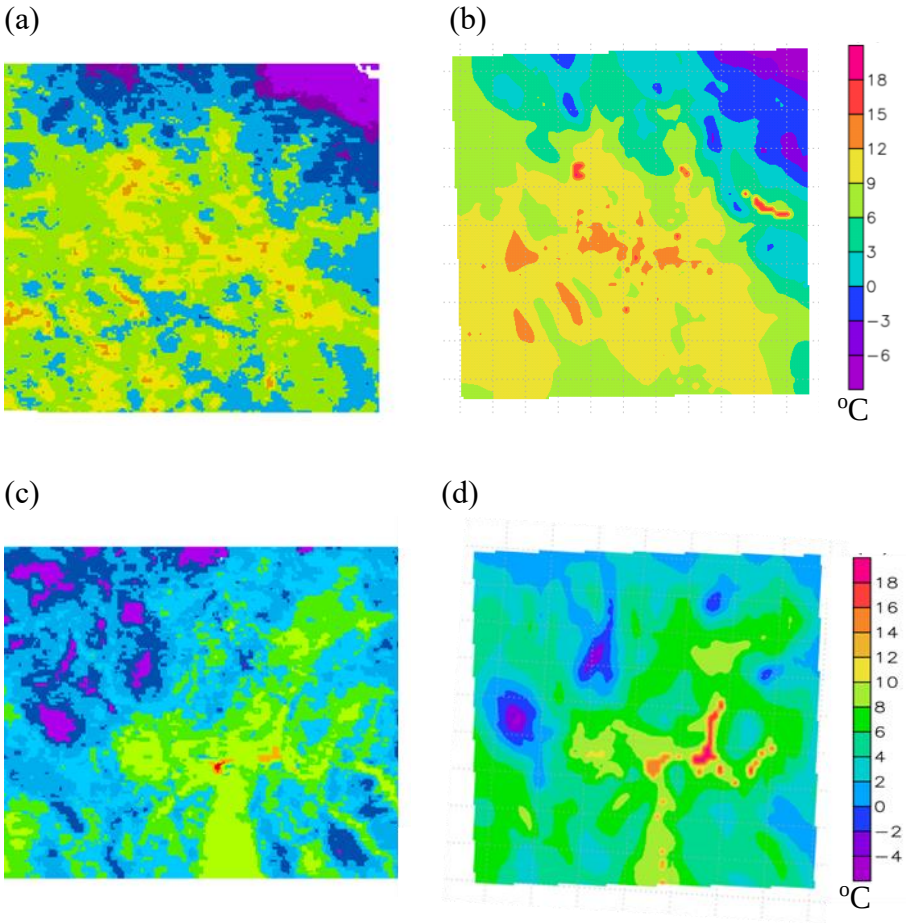

Figure 3.3. Land surface temperature comparison between MODIS data (a,c) and WRF simulation (b,d) results, averaged from January 01-08, 2010 for nightime over Phoenix (a,b) and Las Vegas (c,d)

3.3.2. Thermal Impact of LULCC

After the model evaluation, the impact of urban growth in the three cities was assessed. Two time periods, averaged over daytime (08:00 – 20:00 LT) and night time (20:00 – 08:00 LT) were selected to analyze the spatial distribution of the urbanization impact.

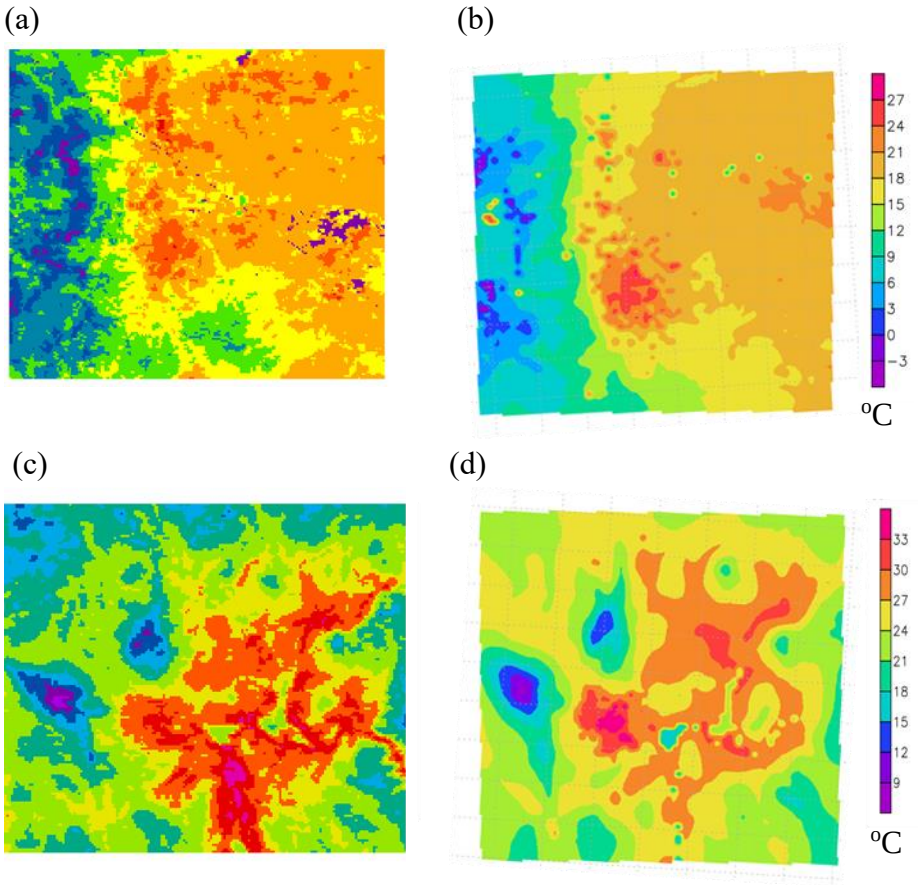

Figure 3.4. Land surface temperature comparison between MODIS data (a,c) and WRF (b,d) results, averaged from January 01-08, 2010 for daytime over Denver (a,b) and Las Vegas (c,d)

During the daytime, the projected urban growth leads to cooling for Phoenix, warming for Denver and mostly warming with slight cooling for Las Vegas was observed (Fig. 3.5). In the nighttime, warming in all the three cities is observed (Fig. 3.6). However, the daytime oscillation is of comparatively less degree than nighttime warming. The impact follows the pattern of landscape modification, with the areas undergoing urbanization experiencing the major impacts (Figs. 3.5 and 3.6).

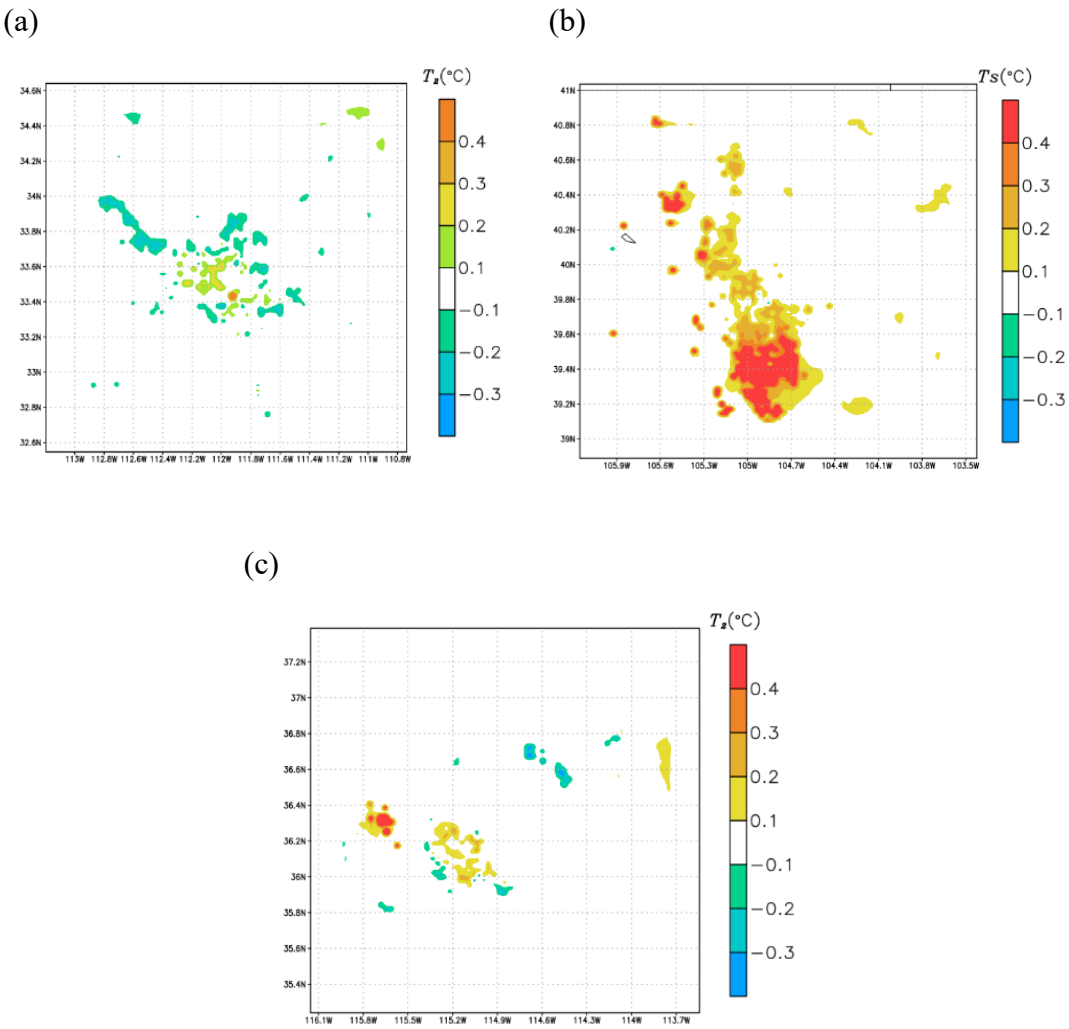

Figure 3.5. 2-m air temperature daytime difference between 2100 and 2010 during Spring season for (a) Phoenix, (b) Denver, and (c) Las Vegas

The warming impacts seem to be maximum for Denver with maximum nighttime warming (Fig. 3.6b) as well as slight daytime warming (Fig. 3.5a) at the urbanized area.

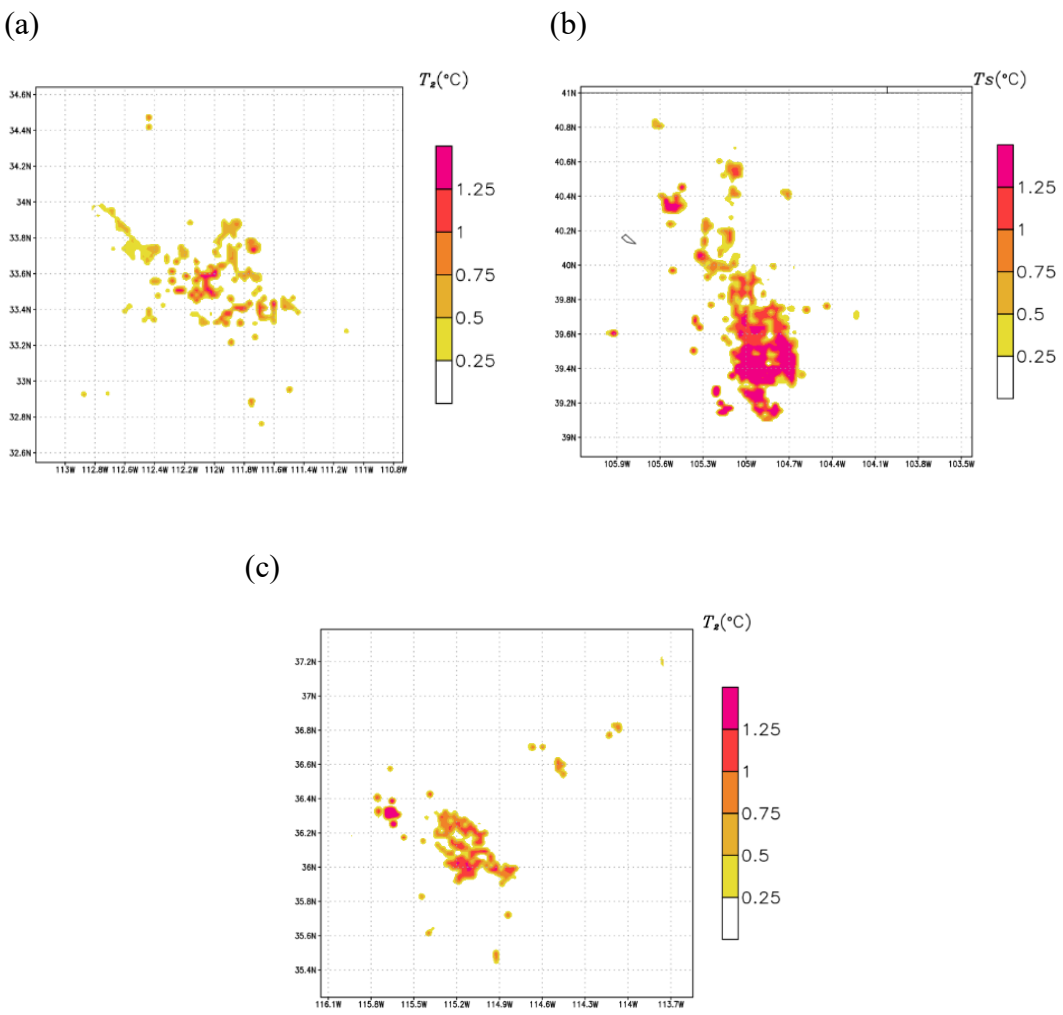

Figure 3.6. 2-m air temperature nighttime difference between 2100 and 2010 during Spring season for (a) Phoenix, (b) Denver, and (c) Las Vegas

The average annual daytime and nighttime T_2 difference between the urban pixels of WRF_2100 and WRF_Control for the three cities can be seen in Fig. 3.7. The phenomenon of daytime cooling in average (albeit small) is observed for Phoenix while Denver and Las Vegas show slight daytime warming. The results of daytime cooling and nighttime warming in Phoenix, is consistent to the previous findings reported by

Georgescu et al. (2011), due to conversion of shrub to urban. Brazel et al. (2000) also documented negative temperature difference between rural (undeveloped area) and urban near surface temperature in the daytime, with observational experiments. Comprehensive results of simulations for temperature (surface and near-surface) are detailed in the Appendix.

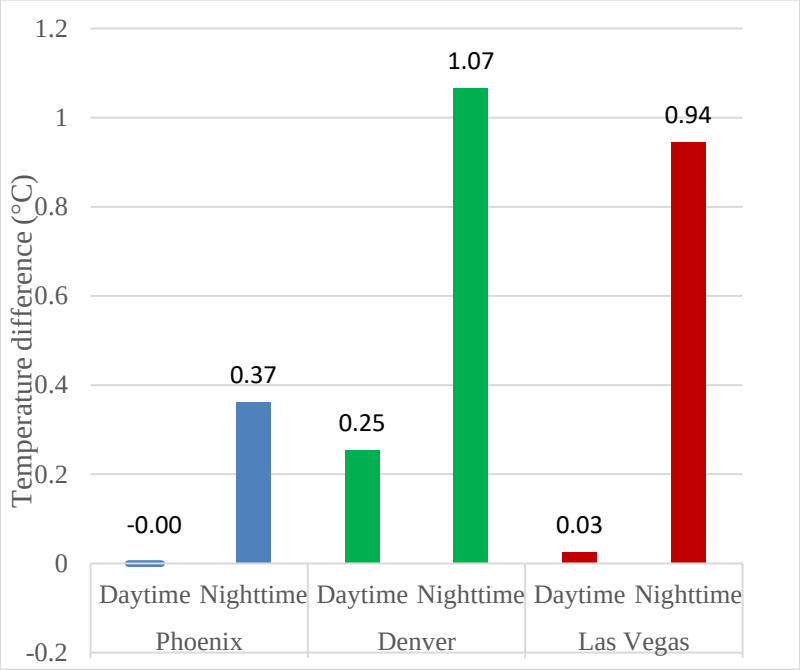

Figure 3.7. Annual 2-m air temperature daytime and nighttime difference between 2100 and 2010 for Phoenix, Denver, and Las Vegas

In addition, the detail study of the thermal impacts in the three cities in various season was conducted by obtaining the diurnal figures of the differences between the temperature and fluxes for WRF_2100 and WRF_Control.

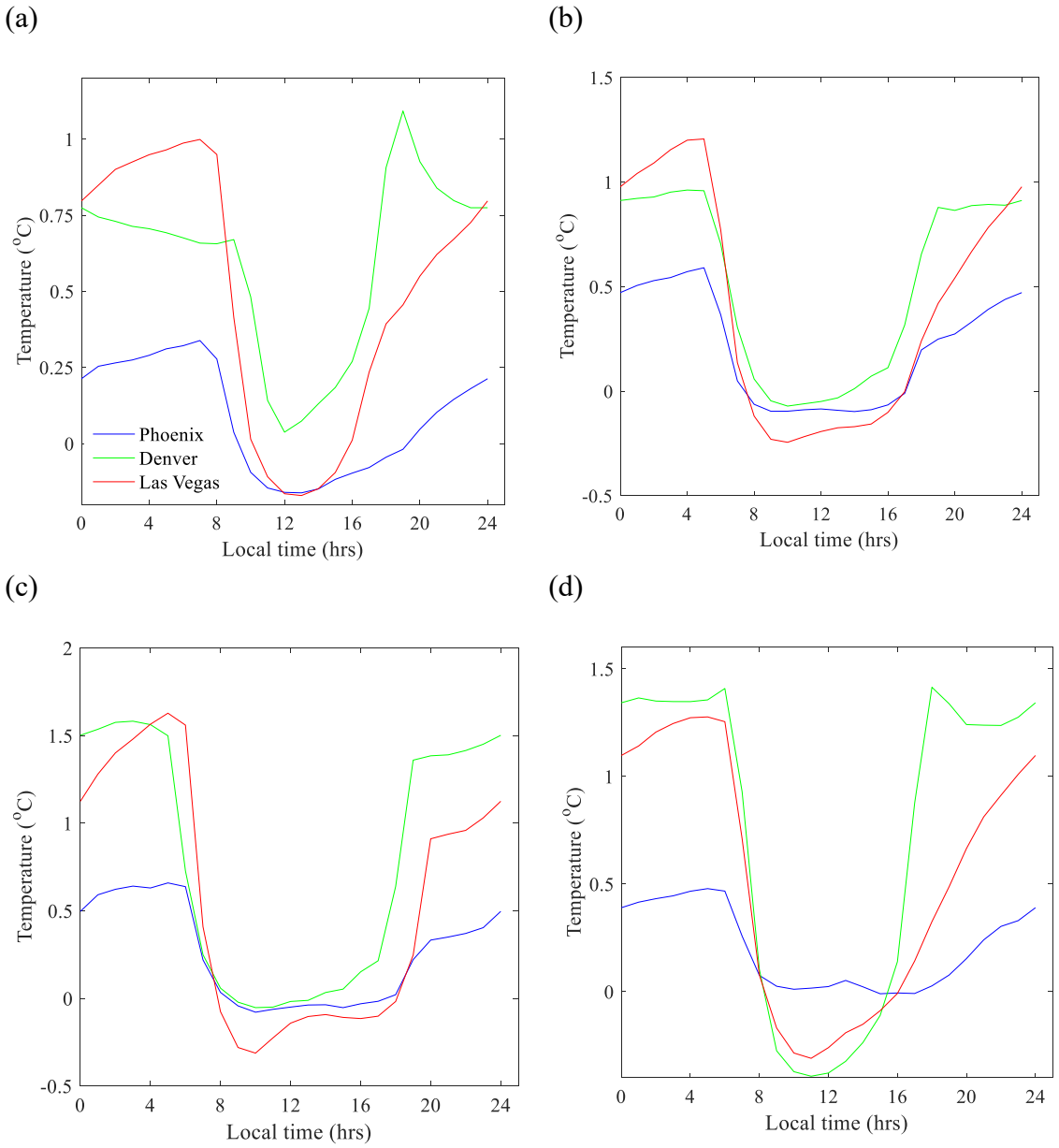

Figure 3.8. Diurnal difference of 2m air temperature (T_2) between 2100 and 2010 in three cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall

The diurnal difference in T_2 and surface temperature (T_s) for 2100 and 2010 as shown in Figures 3.8 and 3.9 demonstrate the nighttime warming and daytime cooling effect of the urban growth as seen earlier. In average the nighttime T_2 warming for Phoenix, Denver and Las Vegas is found to be 0.36 ^{0}C, 1.07 ^{0}C and 0.94 ^{0}C respectively

and the Ts warming was 0.92 ^{0}C, 2.07 ^{0}C, and 2.17 ^{0}C. The maximum warming and cooling effect in both temperatures, surface and 2-m air temperature is found to be during the Summer followed by Fall, Spring and then Winter.

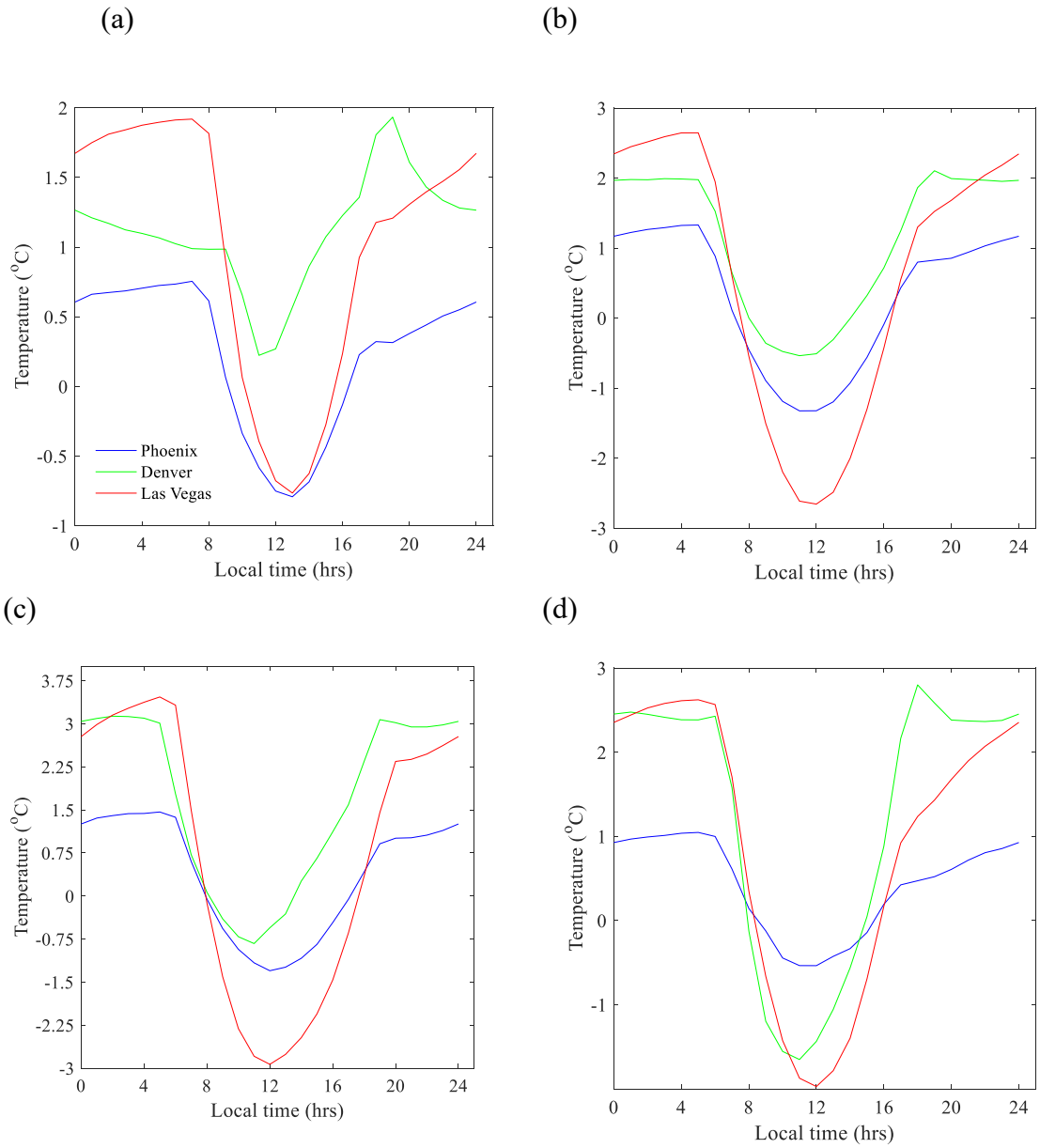

Figure 3.9. Diurnal difference of surface temperature between 2100 and 2010 in three cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall

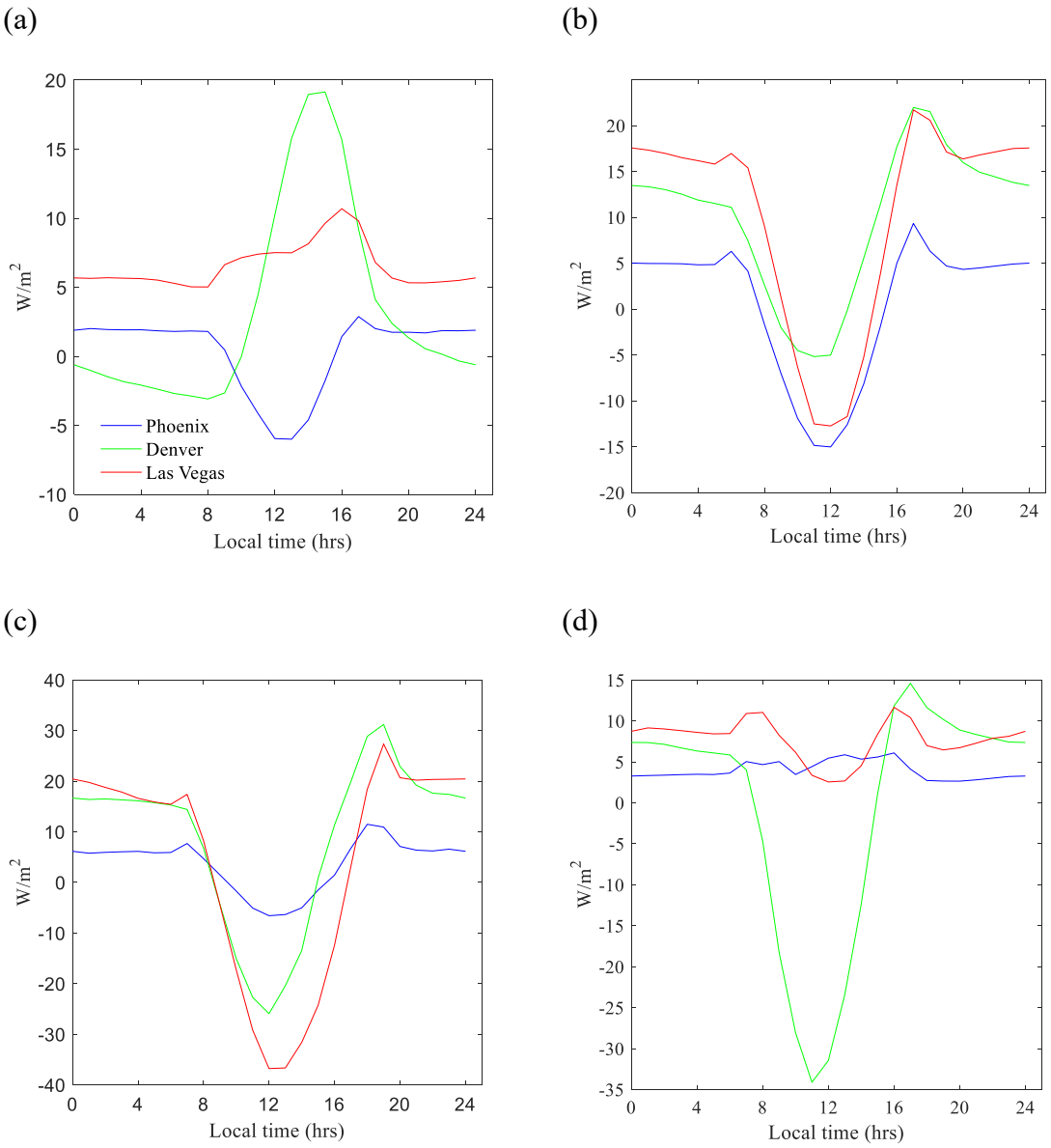

Figure 3.10. Diurnal difference of sensible heat flux between 2100 and 2010 in three cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall

The nightime warming is attributed to the slow release of the stored daytime heat and enhanced emission of longwave radiation toward the surface from within the urban canopy for the urbanizing areas.

Following the trend of the temperature, the increase in sensible heat (*H*) was observed during the nightime and decrease during the daytime (Fig. 3.10). This increase in urban heat storage, which occurs largely during daytime, results in increased sensible heat flux during the nighttime. The daytime decrease of the sensible heat is attributed again to the urban fabric with increased heat capacity; WRF_2100 with more urban environment taking longer time to absorb large amount of heat during the daytime thus resulting in negative sensible heat difference with WRF_Control for Spring, Summer and Fall. However, the difference in sensible heat demonstrates a different trend in Winter for Denver and Las Vegas, with increase in sensible heat flux in the daytime (Fig. 3.10a). Incase of the Denver, the possible reason for different trend might be the winter with average seasonal snow fall of 22.8" for 2010-2011 (National Weather Service, n.d.) which changes the surface energy budget with increase in albedo and thus the heat storage.

Negative ground heat (*G*) difference during the dyatime and positive during the nightime is observed for WRF_2100 compared to WRF_Control for all three cities and all the seasons (Fig. 3.11). Ground heat flux is assumed to be positive when directed away from the surface and negative when directed towards the surface. The high heat capacity of the built environment is accountable for storing a large fraction of available energy (Oke 1982). The negative differences of the ground heat flux indicate greater heat storage for WRF_2100 with respect to WRF_Control. Greater negative values of ground heat flux are obtained for WRF_2100 than the WRF_Control, resulting in the negative differences in Fig. 3.11 for daytime. With higher heat storage during the daytime, release

of more ground heat is observed during the nightime, thus positive difference between WRF_2100 and WRF_Control.

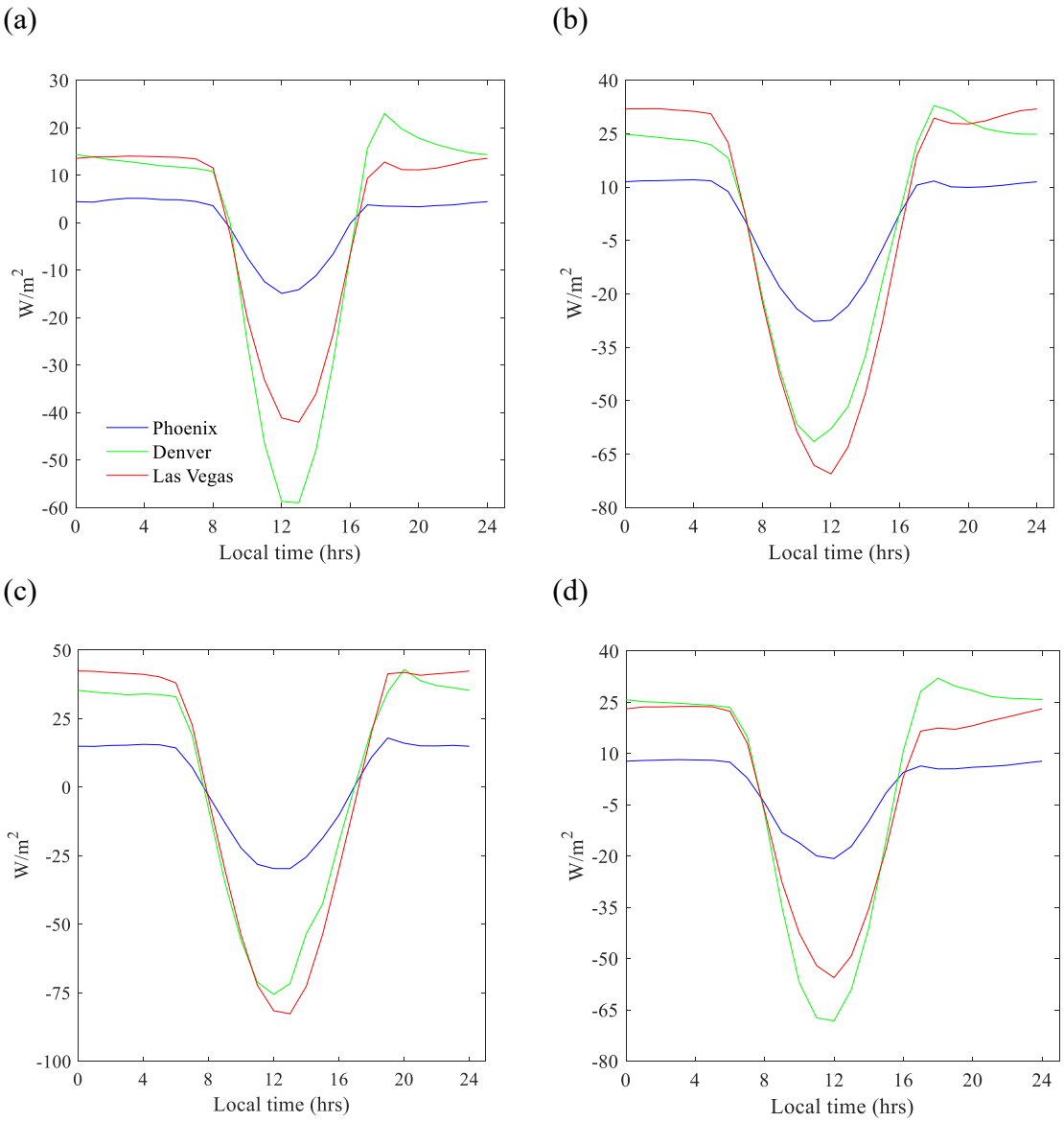

Figure 3.11. Diurnal difference of ground heat flux between 2100 and 2010 in three cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall

Decrease in latent heat energy (*LE*) from WRF_Control to WRF_2100 is observed for Denver (Fig. 3.12). Considering the change in land use from green

vegetation to urban intensification in Denver compared to conversion of desert or semi-desert to urban sprawl for Phoenix and Las Vegas, there is significant decrease in the available surface moisture thereby decreasing the latent heat component. The change in latent energy for Phoenix and Las Vegas seems to be of small magnitude with almost no

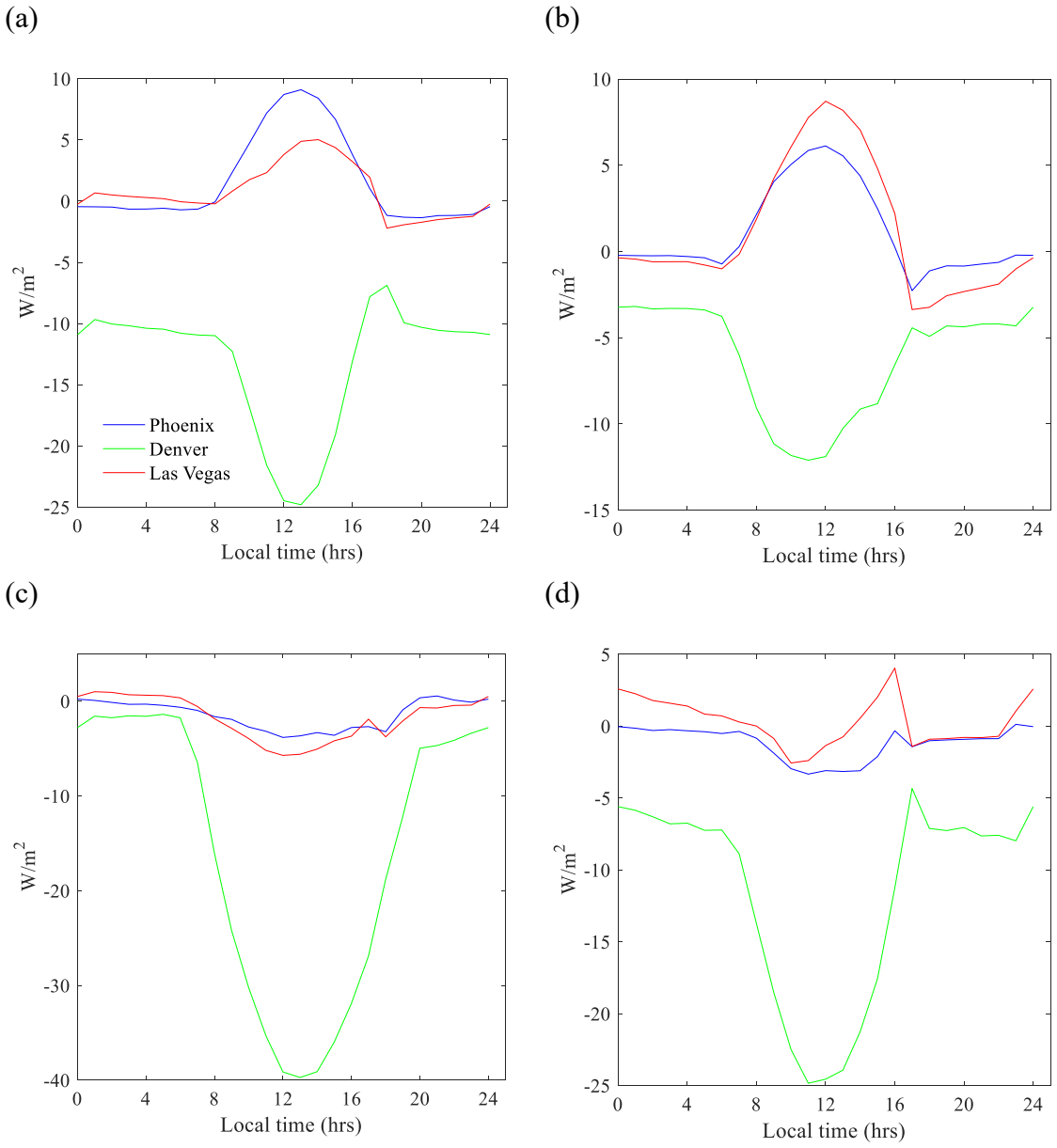

Figure 3.12. Diurnal difference of latent heat flux between 2100 and 2010 in three cities for (a) Winter, (b) Spring, (c) Summer, and (d) Fall

changes during summer and fall because of the low moisture in the semi-arid climate in both scenarios. The slight increase in the Winter and Spring during the daytime for phoenix and Las Vegas may be attributed to the oasis effect created by the urban sprawl whereby the inner urban area with parks has more moisture than the surrounding dry area.

The impact of the urban expansion on the energy balance of impervious surface for the urban area of all cities for WRF_2100 are shown in figures 3.13 and 3.14. The daytime impact for three cities (Fig. 3.13) demonstrates increase in release of sensible heat and storage of ground heat. Increase in net radiation to the surface and latent heat release (small scale) is observed for Phoenix, Las Vegas while the latent heat and net radiation seem to be decreasing in case of Denver. As for the nighttime impact (Fig. 3.14), all the cities exhibit increase in release of net radiation from the surface, ground heat to the surface, and decrease in release of latent heat. As for the sensible heat, decrease in heat transfer to the surface is observed in Phoenix and Las Vegas with release in small amount of heat from the surface for Denver.

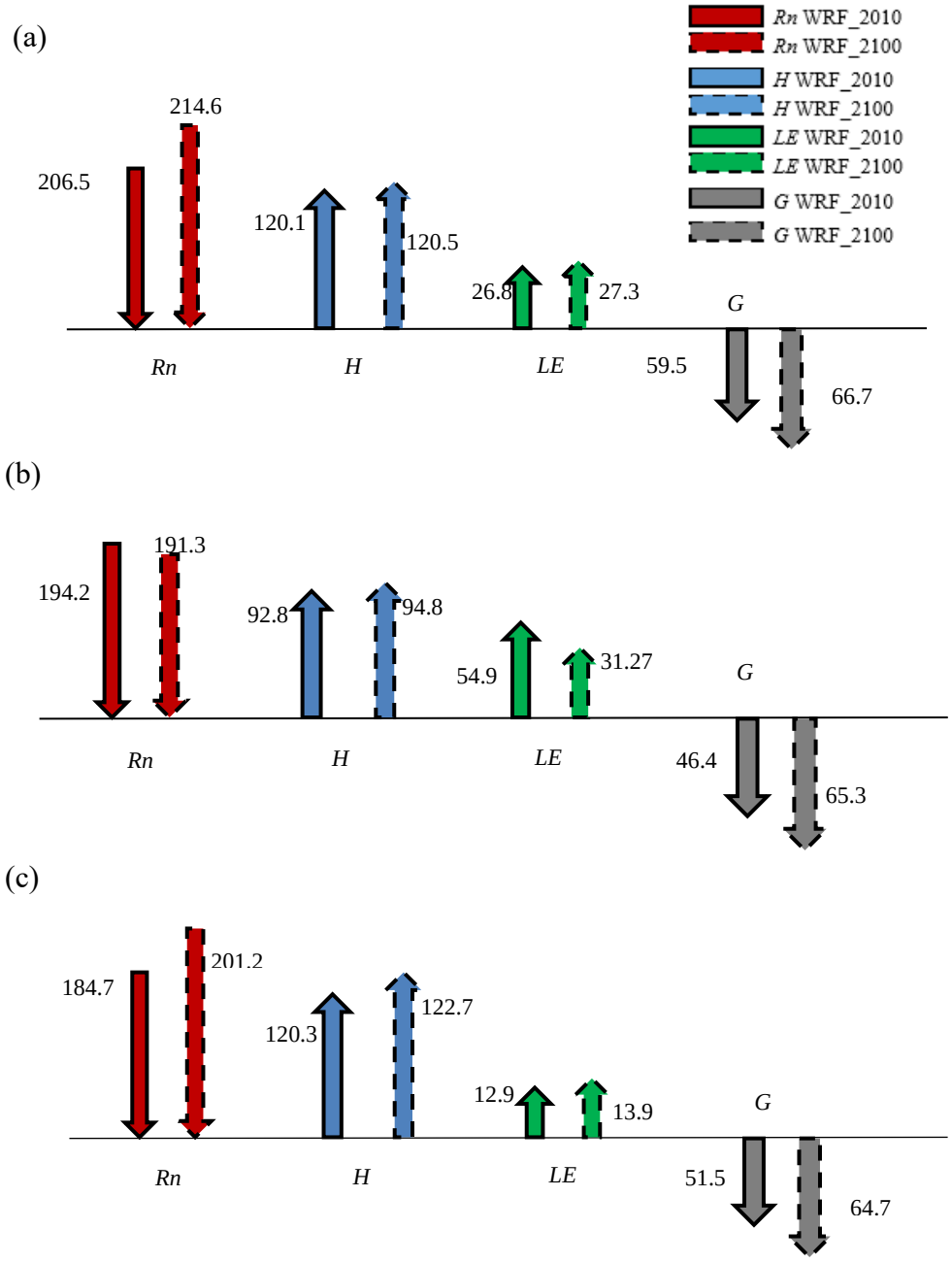

Figure 3.13. Impact of urban expansion on the energy balance of urban surface over daytime for (a) Phoenix, (b) Denver, and (c) Las Vegas. Rn is the net radiation (positive downwards); H is sensible heat (positive upwards); LE is latent heat (positive upwards); G is the ground heat (negative downwards). All values are in W/m^2.

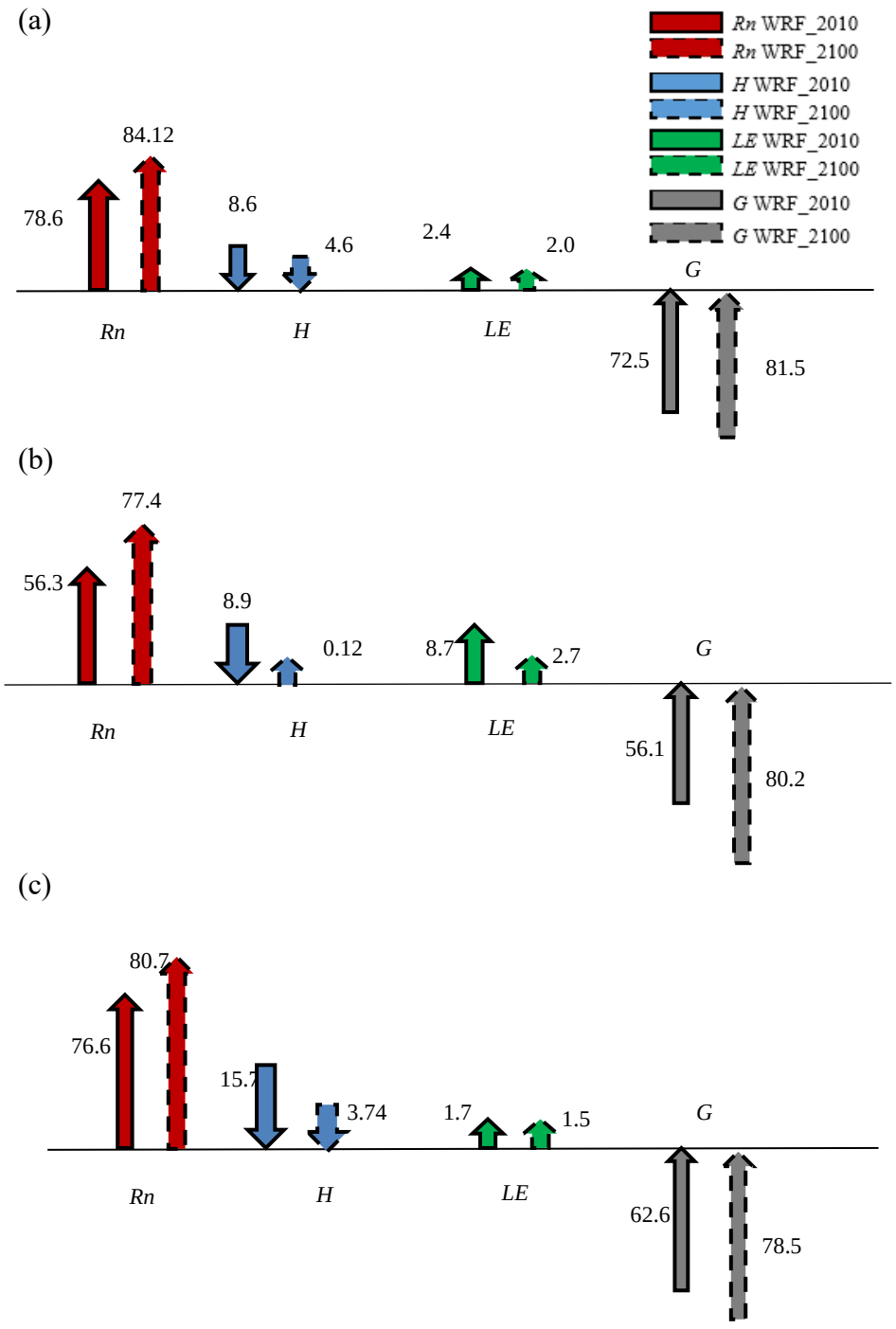

Figure 3.14. Impact of urban expansion on the energy balance of urban surface over nighttime for (a) Phoenix, (b) Denver, and (c) Las Vegas. Rn is the net radiation (positive downwards); H is sensible heat (positive upwards); LE is latent heat (positive upwards); G is the ground heat (negative downwards). All values are in W/m^2.

CHAPTER 4 CONCLUSIONS AND PERSPECTIVES

4.1. Conclusions and Recommendations

The thesis presents an elaborative effort to determine the impacts of LULC change on the urban hydroclimate. Using the Weather Research and Forecasting (WRF) system coupled with the single layer urban canopy model, we carried out study of three major cities (Phoenix, Denver, and Las Vegas) in Colorado River Basin (CRB) region under the influence of urban landscape changes. Identifying the necessity of understanding local and regional climate change due to urbanization, this study accomplished the assessment of the response in urban hydroclimate due to urban expansion as well as incorporation of shade trees. These studies shed some new lights on how urbanization influences the local and regional hydroclimate and how effective mitigation strategies can be employed to ameliorate the thermal environment of cities.

In this thesis, we first investigated the radiative and shading effect of urban trees using the WRF-urban modeling modeling system in Chapter 2. The impacts studied over Phoenix metropolitan region showed decreases in 2-m air temperature, surface temperature, and ground fluxes with cooling effect being more effective at the nighttime. This cooling effect of the urban trees was attributed to the reduction in heat storage in built materials resulting from blockage of incoming solar radiation by the trees in the daytime. However, since only radiative shading effect was considered in the study, consideration of other tree related processes such as evapotranspiration through leaves, root uptake of energy and water, seasonal variability and plant dynamics are recommended for future studies.

In Chapter 3, the change in urban hydroclimate due to urban expansion from 2010 to 2100 was studied for Phoenix, Denver and Las Vegas to determine the local and regional impact in CRB regions and compare the differences between the cities. The scenario of maximum expansion of the urban areas, viz. the A2 scenario, resulted in prominent nocturnal warming for all the three cities. Within the three cities, maximum impact of urbanization observed in Denver due to the synergistic effect of urban expansion and intensification. The semi-arid climate and the dominant mode of urbanization (expansion) of Phoenix and Las Vegas were responsible for the similar patterns in predicted hydroclimate changes in these cities. In the case of Denver, temperate climate with different surroundings and urban growth associated with both expansion and intensification induced different and intense results. Further research in this study comprises inclusion the global climate change in combination with the regional climate, and the direct impacts on the hydrology of the CRB in the future.

The climatic impacts from the simulation of LULC change provide an insight regarding the pathways for urban development. For a sustainable future, it is imperative to understand and compare all the viable options and determine the one with least adverse environment impacts. The studies carried out can be a major guidance for the city, water and energy planners to steer the cities towards development through a sustainable pathway.

4.2. Future Work

The research work presented in this Thesis can be extended in a number of ways to deepen the understanding of future urbanization, mitigation strategies, policy implications, and their interactions in the water-energy-climate repercussions.

First, this thesis presents a pioneer effort in incorporation of radiative shading effect of the urban trees in the WRF-UCM modeling system. Nevertheless, other biometeorological functions such as evapotranspiration, irrigation demand, plant dynamics, etc. remain missing in the online WRF modeling framework. Representation of these ecohydrological processes of urban tress into urban canopy models will improve the model capacity in evaluating more accurately the environmental co-benefit of trees as an attractive mitigation strategy for urban climate change.

In addition, it has been found that future urbanization, be it intensification or expansion, leads to more prominent nighttime warming, and reduction of the diurnal temperature ranges. In contrast, most of the current urban mitigation strategies have put more focus on reducing the daily maximum temperature, but largely ignore the nighttime thermodynamics of cities. A famous example is the popular use of reflective materials on roofs (aka white or "cool" roofs), which alleviates urban temperature by reflecting solar radiation during daytime, but remains unserviceable during nighttime in the absence of solar radiation. The findings in this study apparently suggest a shift of paradigm in the current practices of urban mitigation strategies to focus more on infrastructural development that can provide nighttime cooling. This is even more important for cities located in an arid environment are already suffering high UHI intensity, such as Phoenix or Las Vegas where outdoor activities are concentrated during nighttime in hot seasons.

The determination of local and regional climate change due to urbanization in major cities in CRB and their intercomparison provide a perception of necessity for addressing the sustainable urban development. In the energy-water-climate nexus, this study constitutes an important step towards assessing the sustainability of water resource and

the total urban environment. The impact of regional climate changes, not accounted in this study, can be supplied to the projected urbanization in the future in the WRF-urban modeling system, to obtain more realistic results with hydroclimate predictions. In addition, distributed hydrological models should be incorporated with urban energy transport to yield better description of urban water cycle, in particular, the lateral transport of water cross adjacent pixels of WRF-UCM. These studies will provide a solid platform in determination of the transformational solutions for the water sustainability in the CRB region and beyond.

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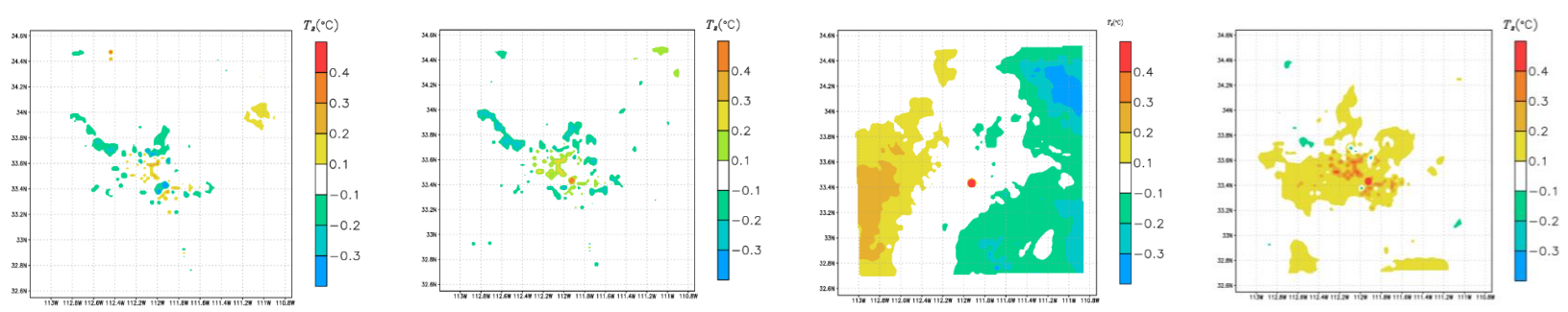
APPENDIX A

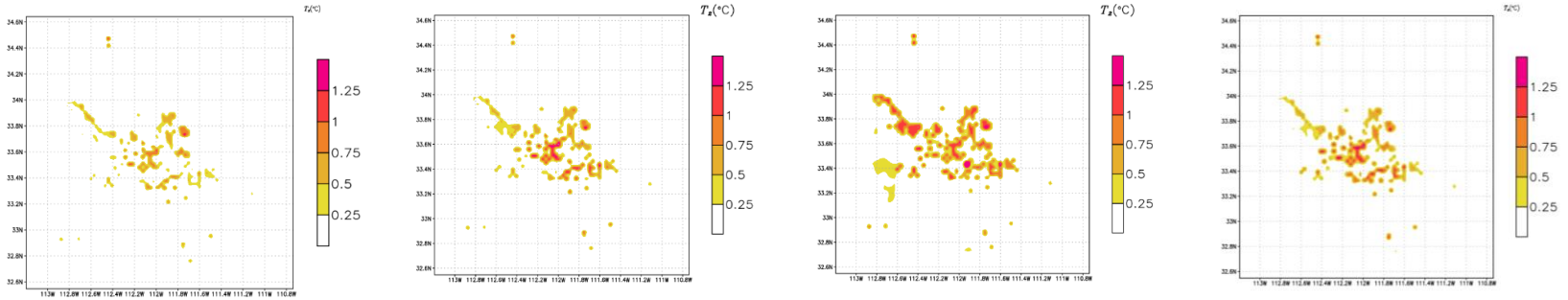
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF 2-M AIR TEMPERATURE FOR ALL SEASONS IN PHOENIX

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

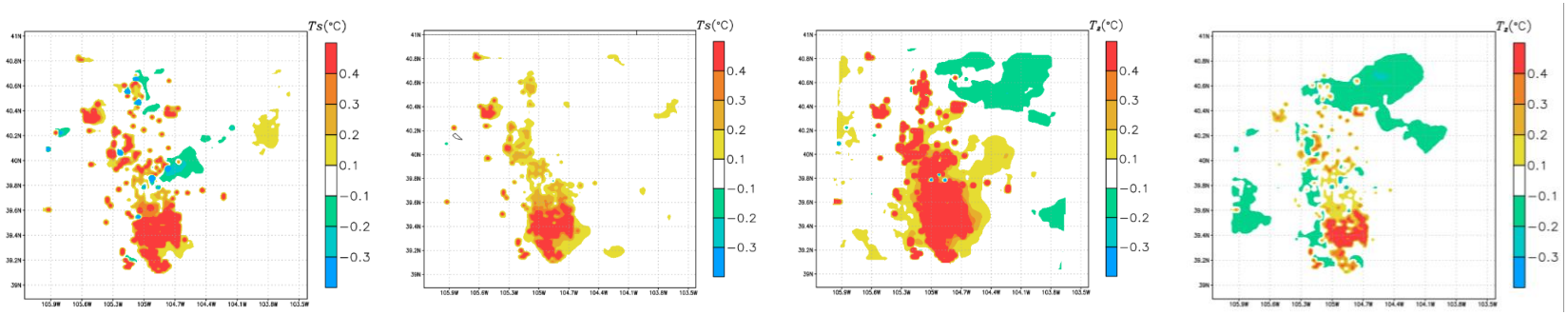


APPENDIX B

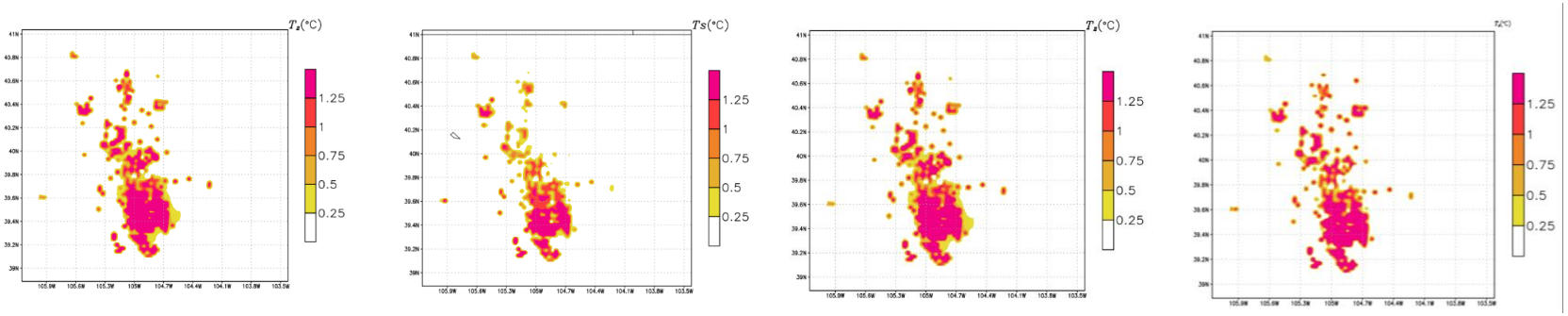
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF 2-M AIR TEMPERATURE FOR ALL SEASONS IN DENVER

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

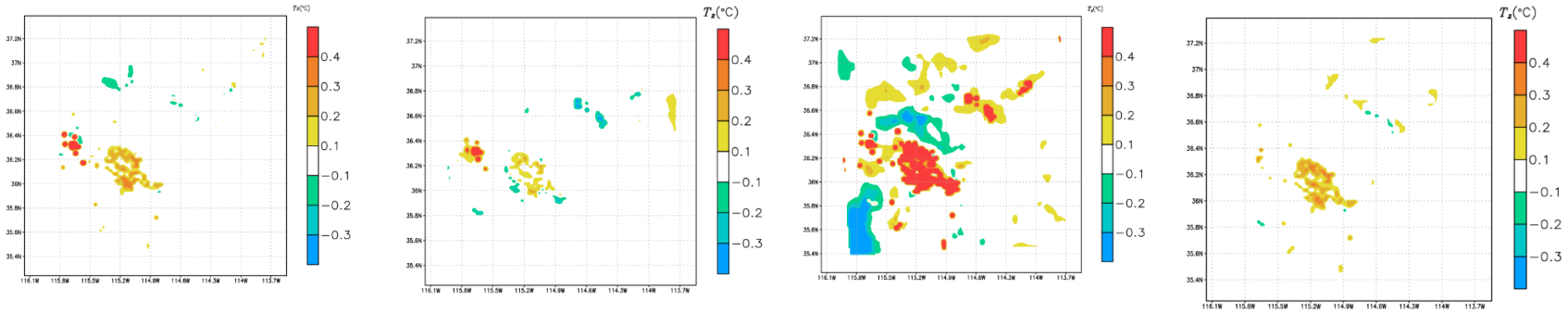


APPENDIX C

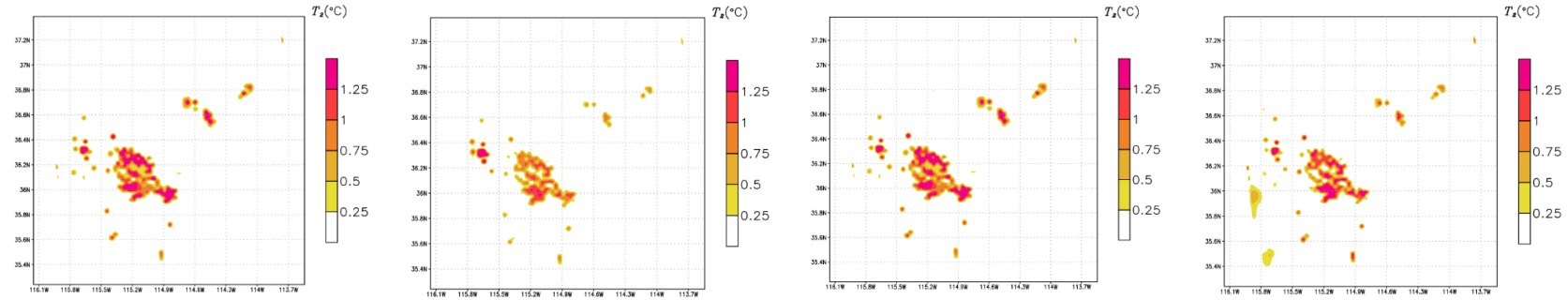
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF 2-M AIR TEMPERATURE FOR ALL SEASONS IN LAS VEGAS

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

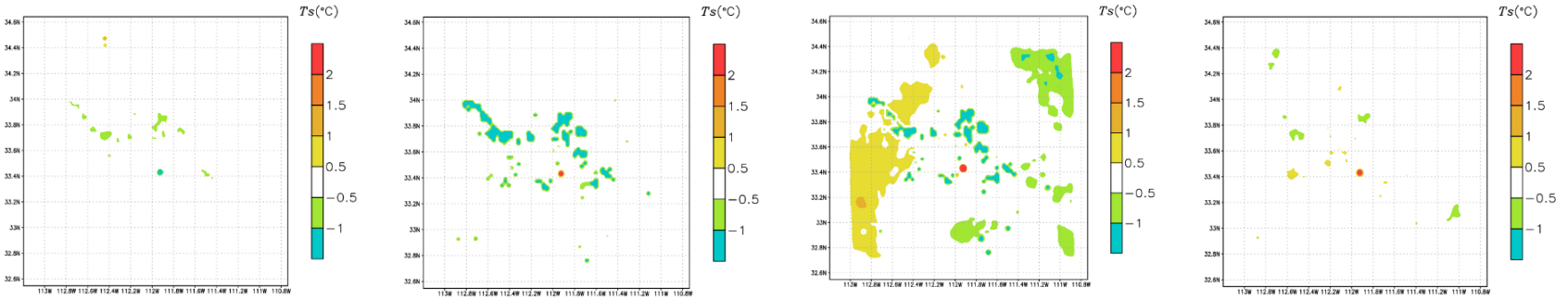


APPENDIX D

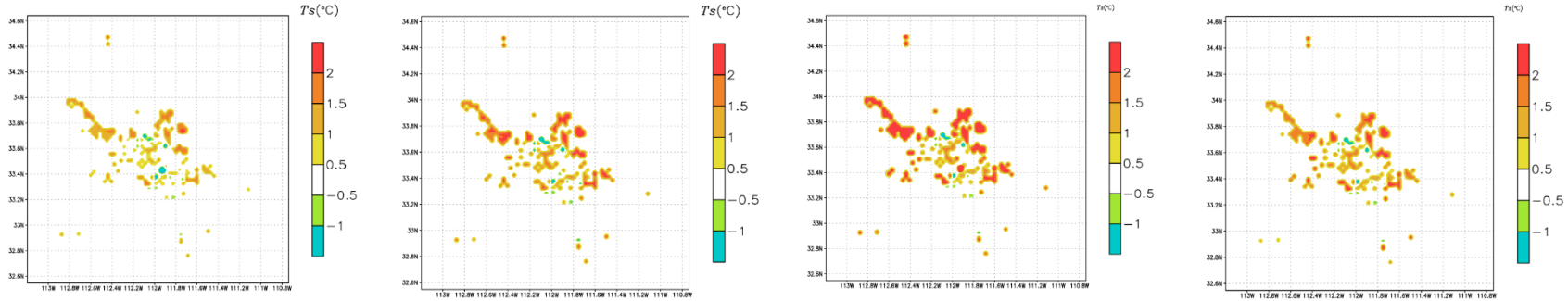
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SURFACE TEMPERATURE FOR ALL SEASONS IN PHOENIX

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

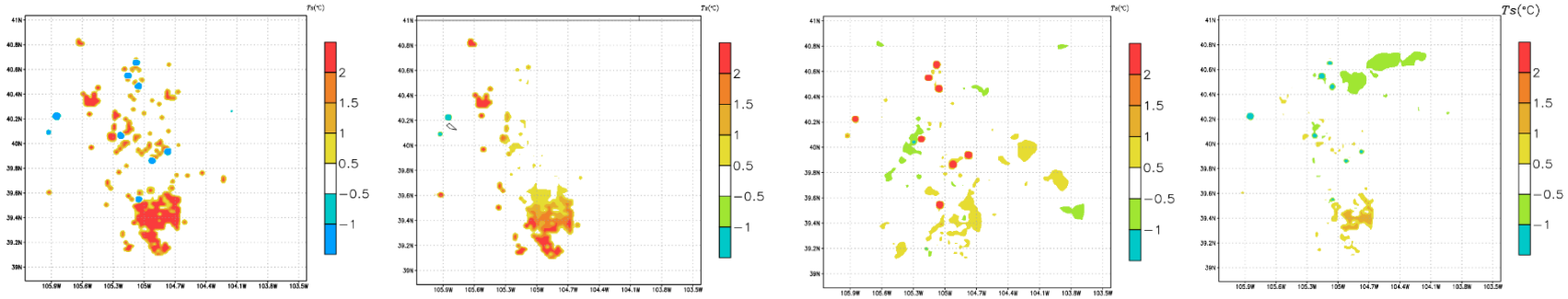


APPENDIX E

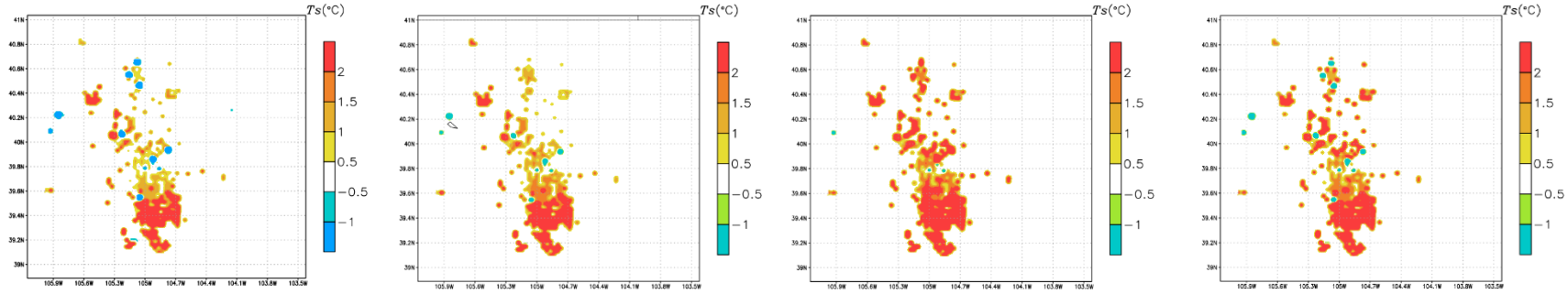
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SURFACE TEMPERATURE FOR ALL SEASONS IN DENVER

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

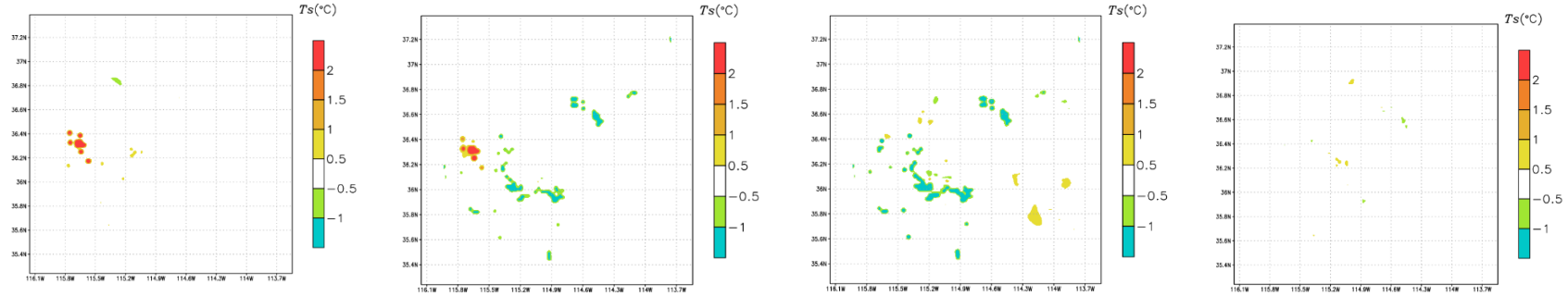


APPENDIX F

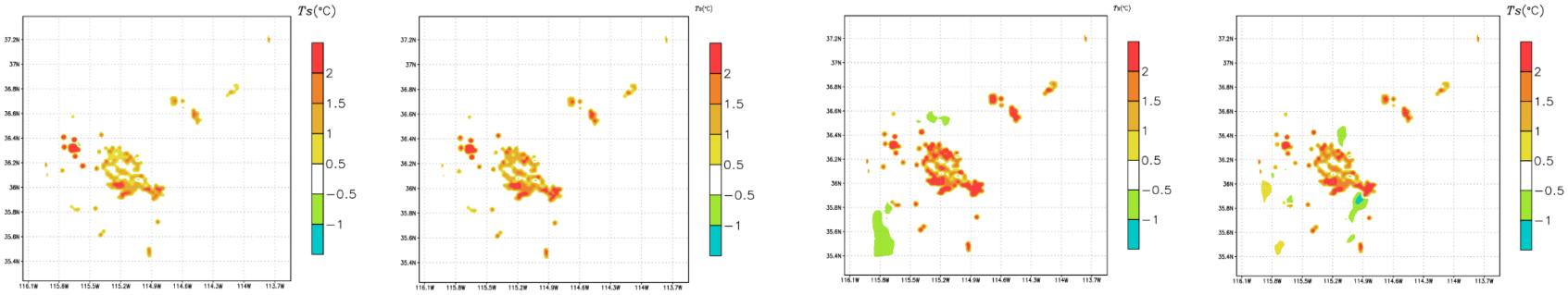
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SURFACE TEMPERATURE FOR ALL SEASONS IN LAS VEGAS

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

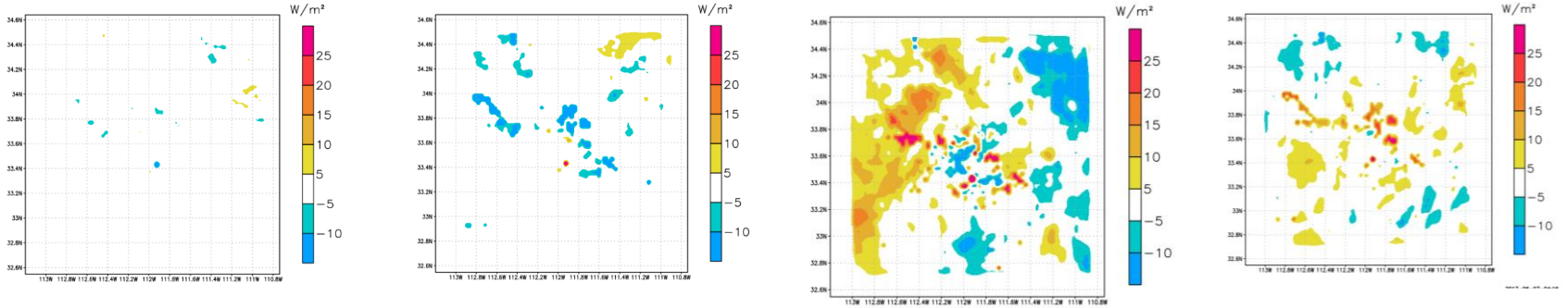


APPENDIX G

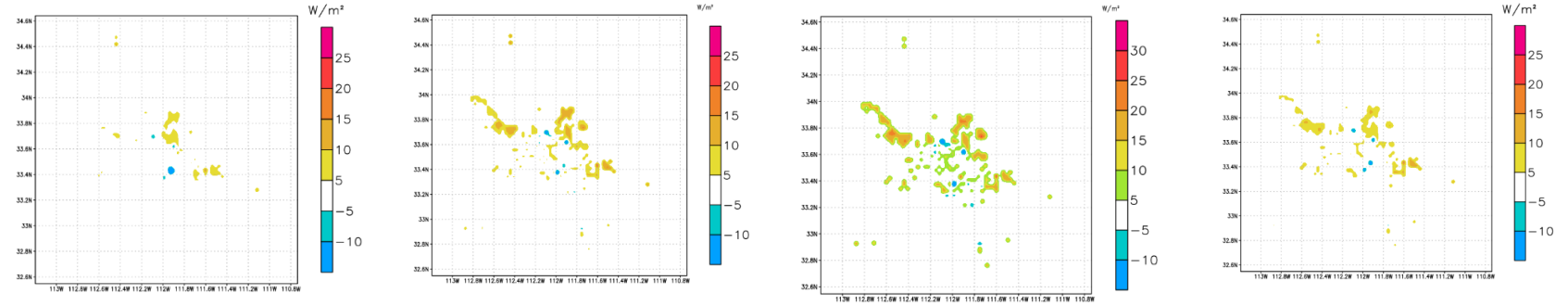
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SENSIBLE HEAT FOR ALL SEASONS IN PHOENIX

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

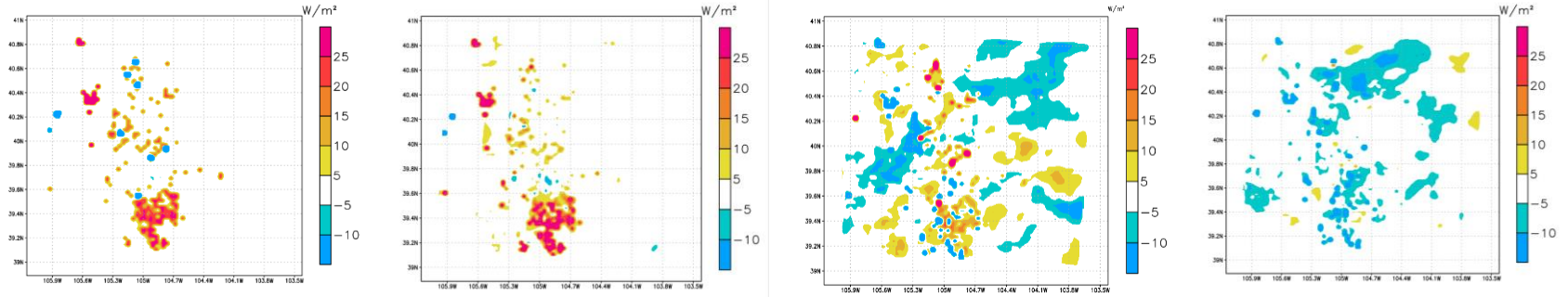


APPENDIX H

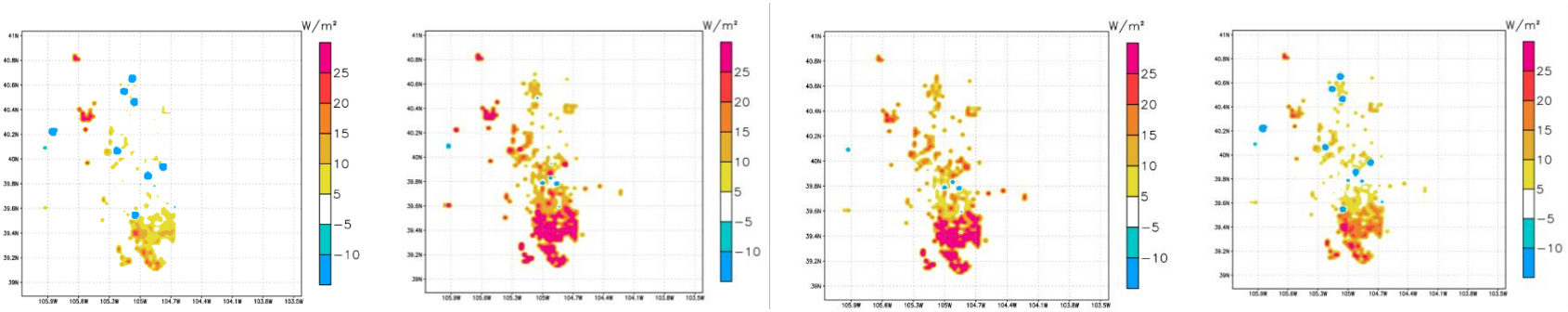
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SENSIBLE HEAT FOR ALL SEASONS IN DENVER

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

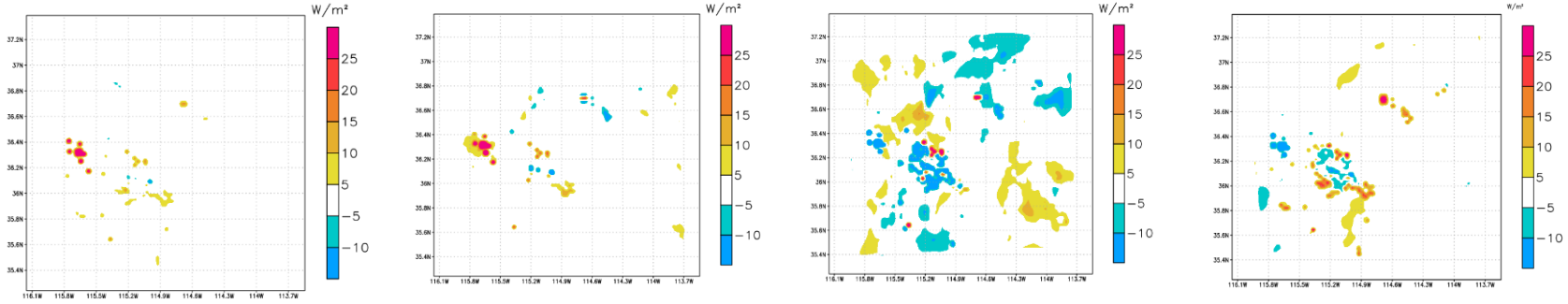


APPENDIX I

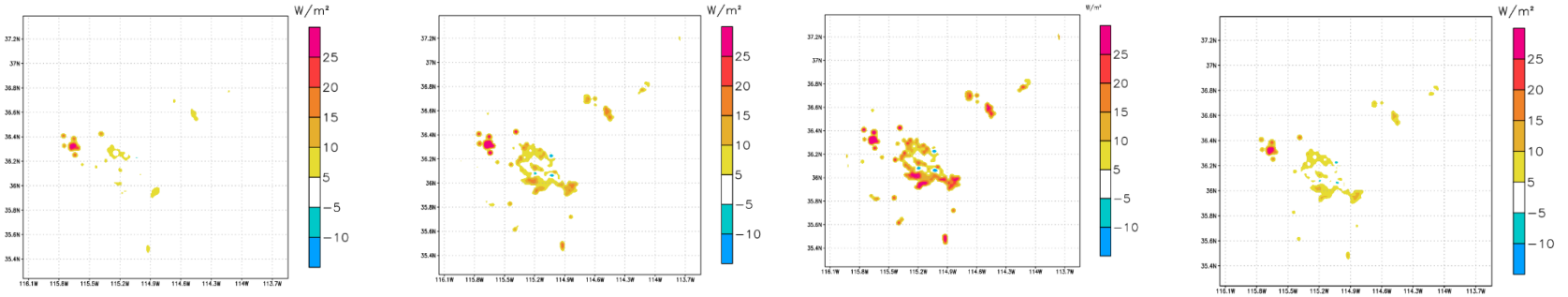
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF SENSIBLE HEAT FOR ALL SEASONS IN LAS VEGAS

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

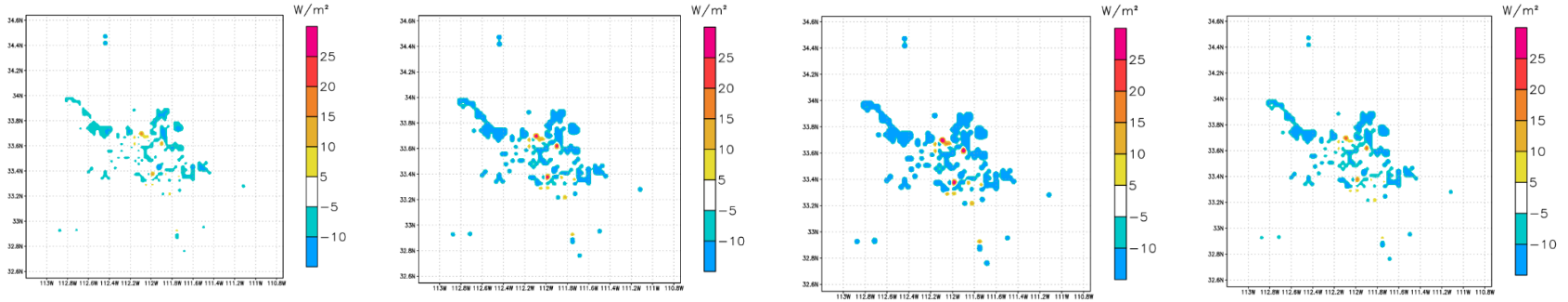


APPENDIX J

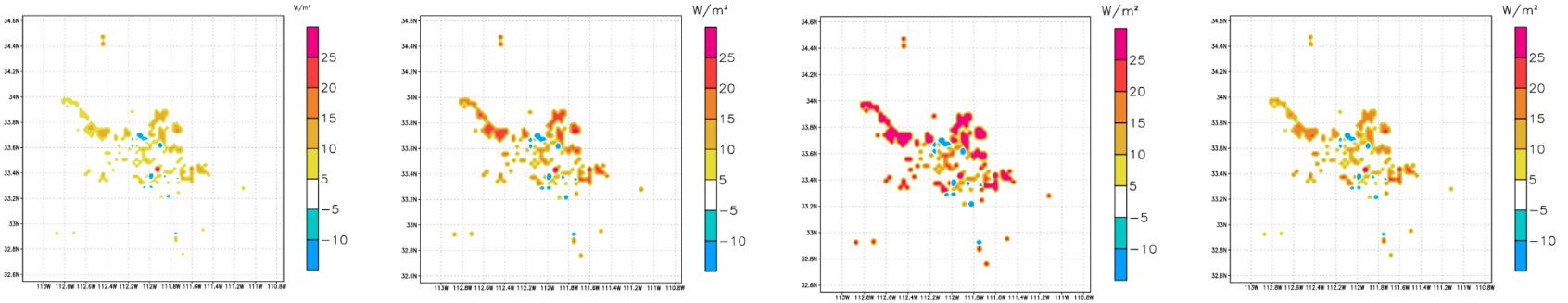
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF GROUND HEAT FOR ALL SEASONS IN PHOENIX

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

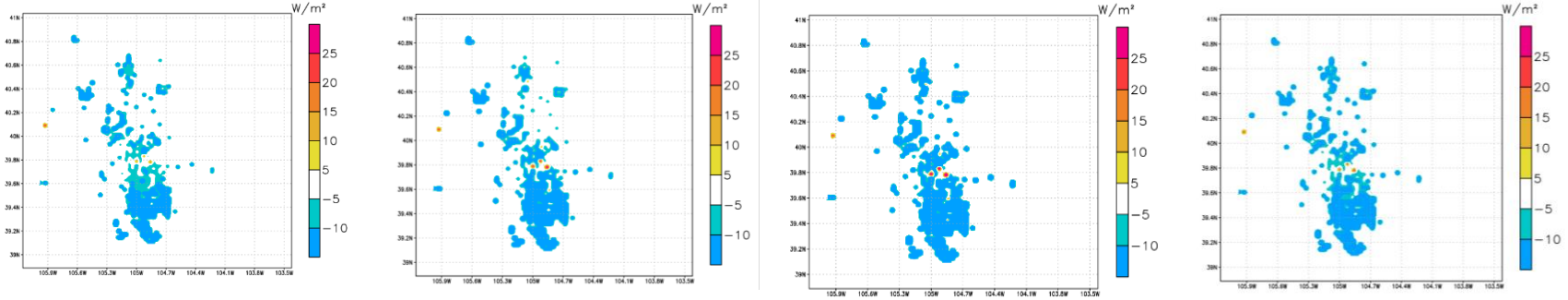


APPENDIX K

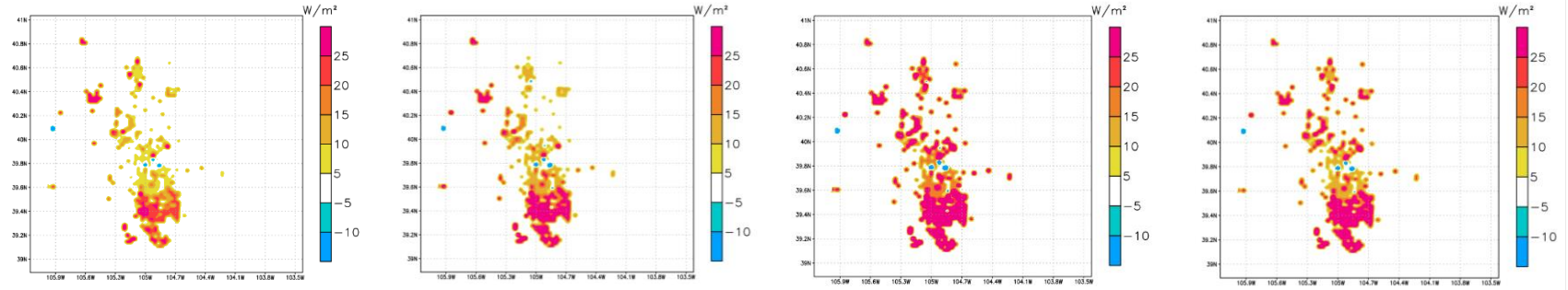
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF GROUND HEAT FOR ALL SEASONS IN DENVER

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

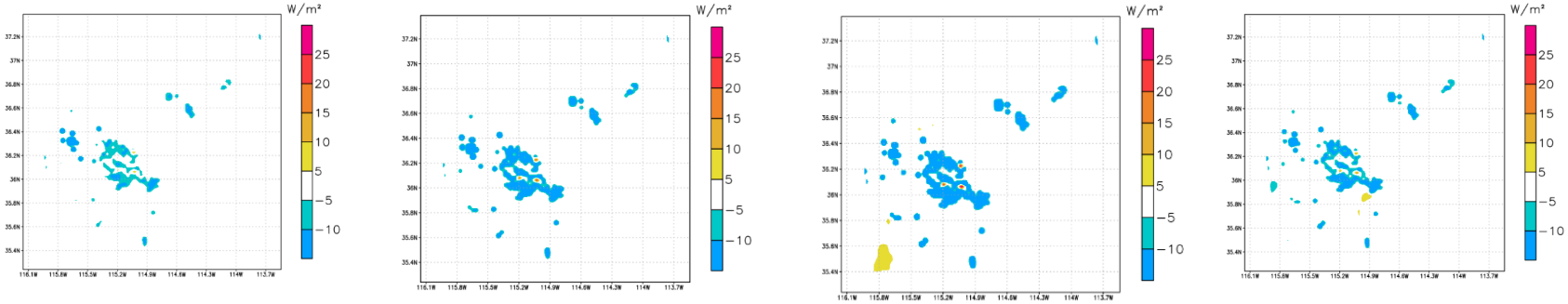


APPENDIX L

SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF GROUND HEAT FOR ALL SEASONS IN LAS VEGAS

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



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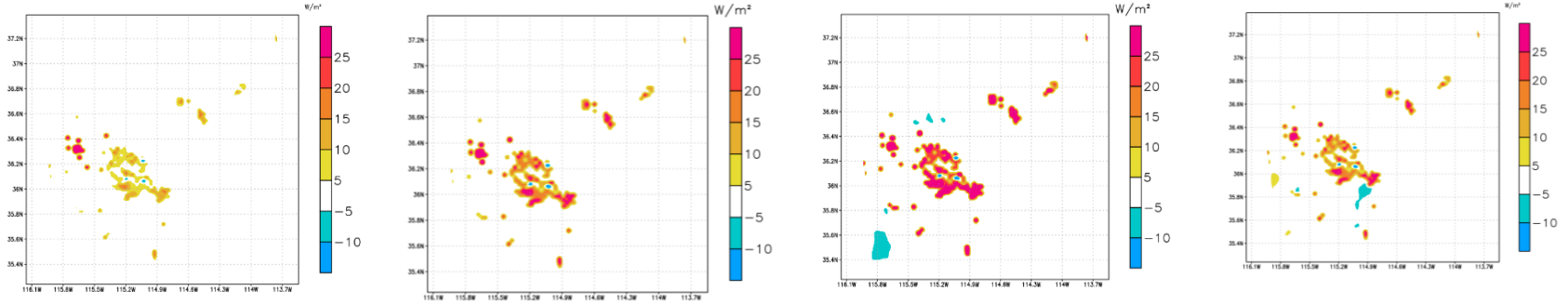
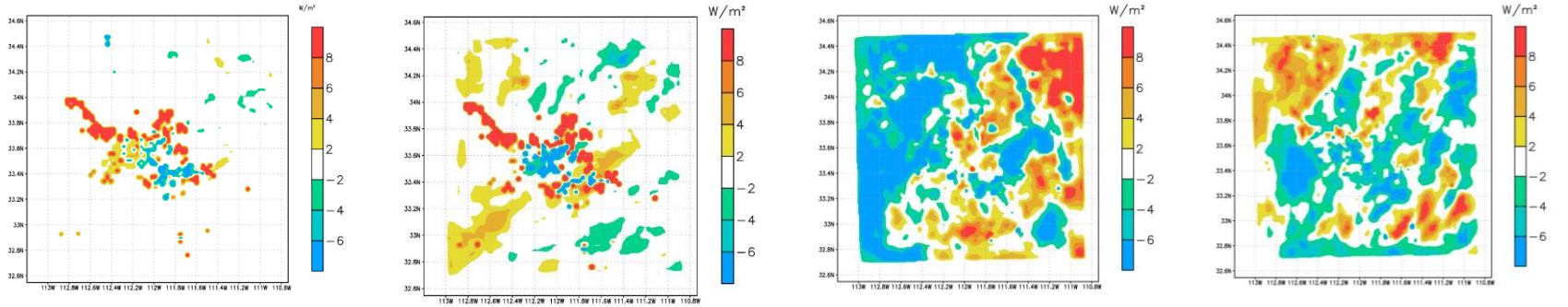


APPENDIX M

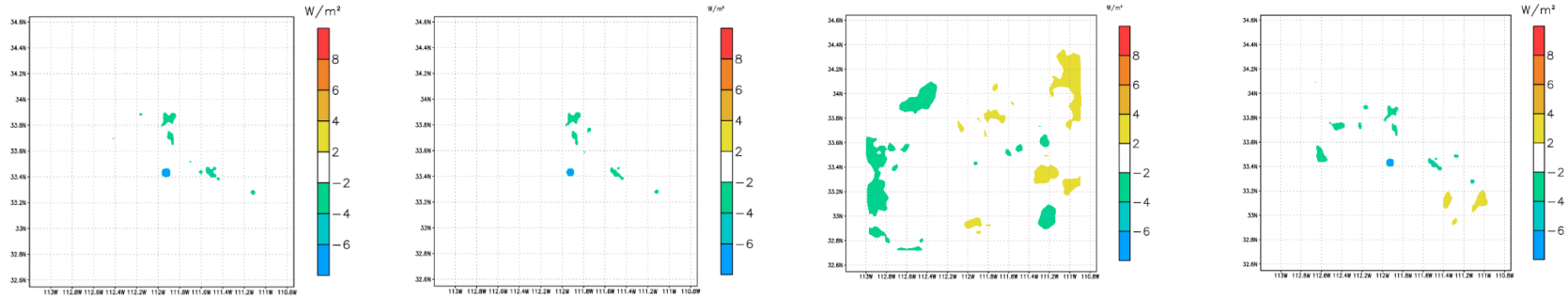
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF LATENT HEAT FOR ALL SEASONS IN PHOENIX

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime

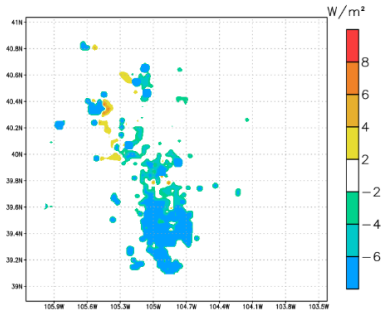


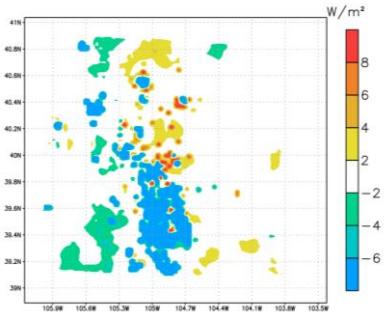
APPENDIX N

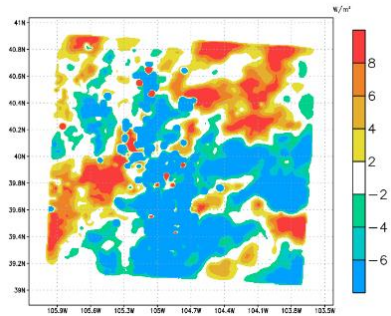
SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF LATENT HEAT FOR ALL SEASONS IN DENVER

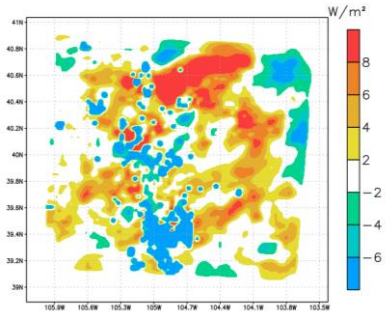
Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime

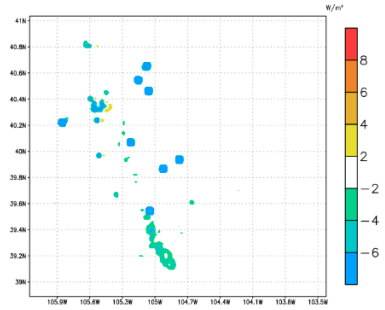


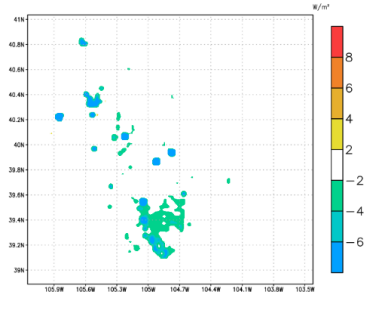


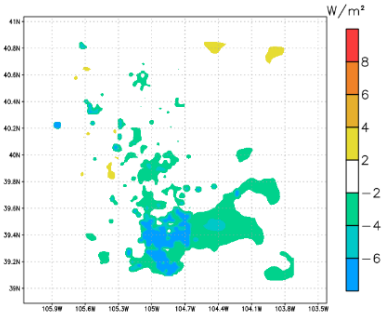


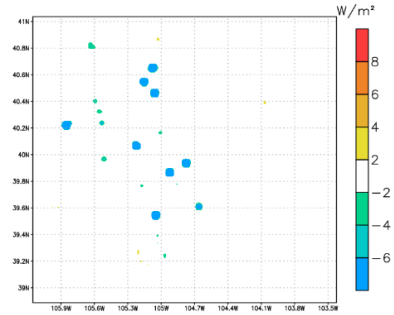


Nighttime







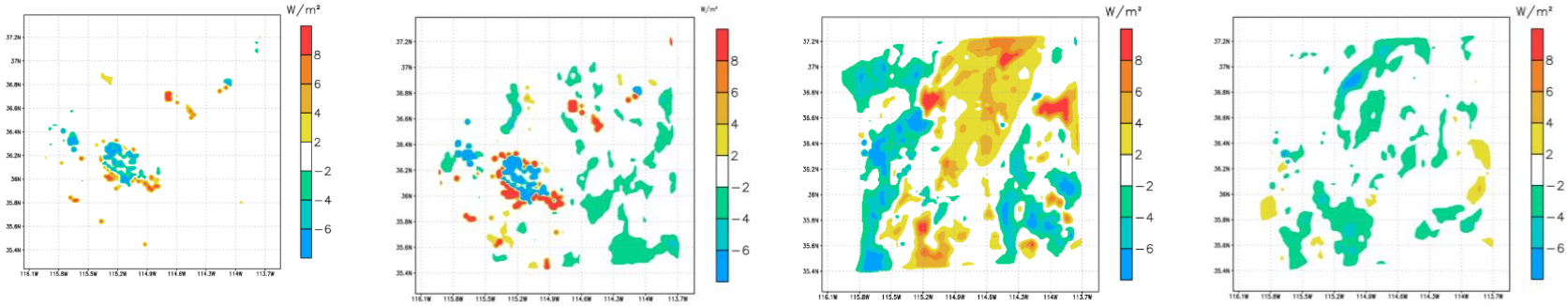
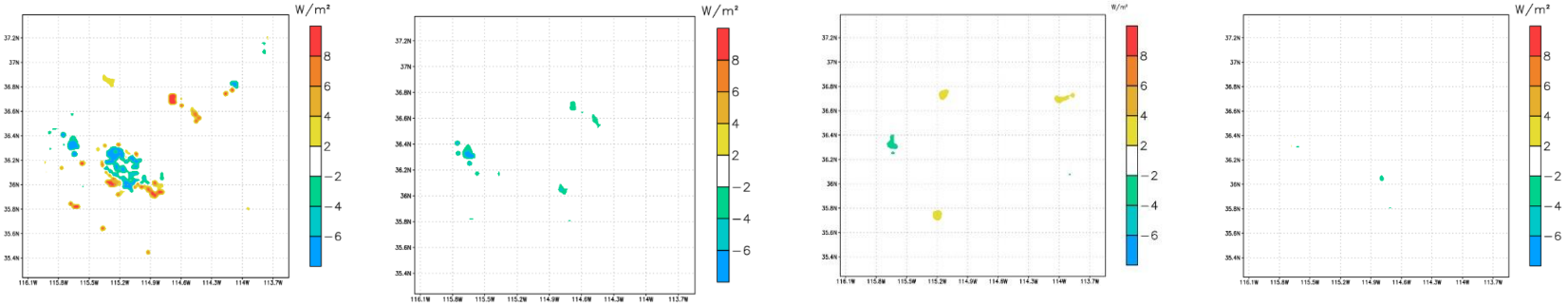


APPENDIX O

SPATIAL DIFFERENCE MAP BETWEEN WRF_2100 AND WRF_CONTROL OF LATENT HEAT FOR ALL SEASONS IN LAS VEGAS

Winter (Dec-Feb) Spring (March-May) Summer (June-Aug) Fall (Sep-Nov)

Daytime



Nighttime