REGIONAL CLIMATE RESPONSE TO LAND USE AND LAND COVER CHANGE IN CONTIGUOUS UNITED STATES

By

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ABSTRACT

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Future land use and land cover (LULC) pattern in the Contiguous United States (CONUS) is expected to be significantly different from that of the present, and as an important surface forcing for earth's climate system, the potential changes in LULC will contribute to climate change at all scales (local, regional to global). While numerous studies have examined how the earth's climate will respond to the anthropogenic increase of greenhouse gas concentrations in the earth's atmosphere, this research aims to quantify the response of several climate variables to the expected LULC change in the CONUS using simulations from a regional climate model. The research is composed of three individual studies. The first study assesses the sensitivity of simulated low-level jet (LLJ) characteristics on changes in LULC pattern. As a prominent weather and climate process responsible for transport of moisture from the Gulf of Mexico northward into central CONUS, LLJ plays an important role in the hydrological cycle and wind energy generation over the Great Plains. Therefore, it is important to quantify the potential changes in jet characteristics, such as jet speed, height and frequency, under the influence of LULC change. The second study investigates the impact of LULC change on frost indices - the dates of last spring frost and first fall frost and the length of frost free seasons. Frost is one of the major factors affecting the growth and development of plants and crop production. Future changes in LULC could make some regions more beneficial, while others more harmful to agricultural practice. Finally, the third study examines the potential impact of the changes in LULC pattern on future wind energy resources.

As a zero carbon energy resource, wind energy helps limit greenhouse gasses emissions and mitigate climate change. Knowledge gained on where in the CONUS wind power class would likely to change from unsuitable or marginal to suitable, and vice versa, as a result of LULC change can be useful for future wind farm sitting and for making better informed energy policies.

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Chapter 1 Introduction and Background

1.1 Introduction

Land use land cover change (LULCC) has long been recognized as one of the important drivers for climate change besides the primary forcing of the increasing greenhouse gas (GHG) emissions (Pielke 2005). The relationship between LULCC and climate is complex and reciprocal, covering multiple spatial and temporal scales. LULCC is included, either implicitly or explicitly, in climate modeling systems used for future climate projections (Betts et al. 2015). LULCC can be caused by both natural and anthropogenic factors and its impact on environment can occur on multiple spatial and time scales. While natural forces are shaping LULCC for thousands and millions of years, human-induced LULCC is recognized as a main driver in recent history and is considered dominant forcing for future changes in land use land cover (LULC) pattern. LULCC occurring at local scale, such as urban sprawl, may result in loss of natural land, giving rise to local changes in temperature, convective precipitation and surface wind patterns (Hale et al. 2006, Kalnay and Cai 2003, Xue 1997, Wu et al. 2016). On a larger scale, LULCC can increase or decrease not only the amount of carbon dioxide (CO_2) stored in both biomass and soil (Schimel 1995), but also surface albedo (Betts 2000, Myhre and Myhre 2003, Niyogi et al. 2010). The changes in surface albedo have a direct effect on surface energy budget that, through land-atmosphere interactions, may alter regional and global atmospheric circulation patterns (Myhre and Myhre 2003). On the other hand, climate change will undoubtedly have an impact on both local and regional land use practices. For example, changes in frequency and intensity of drought due to climate change may result in abandonment or enhancement in irrigation of agricultural land in some areas (Zhang et al. 2015, Zhang et al. 2016). Drought may also result in die off of certain crops and make forest management much more challenging (Vose et al. 2016). Prolonged drought may increase wildland fires, as seen during the 2019-2020 fire season that burned over 18 million hectares in Australia (Boer et al. 2020). On the other end of the spectrum, climate change can result in an increase in growing season length and thus an increase in crop production in high latitude regions (Peltonen-Sainio et al. 2009).

The relationship between LULCC and climate is complex. While LULCC is recognized as an important driver for local and regional climate change, research on regional climate change has been focused primarily on the effects of increasing GHG emissions. Although LULCC is factored into some of the projected scenarios of the GHG emissions, direct contributions of LULCC to regional climate change are yet to be fully assessed. The current research is aimed at isolating potential changes in regional climate induced by LULCC with a focus on processes important to the economy of the United States, particularly, agriculture, water resources, and renewable energy. Specifically, the current research will investigate what would happen to these processes and climate variables in regions of the United States if the current LULC pattern is replaced by the future pattern projected for the end of the century while holding other conditions steady.

1.2 **Research Goal and Objectives**

The overarching goal of the current research is to *assess potential changes in processes and climate variables important to the economy of the United States, particularly, agriculture, water resources, and renewable energy, if only LULC will be changed from the current pattern to the projected future pattern by the end of the century*.

Three processes, as well as climate variables related to those processes, will be examined, including the *low-level jets (LLJs)*, *frost indices*, and *wind energy resources*. The LLJ, defined as a strong wind in the lower troposphere, is one of the most pronounced weather and climate phenomena in the central United States and its influence extends from agriculture (via its influence on moisture transport and precipitation), wind resources, to air pollution, bird migration, and transportation. Changes in the LLJ frequency and intensity will have a significant effect on all of these sectors. Frost, especially earlier spring frost, can cause severe damages to crop, and the length of frost free season is directly related to growing season. Changes in the pattern of spring frost and frost free season length have a direct impact on agricultural production. Wind energy is a major component of renewable energy and understanding potential changes in wind energy resources will help assess economic potential of wind farms and make more reliable energy policy in the future.

The central hypothesis is that *LULCC will result in statistically significant changes in the characteristics of LLJ, spring frost and frost free season length as well as wind resources in the United States, but the direction of the change and the magnitude of the change will vary with region and, in the case of LLJ and wind energy, with season*.

The research will attempt to answer the following questions:

- How would LLJ characteristics respond to the potential changes of LULC from the current pattern to the pattern projected for the end of the century?
    - Will future LLJs become more or less frequent, stronger or weaker and occurring at higher or lower elevation?
    - Will the LULCC-induced changes in the frequency of jet occurrence, jet intensity and jet elevation depend on region?
    - Will there be a diurnal or seasonal dependence of the changes in jet characteristics?

    - What is the relationship between the specific changes in LULC and the changes in jet characteristics?
- How would transition from current to the future LULC pattern affect frost indices?
    - Will LULCC advance or delay the onset of the last spring and first fall frost?
    - How will the changes in the dates of the last fall frost and first spring frost alter frost free season length? What is the relationship between local and regional changes in LULC and changes in frost indices?
    - Are there regions particularly vulnerable to the LULCC-induced changes in frost indices?
- How much near-surface wind climatology will be modified by LULCC and what is the implication to wind energy resources in the United States?
    - Will future wind speed increase or decrease in magnitude under changing LULC pattern?
    - Is there a seasonal dependence of LULCC-induced wind speed change?
    - What is the relationship between wind speed change and the underlying LULCC?
    - Will the changes in wind speed lead to changes in wind energy classes?

1.3 **Background Research**

Even though it is known that LULCC will affect the earth's climate by modifying both the physical and biophysical characteristics of the earth's surface (e.g., albedo, emissivity, soil moisture, evapotranspiration and surface roughness), it is still unclear how much LULCC contributes to overall changes in regional climate, posing additional uncertainty in future climate projections and impact studies. While the central goal of this research is to assess impact of LULCC on regional climate change simulations over the continental United States, the research will also explore the complex relationship and issues involved in land-surface-atmosphere interactions.

This research is carried out in three separate studies under the central theme of assessing regional climate response to changes in LULC between the current and the end of the century patterns over the contiguous United States. The first study focuses on the responses of LLJ frequency, intensity and elevation; the second examines the shifts in the dates of last spring frosts and first fall frost as well as the frost-free season length; and the third study assesses the potential changes in modern wind turbine level winds and wind energy density.

1.3.1. Low Level Jet

Due to friction from earth's surface, winds in the atmosphere normally increase with altitude to reach a maximum near the tropopause between 8 to 14 km above earth's surface (Stull 2000). This upper-level wind maximum, known as jet stream, plays an important role in the development of mid-latitude cyclones that affect much of the United States, especially in the cold seasons. Under certain conditions, however, wind speed may also peak within the so-called planetary boundary layer (PBL) – the lowest 1-3 km of the atmosphere that is directly influenced by the planetary earth (Stull 2000). This wind maximum in the PBL is called the Low-Level-Jet (LLJ), as opposed to the upper-level jet stream. Although not as prevalent as its upper-level counterpart, LLJ is frequently observed in different regions of the world, including South America (Marengo et al. 2004, Vera et al. 2006), the Caribbean (Amador 2008, Hidalgo et al. 2015), West Africa (Grodsky et al. 2003, Pu and Cook 2010, 2012), Southeast Asia (Joseph and Raman 1966, Findlater 1969) and North America (Bonner 1968, Arritt et al. 1997, Higgins et al. 1997, Ting and Wang 2006, Weaver and Nigam 2011). In the United States, LLJ is perhaps one of the most prominent weather phenomena over the Great Plains, as it contributes greatly to moisture transport, nocturnal precipitation (Pitchford and London 1962; Bonner 1968), insect migration (Arritt et al. 1997), fire spread (Sjostedt et al. 1990) and wind resources (Gutierrez et al. 2017).

Various physical mechanisms have been proposed to explain the formation of LLJ, including differential heating over sloping terrain (Holton 1967), inertial oscillation near the top of a stable nocturnal PBL (Blackadar 1957), and deformation frontogenesis (Blumen 1997). Parish and Oolman (2010) used a numerical model to examine the relationship between LLJ formation and topography. They found that heating over sloping terrain leads to stronger LLJ in their simulations. Zhong et al. (1996) analyzed a strong LLJ episode over the Great Plains, and by combining hourly wind profiler observations and numerical modeling, their study revealed that differential heating over sloping terrain played a secondary role in the LLJ formation compared to inertial oscillations. In addition, they found that soil moisture has an impact to jet characteristics, with drier soil corresponding to stronger jet speed oscillations and wet soil associated with stronger rising motion downstream of the jet core. Relationship between soil moisture and LLJ characteristics was also investigated by Fast and McCorcle (1990) that revealed high sensitivity of jet characteristics to small changes in soil moisture content and distribution. Arcand et al. (2019) used the Weather Research and Forecasting (WRF) model simulations incorporated with realistic irrigation, to investigate impact of irrigation on LLJ characteristics. They found an increase to LLJ speeds in the simulation, decrease in jet core height and overall slight increase in jet frequency when irrigation was present.

Climatological studies of LLJ dated back to the classic study of Bonner (1968) who used

2-year twice-daily wind data from 47 rawinsonde stations to create the first LLJ climatology. Whiteman et al. (1997) analyzed 2-year high vertical and temporal resolution observations in the jet core area, north-central Oklahoma, providing more detailed climatology of southerly LLJs. Using 40-year rawinsonde wind observations, Walters et al. (2008) provided a long-term climatology of jet characteristics, such as jet frequency, direction, speed and elevation for the central United States. In a later study, Walters et al. (2014) compared southerly LLJs identified from a gridded reanalysis dataset -the North American Regional Reanalysis (NARR, Mesinger et al. 2006) with those derived from rawinsonde wind observations in the central United states and found generally good agreement with NARR only slightly underestimating LLJ frequency. Doubler et al. (2015) used NARR to develop a jet climatology for North America continent and surrounding oceans. This study found good agreement with previous studies using only observations, but provided more details in spatial and temporal variations of jet characteristics. Tang et al. (2017) compared the North American Regional Climate Change Assessment Program (NARCCAP) regional climate model (RCM) ensemble of future climate scenarios with available rawinsonde observations in order to investigate RCM's capability to capture LLJ climatology and project possible future change. The RCMs simulated an increase in the jet frequency for nighttime jets in the southern Great Plains in spring and in the central Great Plains in summer, while RCM simulations showed little to no change for daytime jets and cool-season jet frequency.

Because future climate change over the United States can be to a large extend explained by changes in LULC, in first study presented here, we are exploring possible impact of LULCC on LLJ characteristics. LULCC plays important role in the interchange of energy and water between the land surface and atmosphere, affecting regional weather phenomena such as LLJ, and to our knowledge, no study has looked at direct impact of expected LULCC on LLJ characteristics over the United States.

1.3.2. Frost Indices

Food production is correlated to the plant's sensitivity to frost events, so timing of frost occurrence and frost free period are crucial factors for crop growth. Frost free season (FFS), defined as a period between last spring frost (LSF) and first fall frost (FFF) over some region, is an important parameter for determining crop production and agricultural practices. Numerous studies, both observational and modeling, have reported an increasing trend in FFS length in recent decades over many regions around the globe (Kunkel et al. 2004, Anandhi et al. 2013, McCabe et al. 2015, Zhong et al. 2017, Kukal and Irmak 2018). Length of FFS is dependent on several factors, such as geographic location (Menzel et al. 2003, Ning et al. 2017), regional characteristics (Anandhi et al. 2013, Walsh et al. 2014, Li et al. 2017, Zhong et al. 2017) and is directly dependent on changes in the occurrence of the dates of LSF and FFF. Length of FFS follows changes in surface temperature trends, especially those in minimum temperature. Projected increase in surface temperature as a result of climate change will likely affect and modify FFS length in many regions (Easterling et al. 1997, Karl et al. 1993, Vose et al. 2005, Li et al. 2017). Kukal and Irmak (2018) explored change in frost indices in the United States by looking at temperature measurements from 1218 stations over 115 years, and found an average increase in frost free season of 12 days, with LSF occurring earlier by approximately 7 days and FFF occurring later by 5 days. In addition to temperature increase as a response to increasing GHG concentrations, LULCC will also have an impact on surface temperature. Limited number of studies have looked at the impact of LULCC on surface temperature trends. Using available observations, Fall et al. (2010) examined historical trends in temperature change as a response to LULCC over the United States, and found a warming trend associated with urban expansion, and a cooling trend related to expansion of cropland. Similar results are found by several numerical studies (Bonan 1997, Li et al. 2017). Li et al. (2017) looked at 121 years available observations record and found that change in FFS lengths depends on regional characteristics. Shangqian et al. (2019) used daily minimum temperature data recorded at meteorological stations in Gansu province, China, to investigate frost trends, and found changes in frost free season lengthening is mainly result of the delay of the first frost date and the advancing of the last frost date.

Expected future changes in temperature will have substantial implications to frost free season length and agricultural productivity. Comprehensive understanding of future change in frost free season is necessary to protect regional and local crops and local changes in LULC will have a significant impact to those future changes. Second study presented here is trying to assess impact of LULCC to future regional and local changes in frost free season length, providing additional input for future climate change assessment studies.

1.3.3. Wind Energy

As one of the major zero-carbon-emission energy production resources, wind energy plays a key role in climate change mitigation efforts. Familiarity with both past and possible future changes in wind patterns has implications to a number of socio-economic sectors. Numerous studies around the globe have found wind stilling over last several decades. In Europe, Wever (2012) analyzed impact of change in surface roughness on wind speed and found a negative correlation between surface roughness and wind speed. Use of theoretical PBL model showed that 70% of the wind speed change can be explained by changes in surface roughness lengths. To understand anthropogenic land use change impact on wind energy resources in China, Li et al.

(2008) analyzed the differences between wind observations at 604 surface stations and the NCEP/NCAR reanalysis data for the period between 1960 and 1999, and found that the impact of land use change on wind speed decline is of equal magnitude as observed climate change. Similar results are found in a study done by Zha et al. (2016) and Wu et al. (2016). Zha et al. (2016) compared surface wind speed from 492 stations to the European Centre for Medium-Range Weather Forecasts reanalysis (ERA-Interim) in order to distinguish natural climate change from anthropogenic LULCC impact on climate, and found a decrease in wind speed of 0.12 ms^{-1} per decade as a result of urban expansion. Wu et al. (2016) compared ERA-Interim and available observations over the Eastern China Plain and found a decrease of 10-m wind speed of 0.17 m $s^{-}1$ per 10-year, with future 10% increase in urbanization resulting in 0.12 m $s^{-}1$ decrease in wind speed. A comprehensive study of wind speed in the United States was carried out by Pryor et al. (2009), where two observational data sets, four reanalysis data sets, and outputs from two regional climate models (RCMs) are compared. Their results indicate the presence of an overall declining trend in mean wind speed over the continental United States in two observational data sets for the 1973-2005 period. Same declining trend in mean annual wind speed is partially reproduced by one of two RCMs. Other data sets experience great variability in sign of the mean wind speed change over the United States for the studied time span. In spite of the disagreement in the magnitude and sign of wind speed changes over some regions, both RCMs show some degree of skill in simulating the mean wind speed across the United States when compared with in situ observations. Later studies also confirmed RCMs' capability in simulating wind speed (Pryor and Barthelmie 2011).

Wind speeds vary on various scales, and the variations are dependent on large-scale circulation, surface energy fluxes, and topography; therefore, wind forecast on higher spatial resolution (Rasmussen et al. 2011), especially when used for application for wind energy production, is necessary. Rassmusen et al. (2011) looked at wind speed simulations for three specific locations in California and found that while spatial wind patterns simulated by RCMs in NARCCAP are in good agreement with those derived from NARR, RCM simulations at three sites show that annual average wind speed change differs across models and magnitude and sign of change vary across locations, posing additional uncertainty in future projections of wind energy potentials. Based on the analysis by Lu et al. (2009) using the Goddard Earth Observing System Model Version 5 (GEOS-5) wind outputs, wind energy potential for the United States reaches its maximum in winter and minimum in summer, opposite to the current maximum demand. In the future, the influence of climate change from GHG and LULCC is likely to increase wind resources in certain regions while reduce wind energy production potential in other regions. Given that wind energy density is proportional to the cube of wind speed, small changes in wind speed can result in significant changes in wind energy density, and therefore, wind energy production.

While wind stilling is observed in many regions around the world, and is expected to continue in the future, little clear explanation is given for certain regions in the world for this phenomena that poses concern for wind energy production. Third study presented here aims to provide insight in impact of expected future LULCC on future wind resources over the United States, providing additional input for future wind farm infrastructure development.

1.4 **Dissertation Structure**

The rest of the dissertation is organized into four chapters. Chapter 2, 3, 4, each presents a manuscript describing the study on the impact of LULCC on LLJ characterizes, frost indices and wind energy resources, respectively. The manuscript in Chapter 2 discusses impact of LULCC on LLJ characteristics (published in the journal, Atmosphere 2019, 10, 174;

doi:10.3390/atmos10040174). In Chapter 3, study evaluates impact of future expected changes in LULC on frost indices (submitted to the Annals of the America Association of Geographers, AN-2019-1297 and the initial reviews asked for a moderate to major revision; the manuscript is currently being revised). The manuscript in Chapter 4 investigates impact of LULCC on future availability of wind energy resources in the continental United States (manuscript is going through internal review and is expected to be submitted to a peer reviewed journal after that process). Finally, Chapter 5 summarizes major findings from Chapters 2-4, discusses the contributions of the current work and outlines future research.

Chapter 2 Sensitivity of Low-Level Jets to Land-Use and Land-Cover Change over the Continental U.S.

In collaboration with
Shiyuan Zhong, Lisi Pei, Xindi Bian, Warren E. Heilman and Joseph J. Charney

Abstract: Lower-tropospheric wind maxima, known as low-level jets (LLJs), play a vital role in weather and climate around the world. In this study, two 10-year (2006–2015) regional climate simulations using current (2011) and future (2100) land-use/land-cover (LULC) patterns over the continental United States (CONUS) are used to assess the sensitivity of LLJ properties, including jet occurrence, maximum speed, and the elevation of the maximum, to changes in LULC. The three simulated LLJ properties exhibit greater sensitivity in summer than in winter. Summertime jets are projected to increase in frequency in the central CONUS, where cropland replaces grassland, and decrease in parts of the Ohio-River Valley and the Southeast, particularly Florida, where urban expansion occurs. Little change is projected for wintertime jet frequency. Larger modifications to jet speed and elevations are projected in parts of the Ohio River Valley, the upper Southeast, and the Intermountain West. While there is some evidence of weaker, more elevated jets with urban expansion, the connection between changes in jet speed and elevation and changes in LULC patterns at a given location is weak. This result suggests that LULC will primarily affect the large-scale atmospheric conditions that contribute to the formation of LLJs, particularly in winter.

2.1 Introduction

A low-level jet (LLJ) is a lower-tropospheric wind maximum, as opposed to its counterpart near the top of the troposphere, which is commonly referred to as the jet stream (Blackadar 1957). While LLJs have been observed globally, the most prominent (Bonner 1968, Doubler et al. 2015) and documented LLJs are found over the Great Plains of the central U.S. In the warm seasons, these Great Plains LLJs are responsible for the transport of warm, moist air from the Gulf of Mexico into the central U.S. and for contributing to the formation of thunderstorms and heavy precipitation in the region (Means 1954, Pitchford and London 1962, Arritt et al. 1997). In the cold seasons, LLJs bring cold and dry air from Canada into the Great Plains (Kapela et al. 1995) that can lead to excessively dry winters and more severe wildfires in the following spring seasons in the southern Great Plains (Swetnam and Betancourt 1998). In addition to impacts on weather and climate, LLJs over the Great Plains are an important resource for wind energy in the region even though the phenomenon can generate turbulence that affects life span and efficiency of wind turbines (Banta et al. 2008).

While dynamical features in the upper atmosphere, such as the jet stream, have been found to contribute to their formation (Uccellini 1980), Great Plains LLJs are driven predominantly by diurnal oscillations in the lower planetary boundary layer; in particular, inertial oscillations due to a decoupling of surface friction from layers aloft, and thermal oscillations over sloping terrain. Consequently, changes in surface conditions are expected to modify the characteristics of LLJs. A number of studies have investigated how surface conditions, such as topography, vegetation, soil type, and soil moisture, might affect the characteristics of LLJs. Zhong et al. (1996) carried out a case study of a widespread LLJ episode over the Great Plains using hourly wind profiler data from 31 stations across the Plains and a high resolution numerical model. Their results suggested that diurnal thermal oscillations over sloping terrain played a secondary role in driving the LLJ case compared to inertial oscillations. Their results also indicated that drier soil tends to increase the amplitude of diurnal jet speed oscillations while wet soil appears to be associated with stronger rising motion downstream of the jet core. A study about the effect of soil moisture on LLJs was carried out by Fast and McCorcle (1990) using a two-dimensional atmospheric model linked with a hydrology model. They found that simulated jet characteristics exhibit a strong sensitivity to small changes in soil moisture content and distribution and, to a lesser extent, to changes in soil type. Parish and Oolman (2010) used the Weather Research and Forecasting Nonhydrostatic Mesoscale Model (WRF-NMM) to examine the importance of topography on LLJ formation and found that heating over sloping terrain leads to stronger background geostrophic flow that contributes to maximum simulated LLJs over the Great Plains through the inertial oscillation mechanism following the decoupling of the frictional layer from the free atmosphere above. Recently, Arcand et al. (2019) employed the WRF model to investigate how irrigation, a common practice in the southern Great Plains, may affect LLJ properties and identified changes in LLJ characteristics over and especially downstream of heavily irrigated regions.

Early climatological studies of LLJs relied exclusively on upper-air sounding data. Regarded as a landmark study of LLJ climatology in the U.S., Bonner (1968) was the first to analyze two-year twice-daily rawinsonde data from 47 upper-air stations across the U.S. with the purpose of documenting geographical and diurnal features of LLJs in the U.S. Bonner’s analysis revealed that LLJs over the U.S. occur most frequently over the south-central Great Plains, and jets in this core region are predominantly from the south in the early morning soundings, although they also occur in other directions, particularly from the north in the afternoon soundings. Whiteman et al. (1997) analyzed two-year rawinsonde data with enhanced temporal resolution of up to eight times per day at a site in north-central Oklahoma in the center of the maximum jet frequency region and identified the presence of a LLJ in 47% and 45% of the warm and cold season soundings, respectively. They also found that jets with southerly wind direction tend to occur in warm seasons and at night, and those with northerly winds, which are typically associated with southward moving cold fronts, occur year-round and at all times of the day. Walters et al. (2008) extended Bonner's classic LLJ study to include 40-year rawinsonde observations at stations across the U.S. and produced an updated climatology of LLJ frequency, speed, direction, and jet height.

While the aforementioned rawinsonde-based LLJ analyses helped advance our knowledge about this weather phenomenon in the U.S., the conclusions are affected by the temporal and spatial resolution of the upper-air sounding network. Reanalysis datasets that emerged in late 1990s and that span multiple decades with better spatial and temporal resolution than that of sounding network could serve as an alternative for understanding the LLJ climatology. But before reanalysis data can be used for this purpose, the ability of reanalysis wind data to capture LLJ vertical structure as well as spatial and temporal variability needs to be evaluated. Walters et al. (2014) compared LLJ characteristics derived from the North American Regional Reanalysis (NARR; Mesinger et al. 2006) with those based on rawinsonde observations at 12 stations for four representative years in the rawinsonde era. They showed that NARR wind data are capable of adequately capturing the observed spatial differences in the jet characteristics among the 12 stations and the diurnal variations between the two sounding times. They also noted that at most stations, the jet speed and height are in good agreement between NARR and the soundings, but NARR slightly underestimates the jet frequency. This favorable comparison between the NARR and sounding-based jets paved the way for an improved understanding of the LLJ climatology for North America and its costal environments with better spatial and temporal resolution over a much longer time period (Doubler et al. 2015). In addition to confirming many of the known features identified in earlier jet climatology studies, the updated LLJ climatology also revealed two additional jet frequency hot spots in central and southern Texas, among other features (Doubler et al. 2015). The sounding-based climatology was used to evaluate the performance of a suite of regional climate models in simulating LLJ climatology over the central U.S., where LLJs are an important contributor to the region's climate (Tang et al. 2015).

Because of the role that LLJs play in shaping the climate of a region where LLJs are prevalent, understanding how the characteristics of LLJs may change as land-surface and atmospheric conditions change in the future is essential for future climate projections and climate adaptation for these regions. In one of the early studies of the potential impact of climate change on the Great Plains LLJs, Turner (1993) used an atmospheric boundary layer model forced by conditions similar to those predicted by global climate models to examine how jet characteristics may be altered under a doubled CO_2 scenario. The results revealed a decrease in jet strength with increasing temperature and stratification and decreasing diurnal temperature range and geopotential height gradient. More recently, Tang et al. (2017) assessed future changes in the Great Plains LLJ frequency using an eight-member ensemble of regional climate simulations for the mid-21st century. The models projected an increase in the jet frequency at night in the southern Great Plains in spring and in the central Great Plains in summer, but little to no change for daytime and cool-season jet frequency.

In this study, the potential impact of projected land-use and land-cover (LULC) change on LLJ climatology in the continental U.S. (CONUS) is investigated using regional climate simulations. It has been shown previously that LLJs are sensitive to surface parameters, such as soil moisture, roughness length, albedo, and heat storage, that depend heavily on LULC patterns

(Fast and McCorcle 1990, Arcand et al. 2019, Turner 1993). With the ongoing population and economic growth in the U.S., LULC is projected to change and the question is whether and how much the projected changes in LULC will modify or alter LLJ behavior in the U.S., especially over the central U.S. where jets are prevalent and significant changes in LULC are projected.

The rest of the paper is organized as follows. The approach taken to answer the above question, including the LULC data, the numerical model and model configuration, as well as climate simulations, are described in Section 2.2. The simulation results are presented in Section 2.3. The implication and limitation of the study are discussed in Section 2.4, while the paper is concluded in Section 2.5.

2.2. Methods

2.2.1. Land-Use and Land-Cover Data

To better account for the potential storage and emissions of carbon dioxide and other greenhouse gases in the ecological system over the United States, the United States Geological Survey (USGS) Earth Resources Observation and Science Center has produced consistent annual national-scale historical (1992–2005) and future (2006–2100) LULC estimates based on their FORE-SCE (Forecasting Scenarios of land-use change) modeling framework (https://landcover-modeling.cr.usgs.gov/projects.php). The projected future LULC was modeled under a set of different Intergovernmental Panel on Climate Change (IPCC)-Special Report on Emissions Scenarios (SRES) (i.e., A1B, A2, B1, and B2) (Nakićenović et al. 2000). For this study, the projected LULC for 2011 and 2100 under the A1B scenario (Figure 2.1), assuming a balanced energy supply mix, is used to represent the current and future LULC conditions inside a regional climate model (see below). The changes in LULC patterns over CONUS, which reflect future economic and population growth demand, can be largely characterized by the replacement of grasslands with croplands in the Great Plains (where the LLJ is active) and regions of the South Atlantic, urban sprawl in many metropolitan areas, in Florida, in South Atlantic states, and along the Atlantic and Pacific Coasts, as well as deforestation over the southeast coastal states.

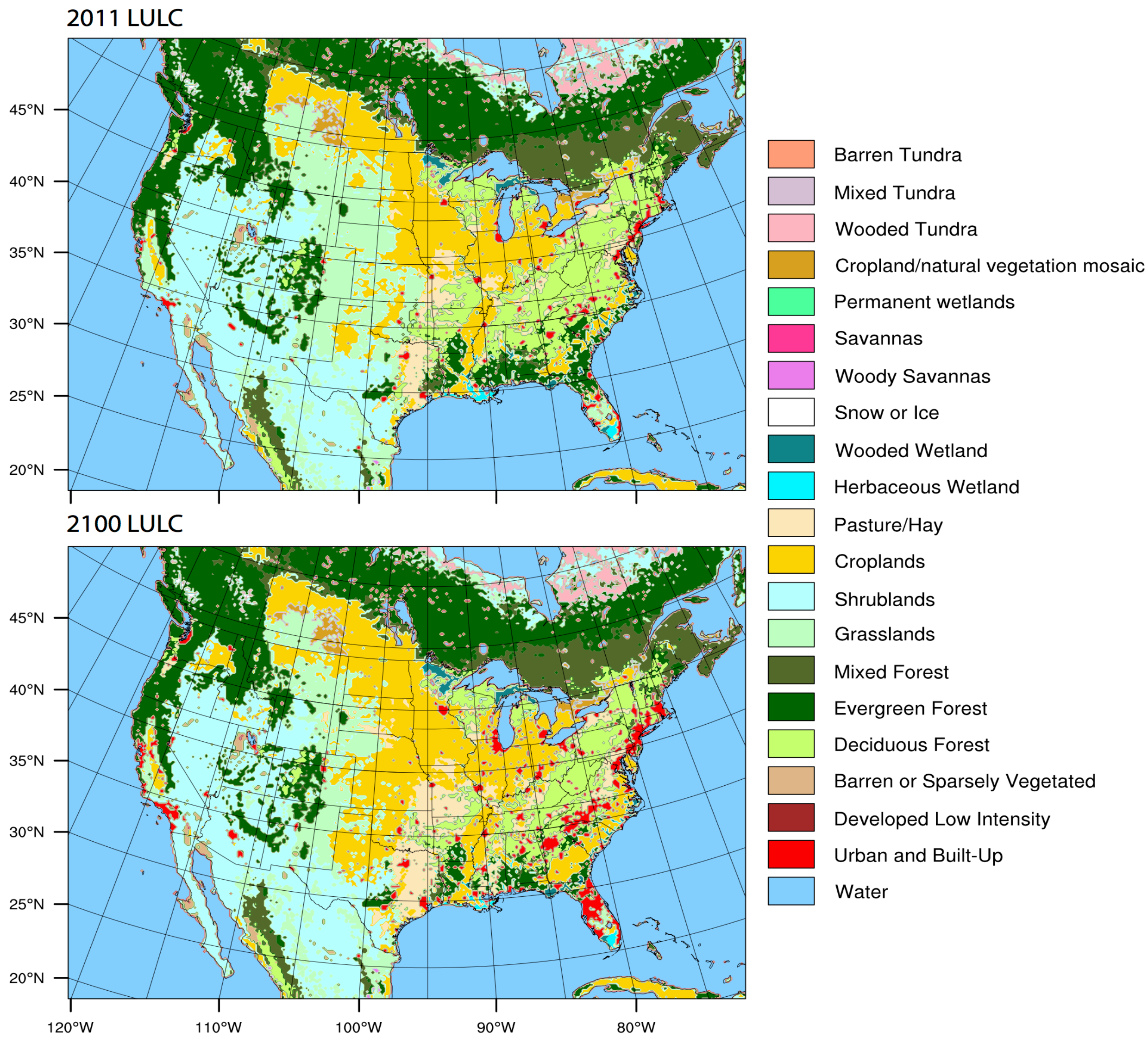

Figure 2.1 Land-use/land-cover (LULC) for 2011 and 2100 and the modeling domain.

To assess the response of LLJ climatology to projected LULC change, regional climate simulations were performed using the WRF model (v3.7.1). Specifically, two 10-year (2006–2015) simulations were carried out with identical model configuration, parameterization schemes and initial and boundary condition, but different surface conditions corresponding to the 2011 and the 2100 LULC patterns.

For these simulations, the model domain (Figure 2.1) is over CONUS, extending into southern Canada and northern Mexico, as well as the surrounding oceans. As the 2011 and 2100 LULC patterns are only produced by USGS within CONUS, the global 21-class MODIS land-use data from the WRF Preprocessing System is merged to cover areas outside of CONUS. The simulations were performed with a horizontal resolution of 15 km and 28 vertical levels extending from near the surface to 100 hPa, with 9 levels below 850 hPa where the majority of LLJ occur. Initial and lateral boundary conditions are derived from the NARR data that has a horizontal grid spacing of 32 km on 29 pressure levels and a 3-hourly temporal resolution. The WRF simulations utilized the well-tested and widely-used Noah land surface model (Chet et al. 1996, Ek et al. 2003, LeMone et al. 2008, Barlage et al. 2013, Pei et al. 2014) for simulating land-surface processes, while the Monion-Obukhov similarity theory-based scheme (Janjić scheme, Janjić 1996) was used for simulating the surface-layer physics. For the planetary boundary layer (PBL) processes, the Mellor-Yamada-Janjić turbulent kinetic energy scheme (Mellor and Yamada 1982, Janjić 1990, Janjić 1994, Janjić 1994) was employed. The radiation process was represented by the Dudhia shortwave scheme (Dudhia 1989) and the Rapid Radiative Transfer Model (RRTM) longwave scheme (Mlawer et al. 1997). The WRF Single-Moment (WSM) 3-class simple ice scheme (Hong et al. 2004) and the modified Tiedtke cumulus parameterization scheme (Tiedtke 1989, Nordeng 1995, Wang et al. 2003, Wang et al. 2004) were applied for the microphysics and convection processes, respectively.

2.2.2. Low-Level Jet Identification

Following Doubler et al. (2015) and Arcand et al. (2019), a LLJ in this study is identified if the simulated vertical wind profile at a particular grid point meets the following two criteria: (1) A wind speed maximum no less than 12 m s^{-1} must be present below 3000 m above ground level (AGL) and (2) the decrease of wind speed from the maximum to the next minimum above (or 5000 m AGL, whichever is lower) and below (or surface, whichever is higher) must be no less than 6 m s^{-1}. These criteria are applied at every surface grid point in the domain and at all the 3-hourly model output times. Once a vertical wind profile at a grid point meets the LLJ criteria, the maximum wind speed and height of the maximum are recorded. At each time and grid point, a monthly mean maximum wind speed and height of the maximum are computed for each month of the year along with the total number of jet occurrences or jet counts for that month.

2.3. Results

The simulated jet properties, including the number of jet occurrences and the maximum jet wind speeds and heights where the maximum occur, are examined for each month of the year and eight times per day. As indicated by the distribution of jet properties across all grid points in the modeling domain for each month at 00UTC for the current and future LULC and their differences (Figure 2.2), all three properties exhibit a strong seasonal variability. A comparison of jet characteristics during different times of the day suggests the existence of a diurnal signature. Thus, the spatial patterns for the months of June (representing summer) and December (representing winter) at 00UTC (representing daytime) and 12UTC (representing nighttime) are presented below to highlight the differences in the response of the simulated LLJ properties to changes in LULC between the warm and cold season and between daytime and nighttime.

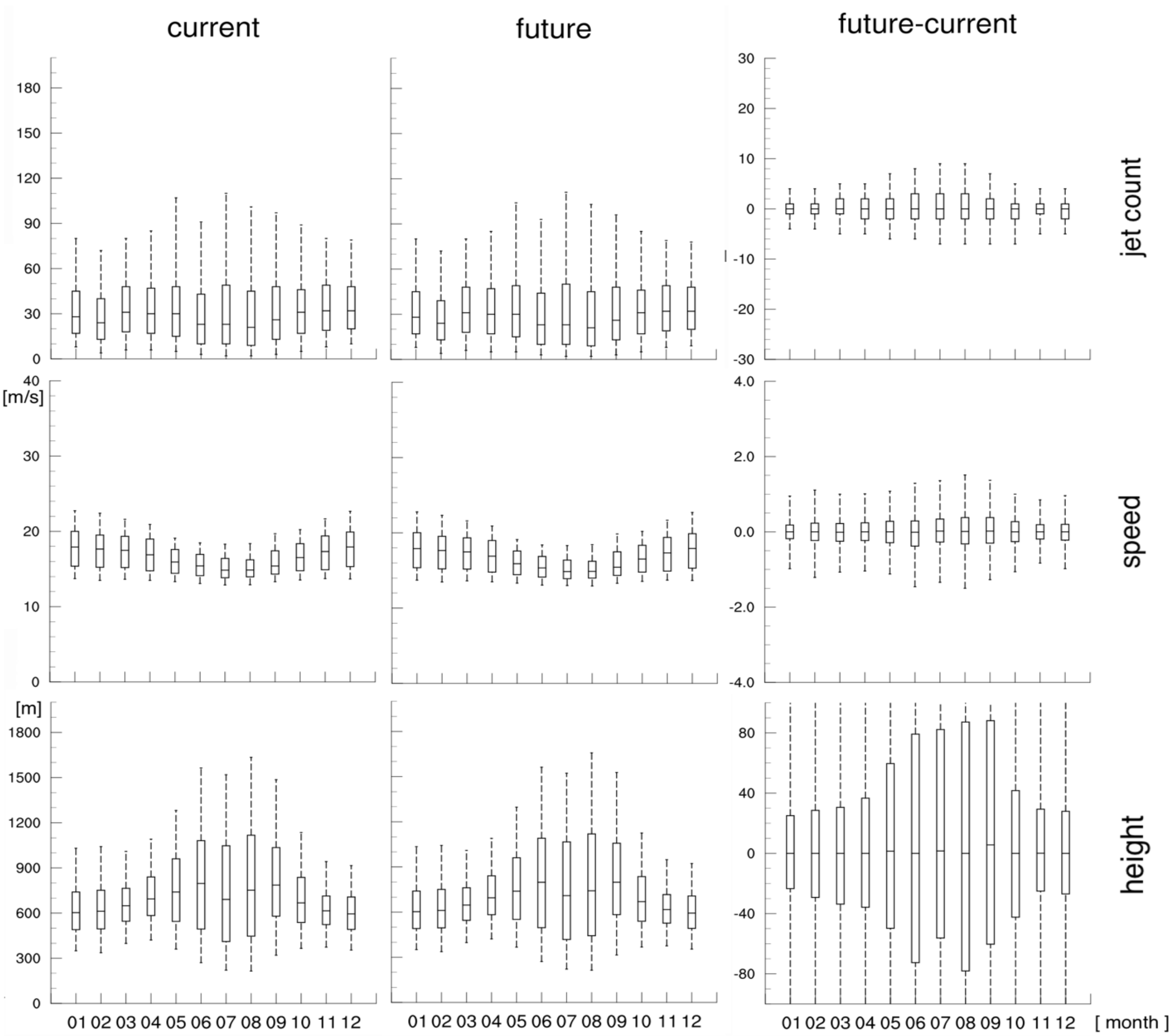

Figure 2.2 Box-whisker plots of simulated low-level jets (LLJ) properties across all grid points for each month at 00UTC under the current and future LULC conditions and their differences. The box denotes the 25% and 75% quartiles, the horizontal line is through the median, and the whiskers indicate the 5% and 95% quartiles, respectively.

2.3.1. Number of Jet Occurrences

The spatial patterns of LLJ occurrences (Figure 2.3) for the current LULC are significantly different between summer and winter and, to a lesser extent, between day and night. For summer, jets occur most frequently over the south-central Great Plains extending from Texas north-northeastward to Nebraska and Iowa. In addition to this core jet region over the Great Plains, higher jet counts are also seen along the South Atlantic coast and in isolated areas of southern California. Although the pattern remains similar between day and night, the nighttime jet number is much higher and the jet core region in the Great Plains is much bigger compared to daytime. These spatial and diurnal patterns are in good agreement with those identified in previous LLJ climatologies (Bonner 1968, Doubler et al. 2015, Tang et al. 2015), which lend confidence to the WRF model's ability and the current model configuration's ability to simulate LLJs. The pattern for winter jets is quite different from summer. While the number is relatively higher in the summer jet core region over the south-central Plains, the highest number of winter jets appears in Montana, Utah, and Colorado near the Rocky Mountains. The number is also relatively high along the Gulf Coast, especially southern Texas and Florida. Similar to summer, the jets are more frequent and widespread at night than day, but the amplitude of diurnal oscillation in winter is much smaller compared to summer.

The projected changes in LULC from current to future result in little difference in the overall spatial and diurnal patterns, but the number of jet occurrences is modified and the degree of the modification depends on the region. There is a clear signal of increased jet occurrences in areas where grassland is replaced by cropland (e.g., the jet core regions in Oklahoma and Kansas of the southern and central Plains) and areas where mixed forest is replaced by cropland (i.e., the southern parts of the South Atlantic states, such as southern Georgia and eastern Carolinas), and a decreased jet occurrence in areas of increased urbanization (e.g., northern Florida and northern parts of the southern Atlantic states, such as western Carolinas as well as in southern and central California). The influence of LULC change on jet occurrences extends beyond the areas where significant LULC changes occur, due possibly to land–atmosphere interactions and the effects of LULC changes on larger-scale atmospheric environments. Overall in summer, larger changes occur over the central and eastern U.S. where jets are more frequent. There is a general increase in jet occurrences in the jet core region over the southern and central Plains and a decrease in the region to the east of it over the Midwest, especially the Ohio River Valley. In winter, larger changes are found in the Southeast, particularly over Florida. It is interesting to note that the differences in jet occurrences between current and future LULC are small in the areas of the Rockies where winter jets are most frequent. This might be due to the fact that these LLJs are most likely downslope wind storms in winter resulting from strong synoptic flows interacting with high mountain barriers. The magnitudes of the changes are considerably larger in summer than in winter, indicating stronger sensitivity of summertime jet occurrences to changes in LULC. This is no surprise considering that LLJs in the summer season are driven predominantly by inertial and thermal oscillations of surface forcing, while jets in winter are typically associated with synoptic weather fronts (Whiteman et al. 1997). Florida is an exception to this general rule, possibly due to the relatively small seasonality of its climate.

2.3.2 Maximum Jet Speed

In contrast to the number of jet occurrences, which is higher in summer than in winter, the maximum jet speeds (Figure 2.4) are much higher in winter than in summer nearly everywhere except for the jet core area at night where the speeds are comparable between the two seasons. Similar to the jet number, winter-season jet speeds show little diurnal variation in both the spatial distribution and magnitude, but summertime jet speeds exhibit strong seasonal and diurnal variability, with high nocturnal jet speeds limited to the jet core region in the south-central Great Plains but strong daytime jets scattered in small areas of the Rocky Mountains. Regions of stronger wintertime jets extend from the upper South Central and Southeast to the lower Midwest and

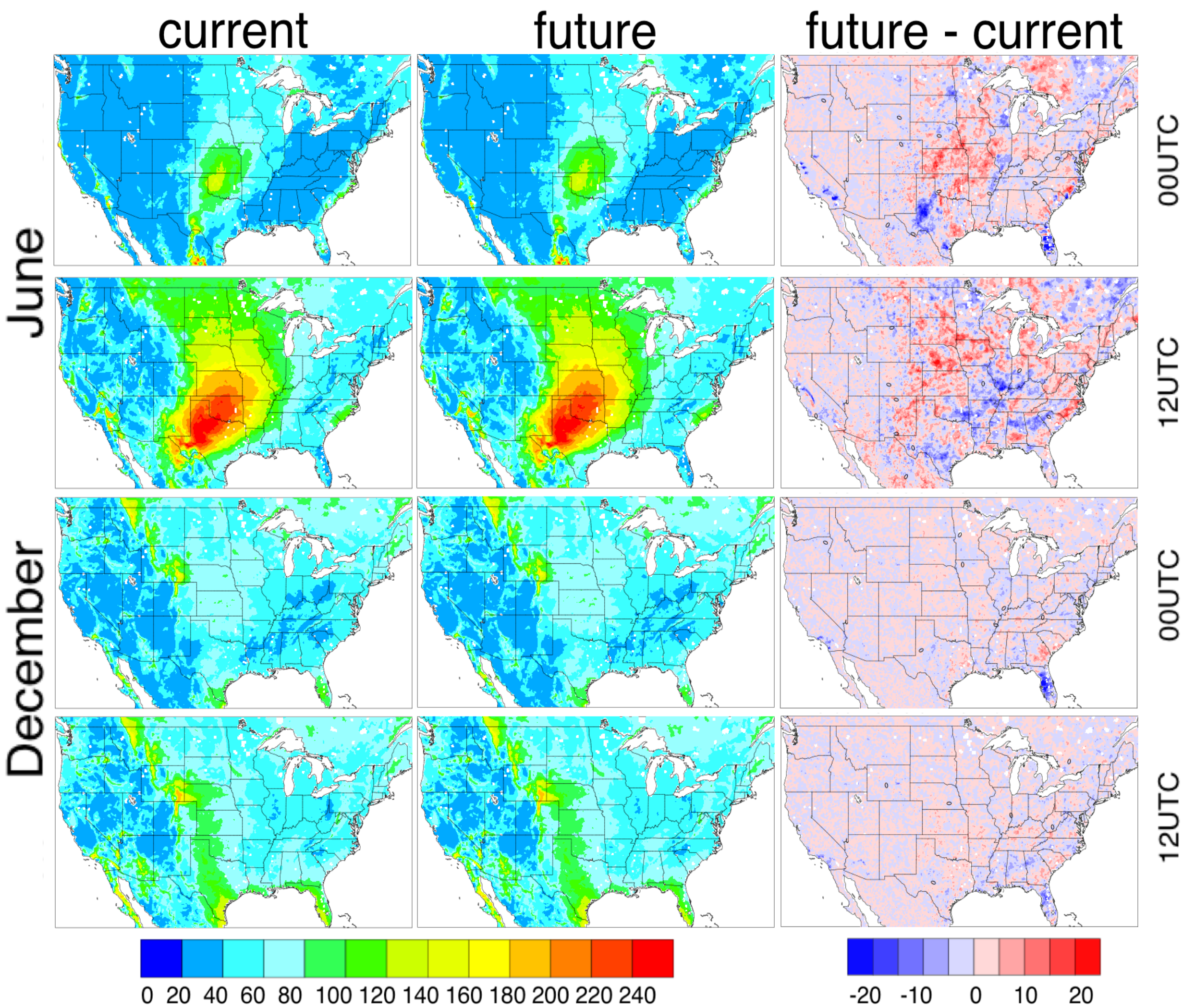

Figure 2.3 The total number of simulated jet occurrences for the months of June and December at 00UTC (day) and 12UTC (night) under the current and future LULC conditions and their differences.

Northeast, reflecting the paths of wintertime cold fronts (Whiteman et al. 1997). In the West, stronger jets appear to be associated with the three major mountain ranges: The Cascades, Sierra Nevada and the Rocky Mountains. These spatial distributions and the magnitudes of monthly mean maximum jet speeds are consistent with the NARR-derived (Doubler et al. 2015) and the multiple model-simulated (Tang et al. 2017) LLJ climatologies.

The changes in the maximum jet speed between the current and future LULC simulations show substantially larger spatial and diurnal variability in the summer than in winter. The speed differences in winter jets, both daytime and nocturnal, are generally within 1 m s^{-1} over the central and western U.S., increasing to 3 m s^{-1} or larger in eastern U.S., especially over upper Southeast and the Ohio River Valley in the lower Midwest, where maximum jet speeds are higher. It is interesting to note that, similar to the number of jet occurrences mentioned above, the areas in proximity to the large mountain ranges in the West where the highest winter jet speeds occur see little change in wind speed between the current and future LULC simulations, further suggesting that LLJs resulting from interactions of large-scale flows and major mountain barriers are not sensitive to the LULC changes. In summer, the speed differences in nocturnal jets also fall within 1 m s^{-1} across most of the U.S., except for the Ohio River Valley, parts of the Northeast, and isolated areas in the Intermountain West, where the differences increase to 2 m s^{-1} or larger. The speed differences are much larger in daytime summer jets where values of 3 m s^{-1} or greater occur across the U.S., except for the Great Plains. In regions with larger changes in wind speed, there is a strong spatial heterogeneity in both the magnitude and direction of change. While there is some indication of reduced jet speed in areas affected by urban expansion, such as those in the Ohio River Valley and upper Southeast, and slightly increased jet speed where cropland replaces grassland in the Great Plains, the relationship is weak, especially for winter-season jets.

2.3.3 Elevation of Maximum Jet Speed

Maximum speed of the LLJ, sometimes referred to as a jet nose (Walters et al. 2008), can appear at different elevations above the ground level (AGL) (Figure 2.5). The maximum jet speeds appear to occur at higher elevations in summer than in winter and during the day than at night. In summer, the daytime jet noses appear higher (>1200 m AGL) across the upper Southeast and lower

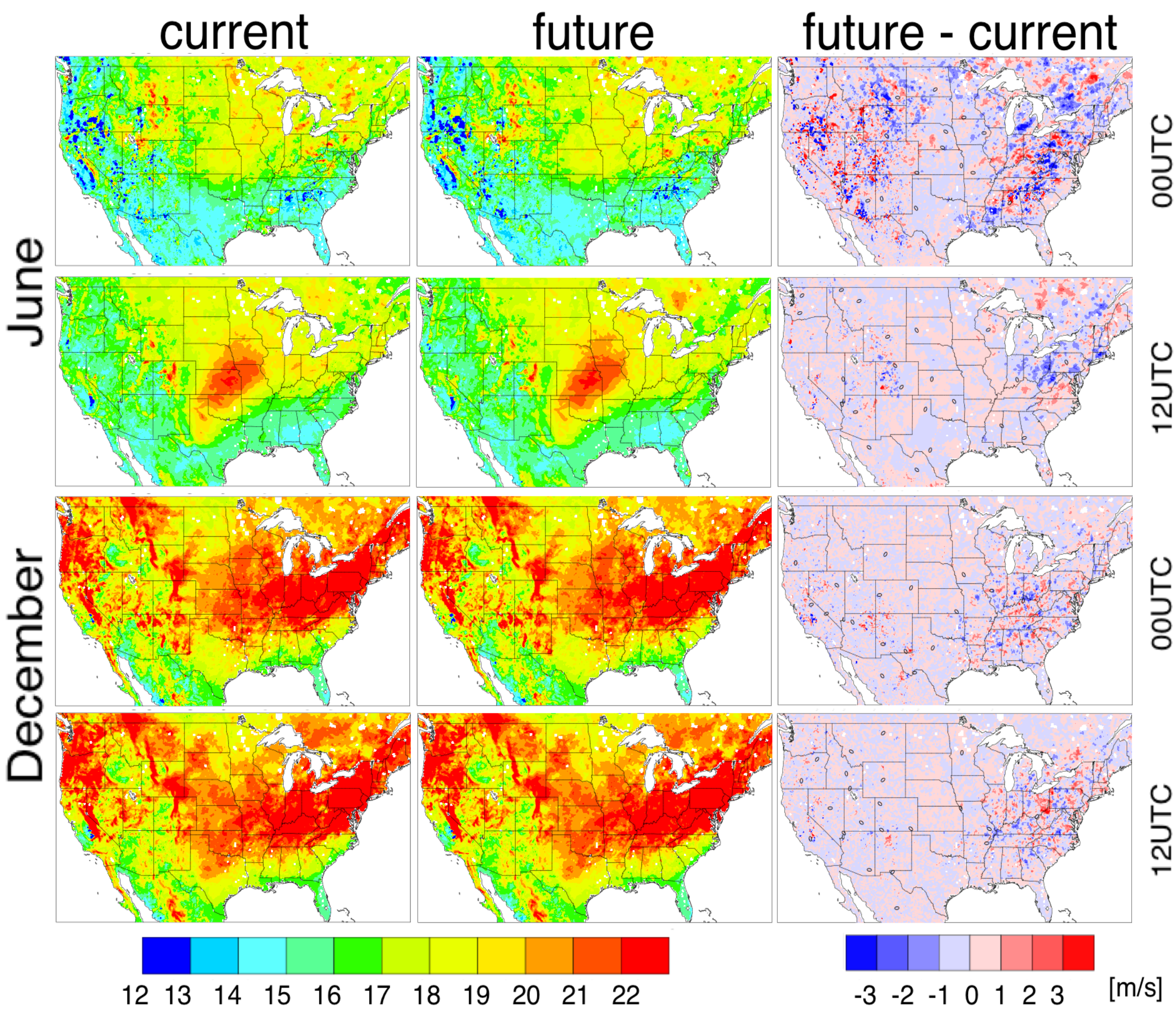

Figure 2.4. Simulated maximum jet speed for the month of June and December at 00UTC (day) and 12UTC (night) under the current and future LULC conditions and their differences.

Midwest and Northeast, while they occur at lower elevations (<600 m AGL) along the Atlantic Coast, parts of Georgia and Florida, and areas in the Intermountain West. The nocturnal summer jets occur generally below 800 m AGL, with the exception of the Gulf Coast, Florida, and a few areas in the West where jet elevation can exceed 1500 m AGL. Winter-season jet heights occur at lower elevations, generally between 500–1000 m AGL, and have smaller spatial and diurnal variability. The spatial patterns of the elevation differences between the current and future LULC simulations are quite similar to those of speed differences. In winter, the differences in the jet nose heights are small, between 200 m, for both daytime and nighttime jets. In summer, the differences in the nocturnal jet nose heights also are small over the central U.S., but are slightly larger and more variable in the eastern and western U.S. Large differences of 600 m are seen for daytime summer jet noses and, similar to the jet speed difference, the magnitudes are larger with greater variation in the eastern and western U.S. and smaller and less variable over the central and northern Plains.

There is no obvious link between jet nose height and LULC change at a given location except for a weak indication of an increase in jet nose height with urban expansion, as reflected in areas of Florida, Georgia, eastern Carolinas, and the Ohio River Valley. Similar to jet speed, the effect on jet height seems stronger in summer than in winter.

2.4. Discussion

There is some evidence that the conversion of grasslands into croplands in the jet core region over the south-central Great Plains in the future would likely lead to an increase in jet occurrences and a slight increase in maximum speed, while urban expansion would likely reduce jet occurrences and jet speed and increase jet height. The evidence, however, is weak especially for daytime and winter jets that are driven largely by large-scale forcing.

The effects of LULC on large-scale atmospheric environments are illustrated in Figures 2.6–2.8, which show the 850 hPa temperature, moisture, and geopotential height fields corresponding to the current and future LULC patterns and their differences over the eastern half of the U.S. (terrain elevations over portions of the western U.S. exceed the 850 hPa height levels).

As one can see, changes in LULC, which are limited only to certain areas, result in widespread increases in 850 hPa temperatures and geopotential heights and decrease in moisture, although the

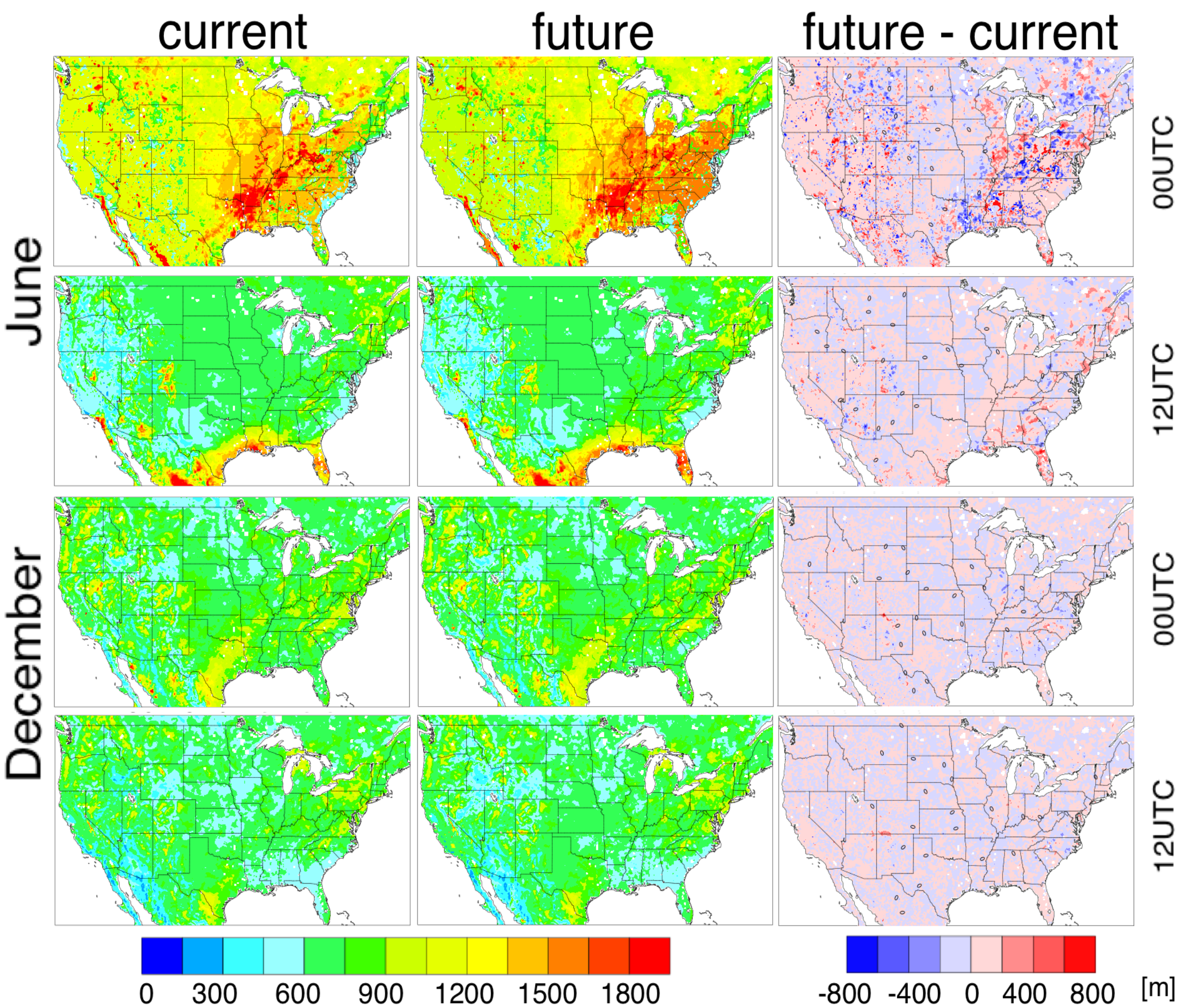

Figure 2.5 Simulated elevation of the maximum jet speed for the months of June and December at 00UTC (day) and 12UTC (night) under the current and future LULC conditions and their differences.

magnitudes of the differences are small. For all three fields, seasonal variations in the magnitudes of the LULC-induced differences overwhelm the diurnal signal. Larger differences are found in summer than winter and in the Ohio River Valley and upper Southeast, which is generally consistent with the pattern in the LULC-induced changes in jet properties (such as jet occurrence, speed, and height) since warmer temperature increases daytime boundary layer heights and decreases nocturnal inversion, resulting in weaker jets at higher heights.

The overall warming and drying effects occur in a deep layer in the lower troposphere, as revealed by the vertical profiles at two locations, one near Atlanta, Georgia where significant urban expansion occurs and another next to North Platte in central Nebraska where cropland replaces grassland (Figure 2.9). The profiles, obtained by averaging all profiles for the month of June at 00UTC and 12UTC, represent the influence of LULC on averaged vertical atmospheric structure at these locations. As expected, the LULC-induced changes decrease with height and with maximum values near the surface. For both day and night, the warming and drying effect is considerably stronger at the Georgia site affected by urban expansion than at the Nebraska site influenced by grassland–cropland conversion, which is in agreement with the relative magnitude of changes in jet speed and heights at these locations. There is a general decrease in wind speed at the Georgia site, except for surface wind at night, and a slight increase at the Nebraska site, which is largely consistent with the changes in roughness length due to LUCL changes at the two sites.

While case studies or short-term simulations assuming idealized atmospheric and/or land-surface conditions have proven useful for understanding how LULC changes might affect local or regional atmospheric features, such as the LLJs (Zhong et al. 1996, Fast and McCorcle 1990, Parish and Oolman 2010), failure to capture the influence of LULC changes on larger-scale atmospheric environments through complex land–atmosphere interactions may lead to inaccurate results (most likely, an overestimation of the local response). Following this argument, a noted limitation of the current study is that the two 10-year climate simulations are driven by the same current climate conditions (2006–2015) derived from NARR. Thus, the results should be interpreted with the understanding that the projected changes in the LLJ properties are due solely to changes in the LULC patterns without considering future changes in climate conditions.

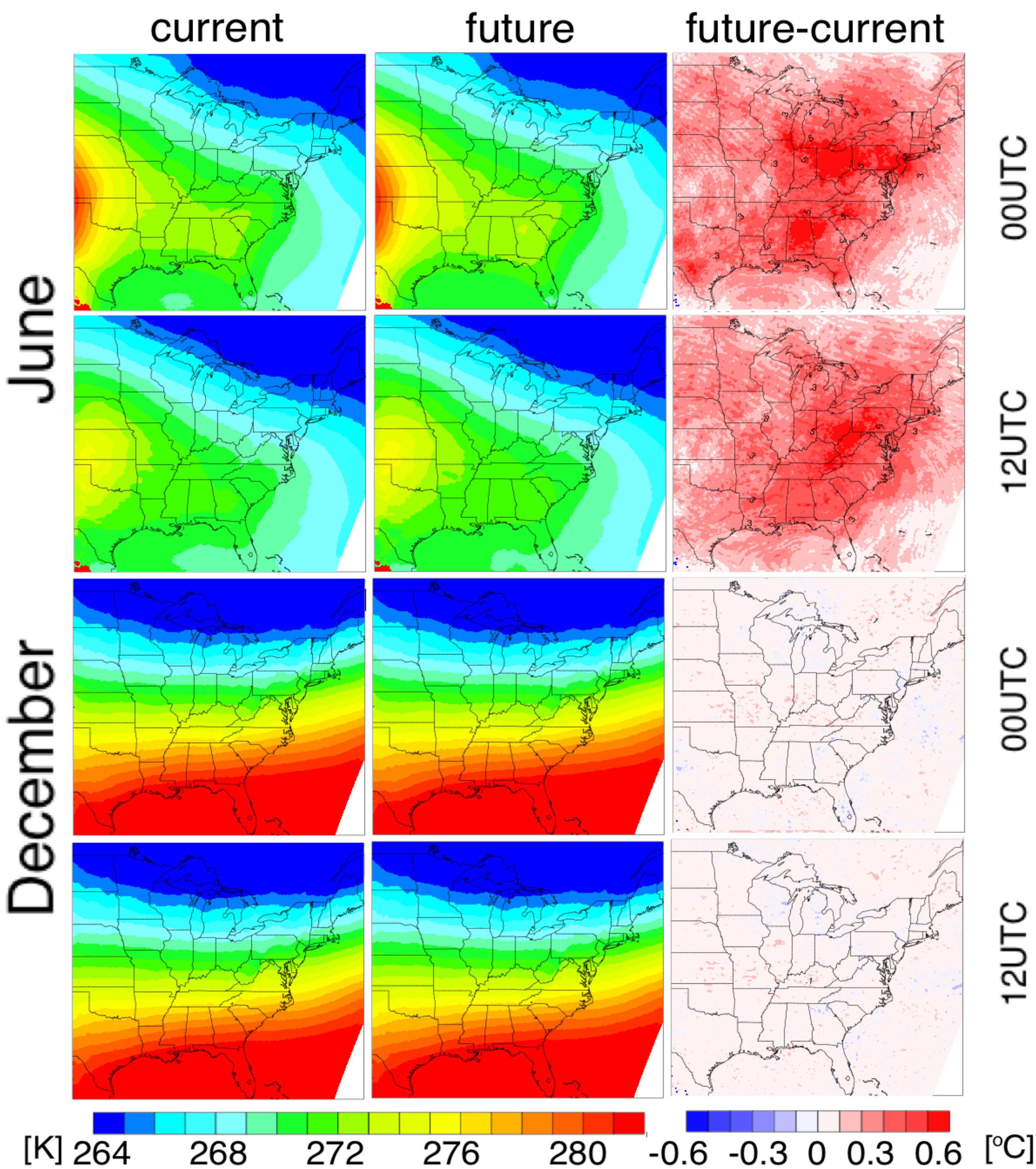

Figure 2.6 Simulated June and December average 850 hPa temperatures at 00UTC (day) and 12UTC (night) for current and future LULC and their differences.

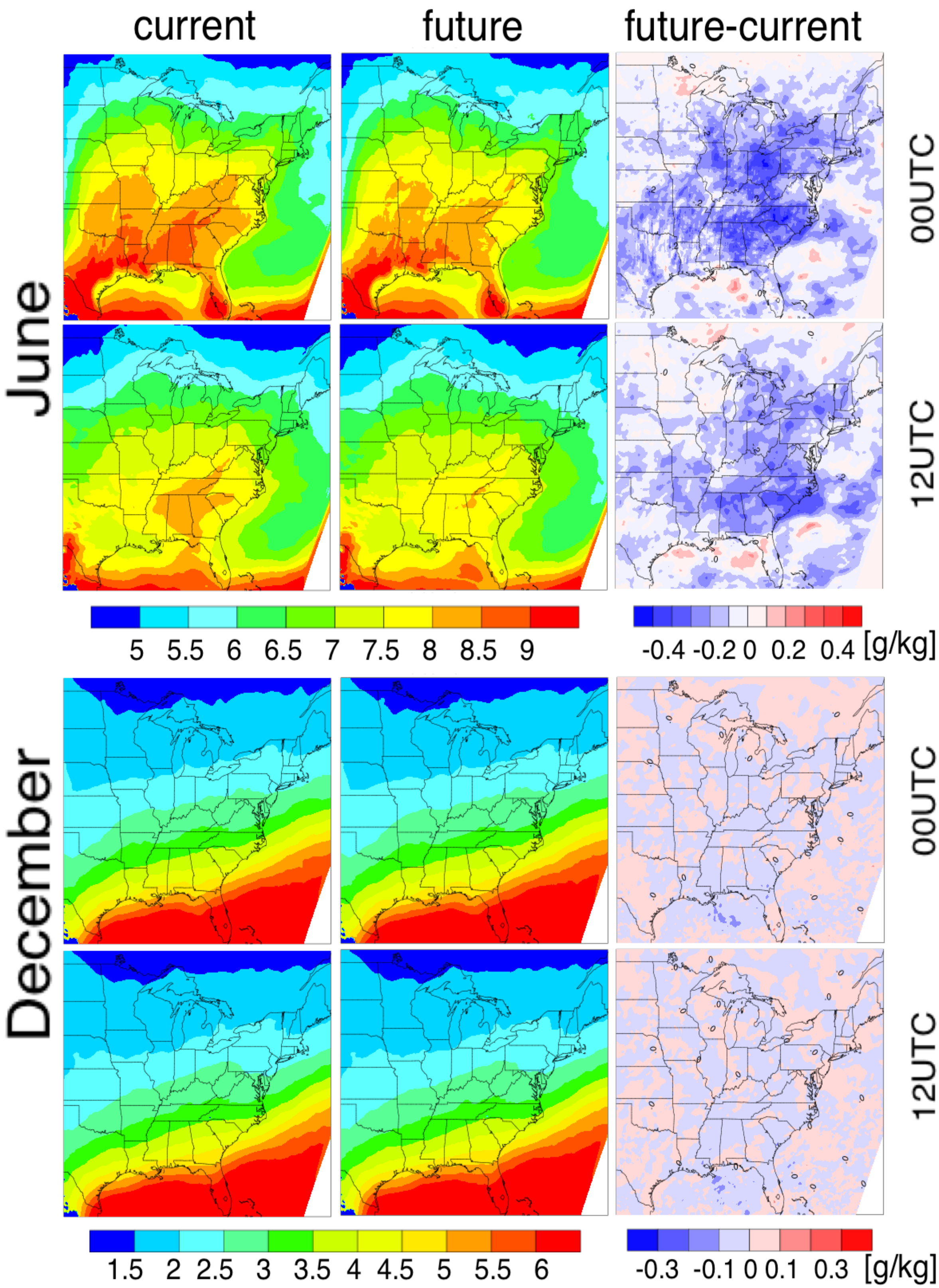

Figure 2.7 Same as Figure 2.6, but for specific humidity.

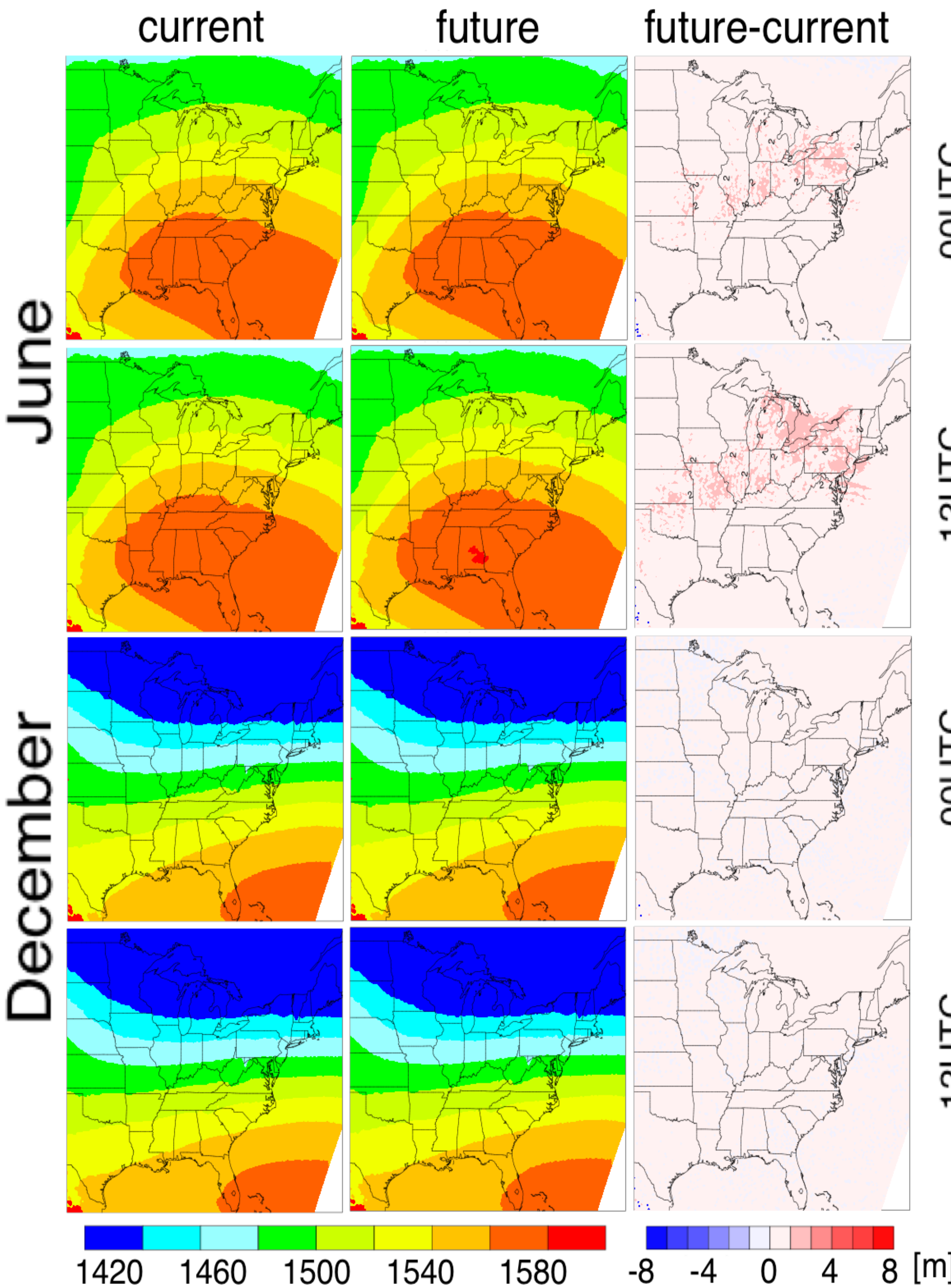

Figure 2.8 Same as Figure 2.6, but for geopotential height.

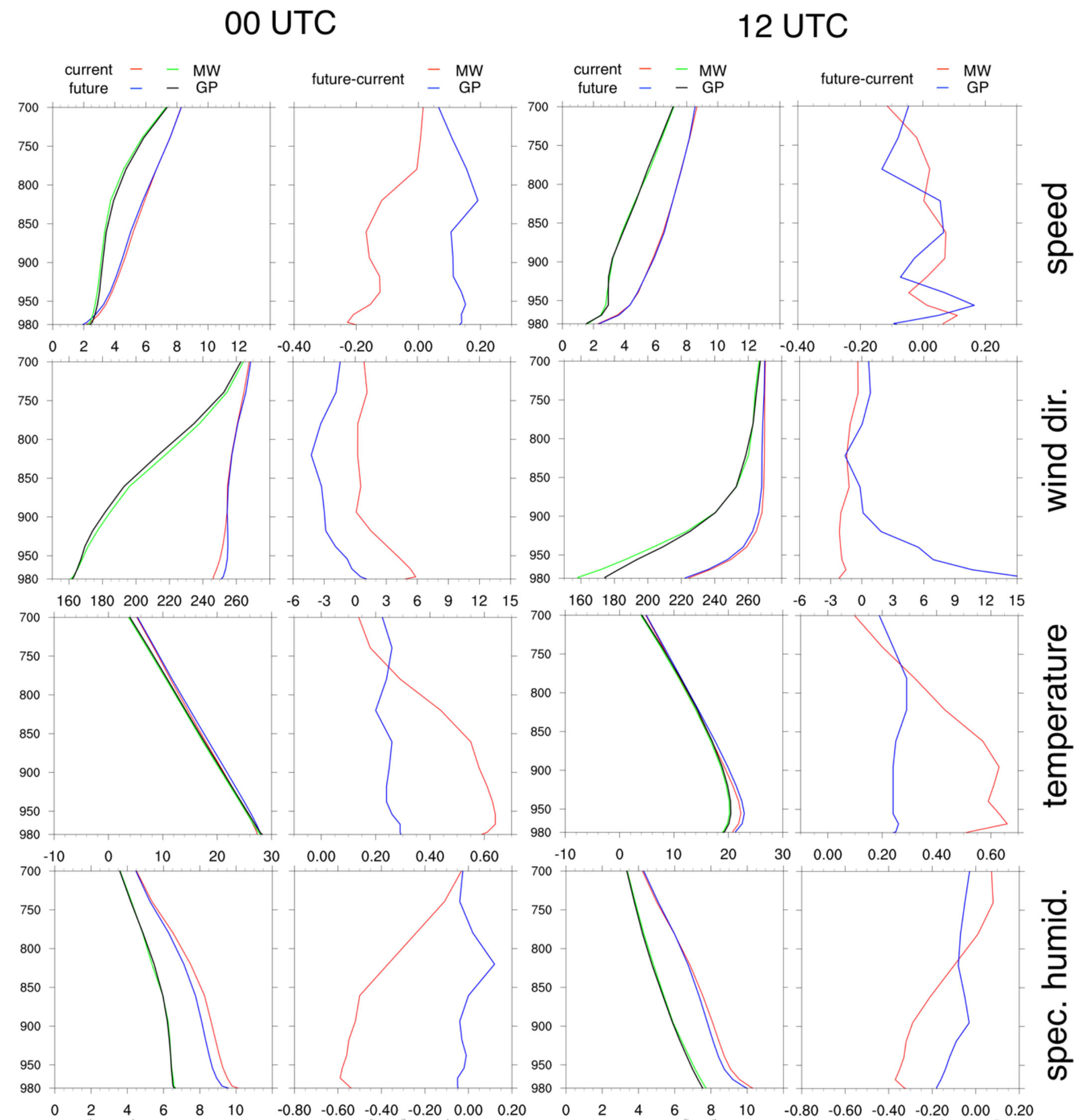

Figure 2.9 Vertical profiles of wind speed (m s^{-1}), wind direction, temperature (C), and specific humidity (g kg^{-1}) at 00UTC (day) and 12UTC (night), averaged over the month of June under the current and future LULC conditions and their differences, at a location in Georgia and in Nebraska.

2.5. Conclusions

In this study, 10-year (2006–2015) regional climate simulations driven by the NARR reanalysis are performed with the current (2011) and future (2100) LULC patterns to assess the sensitivity of LLJ properties, including number of occurrences, maximum wind speeds, and the elevation where the maximum wind speed occurs to projected LULC changes over the CONUS.

The simulation results suggest that winter-season jet properties are less sensitive to the LULC change than summertime jets. In summer, the jet core region over the Great Plains where grasslands are projected to be replaced with croplands is likely to see an increase in the number of jet occurrences and the areas affected by urbanization (e.g., northern Florida and northern parts of the southern Atlantic states) are likely to see a decrease in jet occurrences under the same regional climate forcing. In winter, the number of jets in areas of the Rocky Mountains and along the Gulf Coast where LLJs are most frequent will likely remain similar between the current and future LULC conditions. Somewhat larger changes, both increases and decreases in the jet count, are expected over eastern portions of the lower Midwest and upper Southeast where winter jets are less frequent. The state of Florida, where widespread urban expansion is projected in the future, is likely to experience a decrease in the number of jet occurrences in both winter and summer. The reduction is larger for daytime jets than for nocturnal jets.

For both jet maximum speed and the elevation of the maximum, large differences tend to appear in areas of the eastern portion of lower Midwest, particularly the Ohio River Valley, upper Southeast, and the Intermountain West, where jets are less frequent. In areas where jets are more prevalent, such as the Great Plains in summer and the Rockies and Gulf Coast in winter, the differences are small (±1 ms^{-1}, ±200 m). The largest differences and strongest spatial variability for both speed and elevation are seen for summer season daytime jets. Although there is some evidence of weaker, more elevated jets associated with urban expansion, the connection between changes in jet speed and elevation and changes in LULC patterns at a given location is weak. This, together with the strong spatial variability, highlights the complexity of multi-scale land–atmosphere interactions and the need for capturing the influence of LULC on regional and synoptic-scale forcing for LLJs.

Chapter 3 The Influence of Land Use and Land Cover Change on Frost-Free Season Length Over the Contiguous United States

In collaboration with
Shiyuan Zhong, Lisi Pei, Xindi Bian, Warren E. Heilman and Joseph J. Charney

Abstract: Two 10-year regional climate model simulations are used to investigate the impact of land use land cover (LULC) change on frost-free season length over the contiguous United States (CONUS). Differences in the simulations between current (2011) and future (2100) LULC patterns are analyzed to investigate changes in the timing of last spring frost (LSF) day, first fall frost (FFF) day, and the frost-free season (FFS) length. While the results showed an increase in FFS length over the majority of the CONUS, parts of the Midwest, Great Plains, and coastal areas in the Southeast exhibit a decrease in FFS length. The influence of LULC change on simulated minimum temperatures follows changes on simulated FFS length. Simulated minimum temperatures are higher in the future over areas expected to experience urban expansion. Parts of the Great Plains and coastal regions in the Southeast where a conversion from grassland and forested areas to cultivated land is expected exhibit lower simulated minimum temperatures in the future. The results suggest that LULC change could have a direct effect on FFS length that can be beneficial in some regions, while harmful in other regions to agricultural practice in the CONUS.

3.1 Introduction

Frost can have a major impact on the growth and development of plants. Frost indices, such as the day of the year when the last spring frost (LSF) or the first fall frost (FFF) occurs and the length of the period between them, known as the frost-free season (FFS), are important climate indicators for agriculture in regions susceptible to frost formation. Climatological variations in the dates of LSF and FFF, and in the FFS length, are important for assessing the potential for climate change and land use land cover (LULC) change to affect agricultural sectors as well as other activities that are influenced by plant growth and development.

A historical increase in FFS length in many regions around the world has been reported by a number of studies using both observations (Easterling 2002, Menzel et al. 2003, Kunkel et al. 2004, McCabe et al. 2015, Ning et al. 2017) and numerical model simulations (Walsh et al. 2014, Anandhi et al. 2013, Zhong et al. 2017). According to observational studies, the increase in FFS length across most areas of the contiguous United States (CONUS) started early in the 20th century and continued through the 1990s and beyond (Kunkel et al. 2004), with the magnitude of increase in FFS length being dependent on geographical factors such as longitude and latitude (Menzel et al. 2003, Ning et al. 2017), elevation (Menzel et al. 2003, Ning et al. 2017), and other regional and local characteristics (Easterling 2002, Anandhi et al. 2013, Walsh et al. 2014, Zhong et al. 2017). The increase in FFS length was found to have the largest magnitude in the West and smallest in the Southeast (Walsh et al. 2014, Zhong et al. 2017). The increase in FFS length has been attributed to either an earlier date of the LSF, a later date of the FFF, or a combination of changes in both dates (Kunkel et al. 2004, Easterling 2002, Zhong et al. 2017). The observed increase in FFS length was found to increase forest productivity in some regions (McMahon et al., 2010), while in regions with less available moisture it resulted in reduced tree productivity and a longer fire season (Hu et al. 2010).

The increase in FFS length has been found to be correlated to an increase in temperature (especially minimum temperature) around the globe over the past century (Easterling et al. 1997, Karl et al. 1993, Vose et al. 2005). Many climate projections suggest that global temperature is going to increase throughout this century due to greenhouse gas emissions and, therefore, the increase in FFS length is also likely to continue. Indeed, several studies have indicated that climate change will likely affect the frequency and spatio-temporal distribution of frost, which could result in an increase in FFS length in many regions around the world. This projected increase in FFS length could, in turn, affect plant and crop type, crop production, and vulnerability to frost, and require adaptation and modification of future agricultural practices (Chmielewski et al. 2004, Olesen et al. 2011, Winkler et al. 2013a, Zheng et al. 2015, Ning et al. 2017).

Besides the influence of greenhouse gas emissions on surface temperature and FFS length, LULC change is another factor impacting both surface temperature and FFS length. Fall et al. (2010) used both observations and reanalysis data to examine changes in surface temperature between 1979 and 2003 associated with different LULC changes in the CONUS and found a warming effect with increased urbanization and deforestation and a cooling effect with transitions from forest to cultivated land. Specifically, they found that transitions from some other land-use types to cultivated lands resulted in significant cooling, and that overall transitions between LULC types is a strong driver for changes in surface temperature. In a numerical modeling study, Li et al. (2017) compared simulated surface temperatures using historical and current LULC data and documented significant changes in mean, maximum, and minimum temperatures in regions of LULC change. Mishra et al. (2010) examined the impacts of LULC (e.g. deforestation) and climate change (e.g. increases in precipitation and temperature) on surface water and energy cycle. They found that deforestation, or a transition from forest to cropland, resulted in cooling, while a transition from forest to urban areas resulted in warming. However, they also found that under the influence of LULC change only, domain-averaged total net radiation and temperatures decreased, while under future climate change (including the impact of changes in precipitation and temperature), domain-averaged temperature increased. Bonan (1997) used a coupled land-surface and atmospheric model to investigate the impact of changes in vegetation patterns on the climate in the United States (U.S.). The model results suggested cooling over the eastern and warming over the western U.S. in spring. In summer, the results suggested cooling over most of the U.S., while in presence of wetter soils, cooling was simulated over much of the U.S., in both spring and summer season.

The influence of LULC change on minimum temperature and the dependence of FFS length on minimum temperature suggest that changes in LULC are likely to alter the dates of the occurrences of the LSF and the FFF, and thus change the FFS length. Little is known, however, about how LULC changes will affect FFS length over the CONUS. The goal of this study is to address that knowledge gap. By comparing regional climate simulations using current and future LULC patterns for the CONUS, this study will try to answer the following questions: Will future LULC changes likely result in an earlier or a later date of the LSF and FFF in the CONUS? Do future simulations of the dates of the LSF and FFF suggest longer or shorter FFSs in the future? How much of the projected increase or decrease in FFS length can be attributed to earlier/later dates of the LSF, and how much is due to earlier/later dates of the FFF? Are there regional differences in the changes in the dates of the LSF/FFF, and the resulting FFS length, or are they localized to where LULC changes may occur in the CONUS? Do the regional climate simulations suggest changes in the dates of the LSF/FFF and the FFS length at locations where LULC is not expected to change?

The rest of the paper is organized as follows: the methods utilized for the study, including the numerical model and LULC data, are described in Section 3.2. Section 3.3 presents the results, while Section 3.4 provides discussions of the results. The paper is concluded in Section 3.5.

3.2 Method

This study uses a numerical weather prediction model to produce regional climate simulations for the CONUS. Specifically, two 10-year (2006-2015) regional climate simulations previously documented in Nikolic et al. (2019) are analyzed and compared. The two simulations differ in that the first uses a current LULC pattern and the second uses a future LULC pattern. Results from the two simulations are analyzed to depict the impact of LULC change over the CONUS on the simulated dates of the LSF and FFF, and on the FFS length.

3.2.1 Model and Model Configuration

The numerical model used for the simulations is the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008, v3.7.1). For the two simulations, the WRF model is configured with a single domain centered over the CONUS, with a horizontal grid spacing of 15 km and 28 vertical sigma levels stretching from the surface to the model top at 100 hPa (Nikolic et al. 2019). Each simulation spans a 10-year period (2006-2015), and the simulations employ initial and lateral boundary conditions derived from the North American Regional Reanalysis (NARR, Mesinger et al. 2006). The simulated variables are saved at 3-hourly intervals. Physical parameterizations used for the two simulations include the Janjić (Janjić 1996) and Mellor-Yamada-Janjić (Mellor and Yamada 1982, Janjić 1990, 1994, 2001) schemes for surface and planetary boundary layer processes, respectively. The Dudhia (Dudhia 1989) and Rapid Radiative Transfer Model (RRTM, Mlawer et al. 1997) schemes account for the effects of shortwave and longwave radiation, respectively. The modified Tiedtke (Tiedtke 1989, Nordeng 1995, Wang et al. 2003, 2004a) and the WSM 3-class simple ice (Hong et al. 2004) schemes are used for cumulus and microphysics parameterizations, respectively, and the Noah land surface model (Chen et al. 1996, Ek et al. 2003) accounts for land-surface processes.

3.2.2 Land Use Land Cover Data

The two simulations differ only in the LULC types that are used in the Noah land-surface model. For these simulations, LULC types are prescribed based on the U.S. Geological Survey (USGS) annual national-scale LULC estimates for 2006-2100. These LULC estimates were developed using the FORE-SCE (Forecasting Scenarios of land-use change) modeling framework (https://landcover-modeling.cr.usgs.gov/projects.php) for the purpose of assessing the potential emissions and storage of carbon dioxide and other greenhouse gases in ecological systems in the CONUS under different greenhouse gas emission scenarios. For this study, the LULC patterns under the balanced energy supply greenhouse gas emissions scenario (A1B, Nakićenović et al., 2000) are used. Specifically, the LULC pattern for 2011 is used to represent the current condition, and the LULC pattern for 2100 is used to represent the future condition.

The USGS LULC estimates are similar to the National Land Cover Database (NLCD) classes, with a few steps implemented before they are incorporated into the WRF model runs. First, the corresponding LULC parameters are assigned with the same-class LULC parameters from the default WRF-compatible LULC datasets, i.e., the USGS 24-Category LULC, the MODIS 21-Category LULC, and the NLCD 40-Category LULC. Second, these estimates are only available inside of the CONUS, while the MODIS 21-Category LULC are jointly used to account for the simulation area outside of the CONUS (not used in the current analyses).

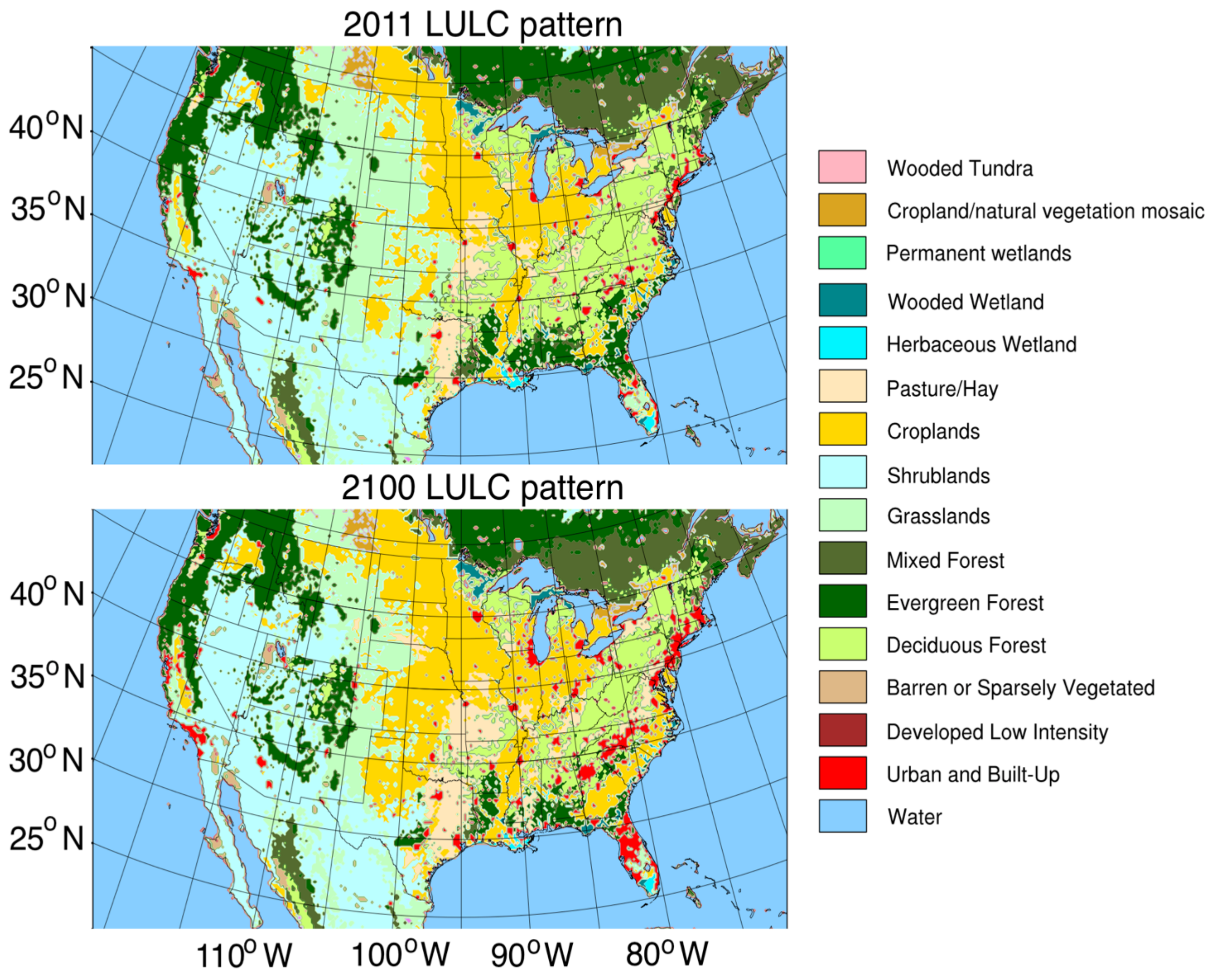

Figure 3.1. USGS estimated LULC categories for 2011 and 2100.

The constructed current (2011) and future (2100) LULC patterns for the two regional climate simulations are shown in Figure 1. Urban expansion into surrounding suburban and rural areas is evident in the patterns (c.f. Figures 3.1a,b). The urban expansion is most pronounced in northern and central Florida, east and south of the Appalachian Mountains, and in the upper

Midwest. In the West, urban expansion is most prominent in southern California and in the Central Valley of California. Across the CONUS, urban land cover increases from 894 model grid cells under current conditions to 2193 model grid cells for future conditions (31.8 % increase) (Table 1). A change from natural land use (i.e. grasslands, shrub lands, and forests) in the current LULC pattern to cultivated land use (i.e. croplands and pasture/hay) in the future LULC is evident. This change is anticipated due to the increasing demand for food production (Bajželj et al. 2014). The change from natural to cultivated land use is most evident over the Great Plains, the southern parts of southeastern states, and in eastern Washington and eastern Montana. In the CONUS, a 48.3% decrease in forest area and a 52.6% decrease in grassland areas are indicated, while a 57.3% increase in croplands and an 26.7% increase in pasture/hay is expected (Table 4.1). Note that some of the reduction in natural land use cover is associated with urban expansion.

Table 3.1. Number of grid cells in the CONUS for selected LULC categories in 2011 and 2100.

LULC type (number of cells)	forest (all)	grassland	cropland	hay/pasture	urban
Current	14046	5953	6820	2179	894
Future	12072	3800	9163	3269	2193
Future minus current	-1974	-2153	2343	1090	1299
Percent change relative to LULC changed grid cells	-48.3%	-52.6%	57.3%	26.7%	31.8%

3.2.3 Frost Indices

As indicated above, the analyses here focus on changes in the dates of the LSF and FFF and resulting changes in the FFS length. Following Zhong et al. (2017), the date of the LSF is defined as the last day between January 1 and June 30 when the minimum daily temperature is at or below 0 °C. Similarly, the date of the FFF is defined as the first day between July 1 and December 31 when the minimum temperature is at or below 0 °C. The number of days between the two dates is defined as the FFS length. If the minimum temperature stays above 0 °C all year long, the LSF is set to Jan. 1, the FFF is set to Dec. 31, and the FFS length is set at 365 days. Note that the regional climate simulation output is saved every 3 hours as instantaneous values, which means that the minimum temperature criteria for some days could have been met in the simulations but do not appear in the saved outputs. Thus, the FFS length appearing in this study is an overestimation of the FFS length in the regional climate model simulations.

3.3 Results

3.3.1 Frost Indices

The spatial distributions of the LSF and FFF dates, and the resulting FFS length, are dependent upon latitude, elevation, distance to oceans, ocean-surface temperature, and other regional and local characteristics. This dependency is evident in the spatial distributions for the LSF, FFF, and FFS simulations for both the current and future LULC patterns (Figure 3.2).

The overall spatial patterns of dates of the LSF and FFF in the CONUS do not appear to be strongly dependent on LULC pattern (c.f. Figures 3.1 and 3.2). For both the current and future LULC patterns, earlier simulated dates of LSF more often occur at lower latitudes, at lower elevations, and away from coastal regions. The earliest dates of LSF occur in southern Florida, southern Arizona, and parts of southern California and the Central Valley of California. The latest dates of LSF occur over high mountains in the Cascades, the Rockies, and the Sierra Nevada. The spatial distribution of the differences in simulated dates of LSF between the current and future LULC patterns reveals that changes in LULC result in earlier simulated dates of LSF across most of the CONUS, particularly in southern and central Florida (25+ days), over the coastal and Central Valley areas of California, and over southern and southwestern Arizona (15+ days).

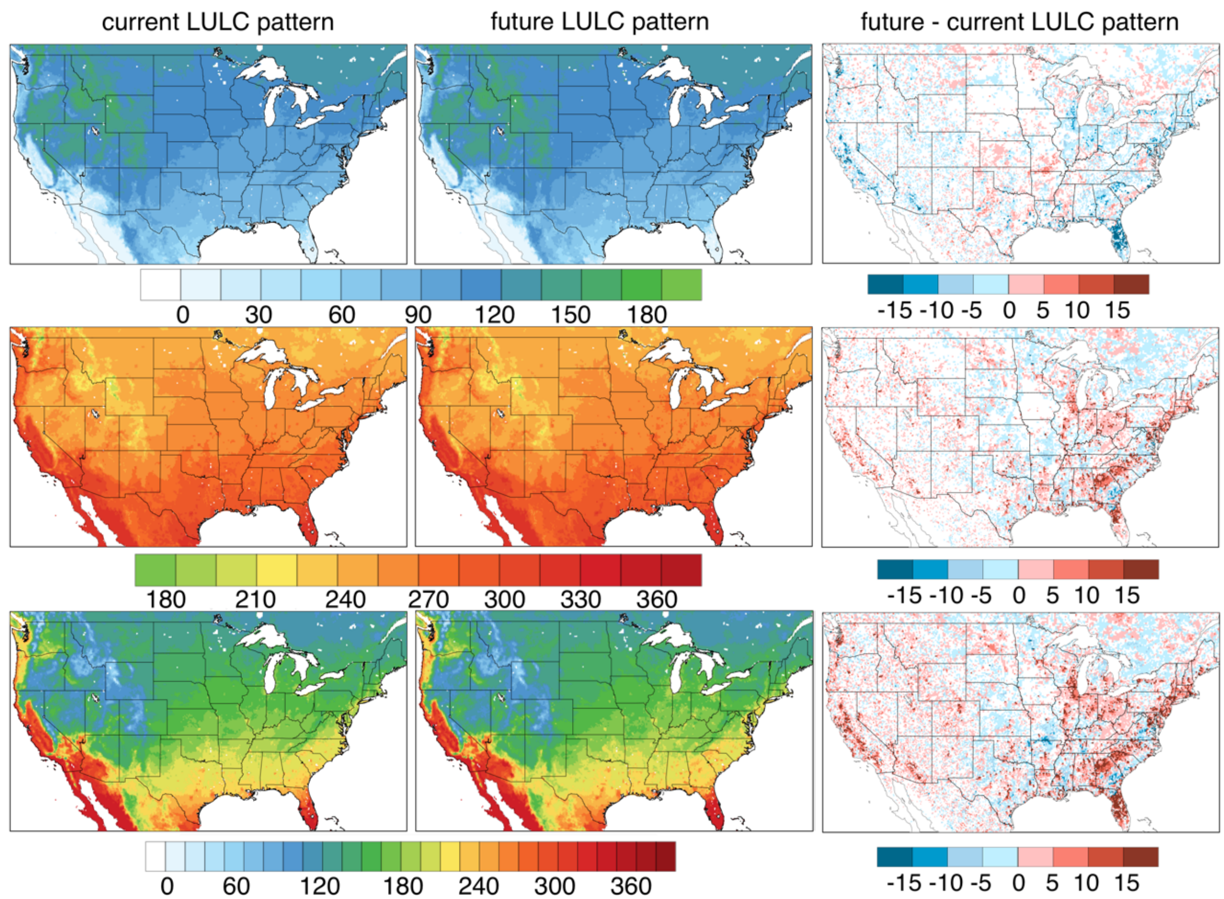

Figure 3.2. The dates of the LSF (top row), the dates of the FFF (middle row), and the FFS lengths (bottom row) for current (left column) and future (middle column) LULC patterns, and their differences (right column). White in the difference plot is where the difference in number of days is less than ± 1 day.

In addition, the simulated dates of LSF occur 10-15 days earlier in areas that are expected to experience urban expansion in the future (Figure 3.1), such as areas along the Mid-Atlantic coast, in the Midwest around Chicago, IL and Cleveland, OH, in the Northwest around Seattle, WA and Portland, OR, and the strip extending from Atlanta, GA northeastward to Raleigh, NC. Earlier simulated dates of LSF also occur in some areas of the central Great Plains and the Southeast. However, areas of the southern Great Plains, where natural grasslands are expected to be converted into cropland, and in the lower Midwest and portions of the Southeast, where conversion from forests to pasture or croplands is expected, a later occurrence of LSF is simulated.

The spatial distribution of FFF dates in the CONUS is nearly an opposite image of the spatial distribution of LSF dates. The earliest dates of FFF occur in the Rockies, Sierra Nevada, and Cascades, and the latest dates of FFF occur in southern and central Florida and in southern and central California. Earlier dates of FFF more often occur at higher latitudes, at higher elevations, and away from coastal regions. The pattern of differences between the current and future LULC patterns also exhibits nearly an opposite distribution to that of the spatial distribution of the dates of LSF, with later dates of FFF simulated in areas of Florida, California, along the Mid-Atlantic Coast, and in the Midwest where urban expansion is expected.

The co-occurrences of earlier dates of LSF and later dates of FFF generally lead to an increase in FFS length. Central and northern Florida experience an average increase in simulated FFS length of 5-6 days, while areas of northern Georgia and western North and South Carolina experience an average increase of 4-5 days. The average increase in simulated FFS length in central and southern California is about 1-2 days. However, some regions in the CONUS experience a decrease in simulated FFS length. A shorter simulated FFS occurs in parts of the Great Plains and coastal regions in the Southeast (e.g. eastern Texas, Missouri, Arkansas, eastern Georgia and eastern North and South Carolina), where grasslands or forests are expected to be replaced by croplands or pasture/hay lands.

A longer or shorter FFS can result from several different combinations of shifts in the LFS and FFF dates. For a given location, the specific change in the FFS length depends not only on the direction of the shift, but also on the amount. Here, the letter E (e) and L (l) are used to denote the shift towards earlier or later LSF or FFF dates, with the upper or lower case letters representing relatively larger or smaller amounts of change in spring or fall. A longer FFS can arise from the following 6 scenarios: a shift towards an earlier LFS and a later FFF, with a larger shift occurring in either the spring (El) or the fall (eL); a shift towards an earlier LSF and an earlier FFF, with a larger shift occurring in the spring (Ee); a shift towards a later LFS and a later FFF, with a larger shift occurring in the fall (lL); a shift towards an earlier LSF with no change in the FFF (E0); and finally a shift towards a later FFF but no change in the LSF (0L). Similarly, a shorter FFS can be caused by following 6 scenarios: a later LSF and an earlier FFF, regardless of the shift amounts (Le, lE); both the LSF and FFF shift towards earlier dates, with the larger shifts occurring in the fall (eE); both the LSF and FFF shift towards later dates, with the larger shifts occurring in the spring (Ll); a shift towards a later LSF and no change in the FFF (L0); and finally, no change in the LSF and a shift towards an earlier FFF (0E).

The relative contributions from the 6 scenarios to an increase or decrease in FFS length for each grid cell in the domain are shown in Figure 3.3. Also shown are the total contributions to an increase or decrease in FFS length in the CONUS for each scenario, calculated as the ratio of the number of grid cells explained by each scenario to the total number of grid cells where FFS increases or decreases in length. The largest contributions to increases in FFS length is due to shifts toward an earlier LSF and a later FFF (eL and El), with a slightly larger amount of change in spring (eL scenario, 14%) compared to the fall (El scenario, 12%). Together, these two scenarios account for 26% of all locations where an increase in simulated FFS length occurs. Longer FFSs are also caused by changes in one season but not in the other, with earlier LSFs and no change in FFF dates accounting for 12%, and later FFF dates coupled with no change in LSF dates accounting for 8%.

Overall, the increase in FFS length is caused more by shifts toward earlier LSF dates (E0 + Ee +El: 31%) than shifts toward later FFF dates (0L + eL+ lL: 27%).

The contributions to the decrease in FFS length is distributed more or less equally among the 6 scenarios, with eE, lE, and L0 all contributing 8%, 0E contributing 7%, Le contributing 6%, and Ll contributing 5%. In contrast to the contributions to the increase in FFS length, the decrease in FFS length appears to be caused more by earlier FFF dates (eE + lE + 0E: 23%) compared to later LSF dates (Le + Ll + L0: 19%).

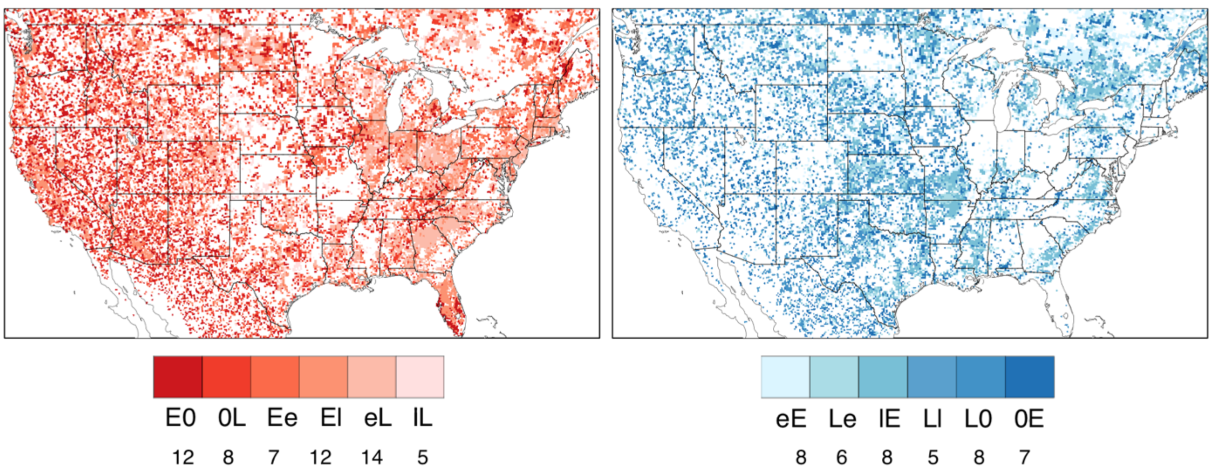

Figure 3.3. The contributions to increase (left) and decrease (right) in the FFS length from all six combinations of changes in the direction (E, e for earlier and L, l for later) and amount (E, L for larger amount relative to e, l). The number below each scenario is the fraction of the grid cells explained by that scenario as calculated by the number of grid cells explained by that scenario to the total number of grid cells with increase and decrease in FFS length.

Figure 3.4 shows the spatial distribution of the contribution to increase or decrease in FFS length, with the previous 12 possible combinations between the direction and relative amount of the changes in LSF and FFF reduced to 4 combinations, where each combination indicates the dominant contribution to an increase or decrease in FFS length. Increase in FFS length can be dominated by an earlier LSF (E0, El, Ee) or a later FFF (0L, eL, lL). Decrease in FFS length can be dominated by a later LSF (L0, Ll, Le) or earlier FFF (0E, lE, eE). In the Southeast, most of the increase in FFS length appears to be associated with later LSF, except for Florida where the increase in FFS length is largely caused by an earlier LSF. Increase in FFS length in California can also be largely attributed to an earlier LSF. For areas that experience a decrease in simulated FFS length, the change is largely caused by a later FFF in the southern Plains, but by an earlier FFF in the Southeast.

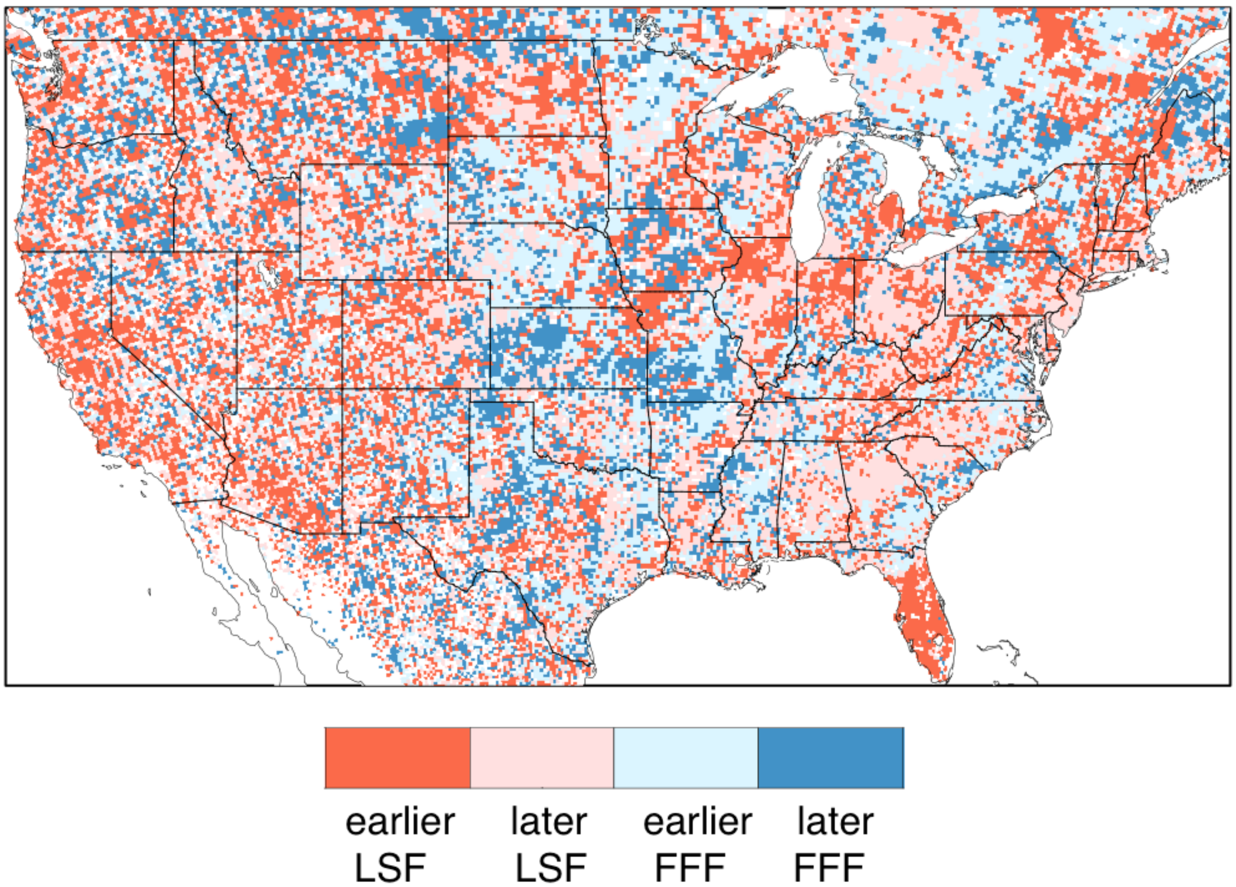

Figure 3.4. The contribution to the increase (red) and decrease (blue) of FFS length from earlier or later occurrences of LSF and earlier or later occurrences of FFF. White areas in the plot indicate locations where there is no change in FFS length.

3.3.2 Minimum temperature

Frost formation is directly related to minimum temperature. To understand the influence of LULC change on frost occurrence, changes in minimum temperature between the two regional climate simulations are examined (Figure 3.5). Average minimum temperatures in the CONUS vary from 10-20 ^{o}C in the South, Southeast, and coastal regions, 0-10 ^{o}C in the Midwest, Northeast and Northwest, and below 0 ^{o}C in parts of the Northern Plains and at high elevations. While changes in LULC do not alter this overall spatial pattern, increases and decreases in simulated minimum temperature occur in some areas, most notably in the eastern CONUS and in California. Specifically, increases in minimum temperature occur in areas where LULC changes from natural to urban land use in the future (c.f. Figures 3.5 and 3.1). This is particularly evident in Florida, the Mid-Atlantic coast, in the Midwest (IL/IN/OH region), the strip of urban areas extending from Atlanta, GA to Raleigh, NC, coastal north Atlantic states and cities in the West. The increase in simulated minimum temperature contributes to earlier dates of LSF, later dates of FFF, and increase in FFS length (c.f. Figures 3.5 and 3.2). While more areas experience increases in simulated minimum temperature, decreases in minimum temperature occur in regions of the Great Plains, the coastal region of southern Georgia and the eastern Carolinas where changes from natural LULC (grassland and forested land) to cultivated lands (cropland or pasture/hay lands) are expected to occur (c.f. Figures 3.5 and 3.1). The decreases in minimum temperature in these regions correspond to locations where a decrease in simulated FFS length occurs (c.f. Figures 3.5 and 3.2). Across the CONUS, 46% of the grid cells experience a change in minimum temperature, while 14.5% of the grid cells experience a change in LULC, indicating that the effect of LULC change on minimum temperature is not limited to the local scale. The decrease in minimum temperature in regions expected to experience transition to cultivated lands generally agrees with the results of Bonan (1999). Note, however, that Bonan (1999) used two 10-year regional climate simulations, but with modern and pre-colonial natural vegetation in the U.S., and showed that conversion of forest to cropland in the eastern and central United States led to a decrease of 0.6-1.0 °C in mean annual surface air temperature.

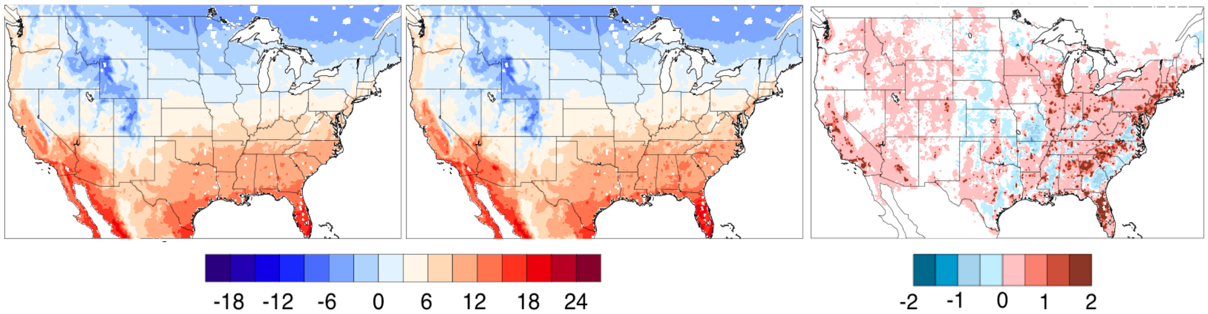

Figure 3.5. Minimum temperature (°C) averaged over the 10-year period for the current (left) and future (middle) LULC pattern and the difference between them (right). White areas in the difference plot correspond to temperature differences of ± 0.05 °C or less.

Figure 3.6 shows the distribution of the differences between current and future minimum temperatures for all 40892 grid cells in the CONUS where a change in LULC is expected, for cells where no change in LULC is expected, and for cells where a change from natural to urban or natural to cultivated LULC is expected. Considering the entire CONUS, the median value of the minimum temperature difference between the current and future LULC patterns is 0.04°C, with 75% of the values falling within 0 and 0.1 °C and 95% within -0.21 and 0.73 °C (Figure 3.6). A similar distribution is found for grid cells where no change in LULC is expected, with 95% of the values falling within -0.1 and 0.43 °C. However, at grid cells where LULC is expected to change, 75% of the values fall in the range of –0.23 to 0.55 °C and 95% of the values are within –0.75 and 3.67 °C. The median value is -0.03 °C.

As shown earlier, expected changes in LULC can be characterized by urban expansion (or transition from natural to urban land use) and conversion from natural to cultivated lands (cropland and pasture/hay). The corresponding changes in simulated minimum temperature for these specific

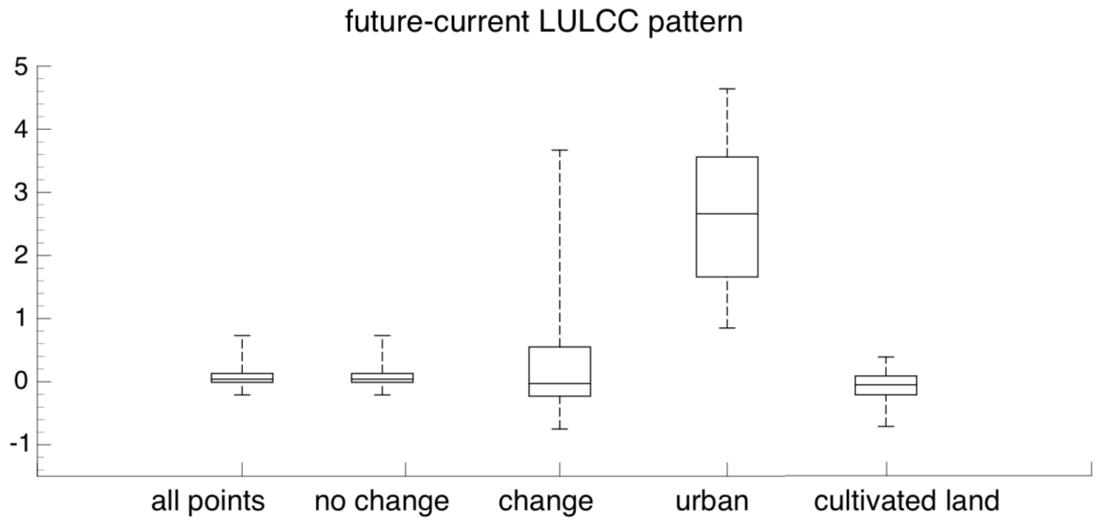

Figure 3.6. Box-whisker plots of differences in minimum temperature between current and future LULC patterns. The box denotes the 25% and 75% quartiles, the horizontal line indicates the median value, and the whiskers indicate the 5% and 95% quartiles.

LULC changes are also shown in Figure 3.6. Conversion to an urban environment is always associated with an increase in minimum temperature, and the spread is large, with the 95th percentile ranging between 0.84-4.63 ^{o}C and a median of 2.65 ^{o}C. The conversion to cultivated land from forests, shrub lands, and grasslands is associated with a decrease in minimum temperature, with a median of -0.07 ^{o}C and the 95th percentile of -0.73-0.37 ^{o}C, which is much narrower than the range associated with changes from natural to urban land. While the temperature increases over locations expected to experience conversion from a natural land to urban is much larger than the temperature decreases over areas expected to experience a conversion from natural to cultivated lands, the area expected to undergo natural to cultivated land conversion is much greater (3433 grid cells) than the area expected to undergo urban expansion (1299 grid cells). The relatively smaller amount of cooling over larger areas compensates for the relatively larger amount of heating over smaller areas, leading to a near zero median value (0.04^{o}C) over the CONUS.

3.4 Surface Energy Budget

LULC change is one of the main factors leading to changes in surface energy fluxes and partitioning of net radiation. LULC transitions are characterized by changes in factors such as surface roughness, leaf area index (LAI) and albedo, which in turn lead to changes in energy, moisture and momentum fluxes (Mahmood et al. 2014). To further investigate the mechanisms through which LULC changes can affect minimum temperatures and the FFS length in the regional climate simulations, surface energy budgets from the simulations and their differences are examined. Following Mahmood et al. (2014) and Li et al. (2017), the land-surface energy budget equation can be written as:

$$R_{net} = SH + LH + GH$$

where R_{net} is net radiation and *SH*, *LH*, and *GH* are sensible, latent and ground or soil heat fluxes, respectively. The net radiation is calculated as the sum of solar radiation (SR) and longwave (LR) radiation

$$R_{net} = SR(1 - a) + LR_{down} - LR_{up}$$

where *SR* is solar radiation, a is albedo, and LR_{down} and LR_{up} are downwelling and upwelling of longwave radiation, respectively.

Figure 3.7 shows average values of the simulated energy budget components in the southeastern CONUS where significant LULC change is expected. In areas influenced by urban expansion, such as northern and central Florida and the corridor from Atlanta GA northeastward to Raleigh NC, there is a decrease in latent heat flux and an increase in sensible heat flux, as forests and other natural land cover is replaced by impervious surfaces. This tends to increase temperatures despite smaller net radiative fluxes due to increased albedo. Net radiative fluxes and latent heat fluxes also decrease in areas of forest-to-cropland conversion, such as southern GA and

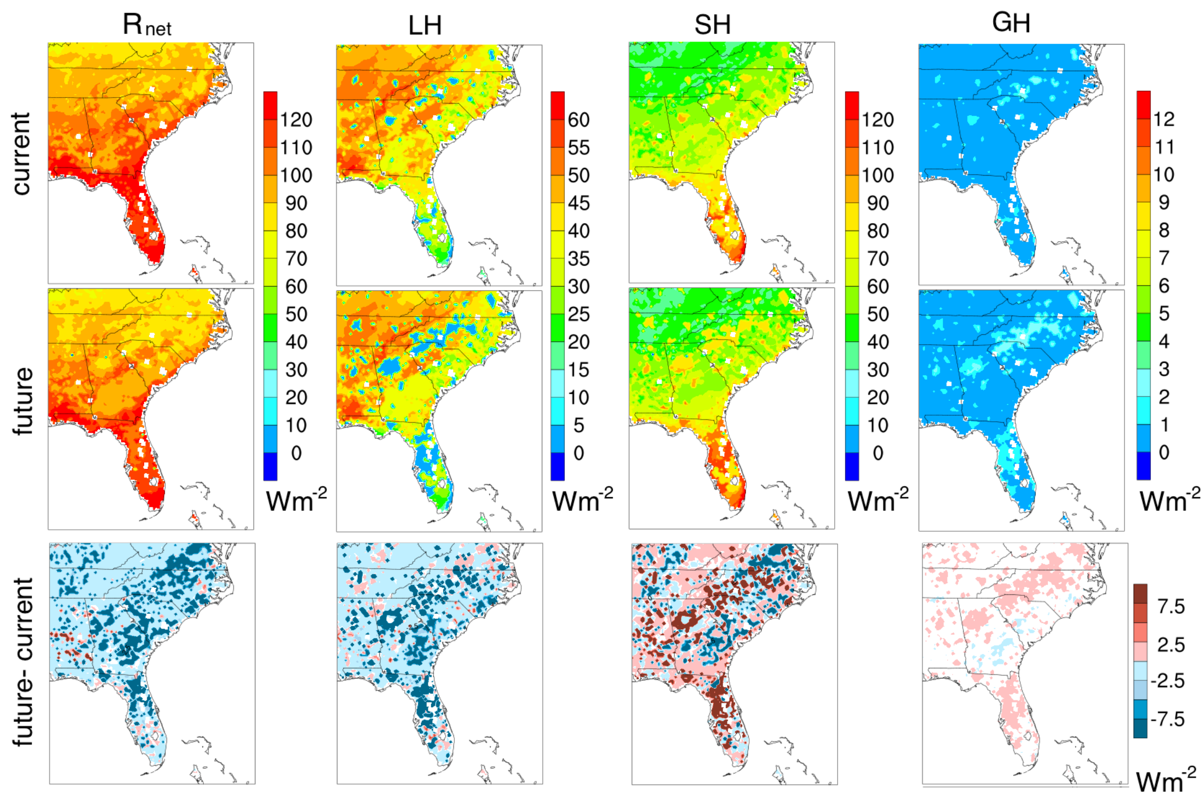

Figure 3.7. Average net radiative flux (first column), latent heat flux (second column), sensible heat flux (third column) and ground heat flux (forth column) for the current (first row) and future (second row) LULC simulations and their differences (third row). The differences $\leq \pm 0.1 \mathrm{Wm}^{-2}$ are indicated in white (third row).

the eastern Carolinas. But instead of an increase in sensible heat flux as associated with urban expansion, forest-to-cultivated land conversion is associated with a decrease in sensible heat flux and a decrease in temperature. For both LULC change patterns, the contribution from changes in GH is relatively small compared to the other components.

These results are in agreement with previous studies on LULC and surface energy budget. In the case of expected replacement of vegetated surfaces with an urban environment, LH fluxes are substantially reduced while SH fluxes become dominant (several orders of magnitude larger than LH fluxes). This results in an increase in surface temperature or the so-called Urban Heat Island (UHI) effect (Grossman-Clarke et al. 2010, Mahmood et al. 2014). On the other hand, LULC change related to transitions from forested or natural grass lands to cultivated land usually results in a reduction of surface temperature. Lowered surface roughness and increased albedo are some of the factors contributing to this change (Bonan 1997). In these regions, LH fluxes may become more dominant than SH fluxes, especially where irrigation occurs (Mahmood et al. 2014). Bonan (1999) and Diffenbaugh (2009) showed that areas experiencing transitions from natural land cover (forests or natural grass lands) to cultivated land are expected to experience decreases in average temperature, with sensible heat fluxes being the major driver of that change (Bonan 1999).

3.5 Conclusion

Regional climate model simulations under current (2011) and future (2100) LULC patterns for climate conditions in the period 2006-2015 were analyzed to examine the influence of LULC change on frost indices including the dates of LSF and FFF, and FFS length. The results reveal longer FFS in the future in areas affected by significant urban expansion and shorter FFSs in areas where conversion from natural (forests or grassland) to cultivated land (cropland, pasture/hay) is expected to occur. The amount of change in the FFS length, however, varies considerably with location. Areas of considerable urban expansion in the Southeast, particularly Florida and around major cities in the South Atlantic States and along the North Atlantic coast, in the Central valley of California and in the Midwest, are expected to see an increase in FFS length from a few days to as much as two weeks. Compared to the increase in FFS length due to urban expansion, the amount of decrease in FFS length associated with the conversion from forests to cultivated lands is less (days to a week). The decrease in FFS length is most noticeable over the southern and central Great Plains, over southern Georgia, and over the eastern Carolinas.

The increase in FFS length is usually the result of an earlier occurrence of LSFs (E0 scenario), in addition to a later occurrence of FFF (both eL and El scenarios), and the decrease in FFS length is mostly a combination of both later and earlier onsets of LSF and earlier dates of FFF, as well as just later dates of occurrence of LSF. Other combinations, e.g., earlier or later arrivals of both LSF and FFF, may also lead to an increase in FFS length, but their contributions are less compared to the described scenarios.

Areas that are expected to see transitions to cultivated land experience a decrease in simulated FFS length and a decrease in minimum temperatures resulting from a reduction in sensible and latent heat fluxes. These results are in agreement with previous studies (Bonan 1999, Diffenbaugh 2009), and suggest transitions to cultivated land may mitigate some of the warming effects of urban expansion in the US.

Finally, it should be noted that the results presented in this study are based on model simulations that only account for changes in LULC patterns; future changes in climate conditions are not considered. This may lead to a possible overestimation of the local response to LULC change. Also, analyzed model results could be affected by physics parameterizations and the current model design. Nevertheless, the presented results suggest that expected changes in LULC in the CONUS should be considered when assessing anthropogenic impacts on future climate conditions.

Chapter 4. Land use land cover change and wind energy resources in the U.S. – a sensitivity study using a regional climate model

Abstract: Over the last several decades, wind energy has emerged as one of the main zero-carbon emission alternatives to energy production. While many have projected how wind energy resources over the United States will respond to greenhouse gas-induced climate change, fewer have assessed the potential response of wind energy resources to changes in land use and land cover (LULC), an important driver for climate change. In this study, we quantify the potential changes in the 50-m wind speed, wind energy density and wind power classes due to LULC changes by comparing results from a pair of 10-year regional climate model simulations with the current and future LULC patterns. In areas of the Southeast (except Florida), the Great Plains and the Ohio and Mississippi River Valley, wind energy potential will likely to be enhanced by LULC change, but in parts of the Midwest, west Texas, Florida and Pacific Northwest will likely to experience a decline in wind energy potential. Overall, majority of changes in wind energy potential result from a direct response to alterations in surface roughness lengths, with decreased roughness lengths (e.g. forests to croplands) corresponding to enhanced wind energy potential, and vice versa. This is not true, however, over areas of Great Plains where areas of increased roughness lengths overlain those of increased wind speed, because winds there are dominated by synoptic- and regional-scale forcing that does not respond directly to changes in underlying surface conditions.

4.1 Introduction

Energy production is estimated to have contributed to about 72% of the world's total emissions of carbon dioxide (CO_2), the gas linked to global warming (World Resource Institute, 2017). In an effort to limit CO_2 emissions and slow down the rate of global warming, traditional fossil-fuel based energy production is being replaced by renewable energy such as solar and wind energy. Over the past several decades, there has been a significant expansion of wind energy as a zero-carbon energy resource and this trend is expected to continue into the future. However, wind speed is expected to change in the future as a result of alterations to atmospheric circulation patterns by global climate change (Jerez and Trigo 2013, Jerez et al. 2013), as well as land use and land cover change (LULCC) (Vautard et al. 2010, Bichet et al. 2012). Understanding distributions and trends in wind energy resources and their relationships to climate change and LULCC, both globally and locally, has important policy implications.

Previous studies, based on model simulations, suggest that climate change will have an impact on surface wind speed, and therefore on wind power generation potential (Pryor et al. 2009, Breslow and Sailor 2001, Segal et al. 2001, Sailor et al. 1999, Pryor et al. 2005). Pryor et al. (2005) compared the Rossby Centre coupled Regional Climate Model (RCM) runs between 1961 and1990 and between 2071 and 2100 under two emissions scenarios and found an increase in wind energy resource potential over northern Europe. Breslow and Sailor (2001) analyzed outputs from the general circulation models (GCMs) and found a decline in simulated wind speed over the United States (U.S.), but the magnitude of change is within the range of inter-annual climatological variability. Pryor et al (2012), based on simulations from the North American Regional Climate Change Assessment Program (NARCCAP, Mearns et al. 2009) RCM model outputs under various greenhouse gas emissions scenarios concluded that mean wind speed will likely to decrease in the

West, Northwest and Northeast, while increase in North Texas and Kansas by mid-century. Johnson and Erhardt (2016) in their analysis of NARCCAP simulations found a similar pattern, with wind energy density (and therefore wind speed) increase in North Texas and decrease in the Northeast and Northwest. The increasing trend in wind speed over Texas is also found in a study done by Craig et al. (2019), while Haupt et al. (2016) indicated that wind speed change in Texas as a result of climate change will experience strong dependency on season and time of the day. Pan et al. (2011) found little or no change between probability distribution of daily wind speeds in the current and future projections over California and Nevada. Segal et al. (2001) indicated that wind speed change is dependable on the season, and that seasonal wind power will decrease over most of the U.S., with exception of small areas in the southern and northwestern U.S. that will experiencing small increase.

While many studies have examined potential influence of climate change on wind speed, fewer have focused on the relationship between LULCC and wind speed change (Radics and Bartholy 2002, Wu et al. 2016, Yan et al. 2008). Radics and Bartholy (2002) found that changes in wind speed are influenced by changes in agricultural practice and land properties, but at the same time, some other factors, such as an increase in temperature in the near future, contribute to changes in wind properties. In Asia, Wu et al. (2016) examined the impact of LULCC over the Eastern China Plain in the period between 1980 and 2011 by comparing statistically downscaled ERA-Interim reanalysis data, which have little or no impact by LULCC effect, with observational data that directly influenced by LULCC. They found that LULCC has a significant impact on the declining trend in surface wind speed by reducing surface wind speed up to 0.17 m s^{-1} per 10 years. They also confirmed that the main driver for the surface wind speed change is the increase in the surface drag force caused by LULCC. Li et al. (2008) used a similar approach with a different global reanalysis (NCEP reanalysis, Kanamitsu et al. 2002) and observations to investigate LULCC induced surface wind speed variations and concluded that the main forcing behind the declining trend in mean wind energy is urbanization and other changes in surface properties over the region. In Europe, studies reported an increase in surface wind speed in the north and a decline in surface wind speed southern Europe and the Mediterranean Sea (Pryor et al. 2006).

The objective of the current study is to quantify the changes in wind energy resources in the contiguous United States (CONUS) caused solely by LULCC. This study will compare model outputs from high-resolution RCM simulations using the current and future land use and land cover (LULC) patterns at the lower boundary. Since the other model settings remain identical between the simulations, the differences can be explained by nothing else but the changes in LULC patterns.

The rest of the paper is organized as follows: the methods utilized for the study, including the numerical model and LULC data, are described in Section 4.2. Section 4.3 presents the results, which is followed by discussion in Section 4.4. The paper is concluded in Section 4.5.

4.2 Methods

The approach taken by this study is commonly used in model sensitivity analyses. In order to understand the sensitivity of a variable to a particular forcing, model simulations are run where all the settings are identical between simulations, except for the characteristics of the forcing. In this case, the variable is wind speed and the forcing is LULC types at the earth's surface or the lower model boundary. In the following, we describe the model configuration including LULC data and the sensitivity simulations. We also describe how the results of the simulations are analyzed, including calculations of wind energy density. It is worth noting that the model simulations had been completed as part of a larger study on the overall impact of LULCC on regional climate in the United States and the current study only analyze the results of the simulations.

4.2.1 Model configuration and land use land cover data

The Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) is used for the simulations. The WRF model is configured with a single domain centered over CONUS and covering most of the North America as well as the adjacent oceans at a constant horizontal grid spacing of 15 km and variable vertical grid spacing stretching over 28 vertical levels from the surface to 100 hPa. Physical parameterizations for the simulations include Dudhia (Dudhia 1989) for solar radiation and Rapid Radiative Transfer Model (RRTM, Mlawer et al. 1997) for terrestrial radiation; the modified Tiedtke (Tiedtke 1989, Nordeng 1995, Wang et al. 2003, 2004a) for cumulus convection and the WSM 3-class simple ice (Hong et al. 2004) for microphysics processes; the Mellor-Yamada-Janjić (Mellor and Yamada 1982, Janjić 1990, 1994, 2001) scheme for and Janjić (Janjić 1996) scheme for boundary and surface layer processes and finally, the Noah land surface model (Chen et al. 1996, Ek et al. 2003) for land-surface processes.

Two 10-year (2006-2015) simulations were performed. These simulations used the same model configurations described above and were driven by the same initial and lateral boundary conditions derived from the North American Regional Reanalysis (NARR, Mesinger et al. 2006). The only difference between the two simulations is the LULC type prescribed at the model's lower boundary. LULC type is a key parameter defining the lower model boundary condition at each model grid point because it directly affects the energy exchanges between lower atmosphere and the underlying Earth's surface. For example, forests have higher evapotranspiration and lower albedo than bare soil, and as a result forested areas usually have lower temperature during the day compared to bare ground. On the other hand, forests have highest roughnesslength among all LULC types and higher roughnesslength creates stronger friction to winds.

The LULC type is prescribed at each model grid point, which remains stationary throughout the 10-year simulation period. For the first simulation, the LULC types are prescribed using U.S. Geological Survey (USGS) national-scale LULC estimate for the year 2011 (referred simply as the current LULC). For the second simulation, the estimate for the year 2100 is utilized (referred simply as the future LULC). For each grid cell in the modeling domain, the dominant vegetation type is used as a representation of that grid cell. For more information about the USGS National LULC estimates, please refer to Land Use and Land Cover Modeling at https://www.usgs.gov/land-resources/eros/lulc. The LULC patterns for the two simulations are shown in Figure 4.1. Overall, comparing the current and future LULC types, the differences are characterized by two major changes: the first is a replacement of grassland by cropland over the Great Plains and forested areas by cropland in the Southeast and parts of Texas; and the second is a considerable expansion of urban areas into surrounding areas. The urban sprawl is particularly evident in the Southeast, especially Florida, and the mid-Atlantic states.

4.2.2 Wind energy density calculations

Wind energy density is a measure of available wind energy for energy production at any location. Wind energy density combines air density with the cube of the wind speed to provide a number representing available resources for wind energy generation:

$$E = \frac{1}{2} \rho \, U^3$$

where ρ is air density (kg m^{-3}), U is wind speed at hub-height (m s^{-1}), and E is energy density (W m^{-2}).

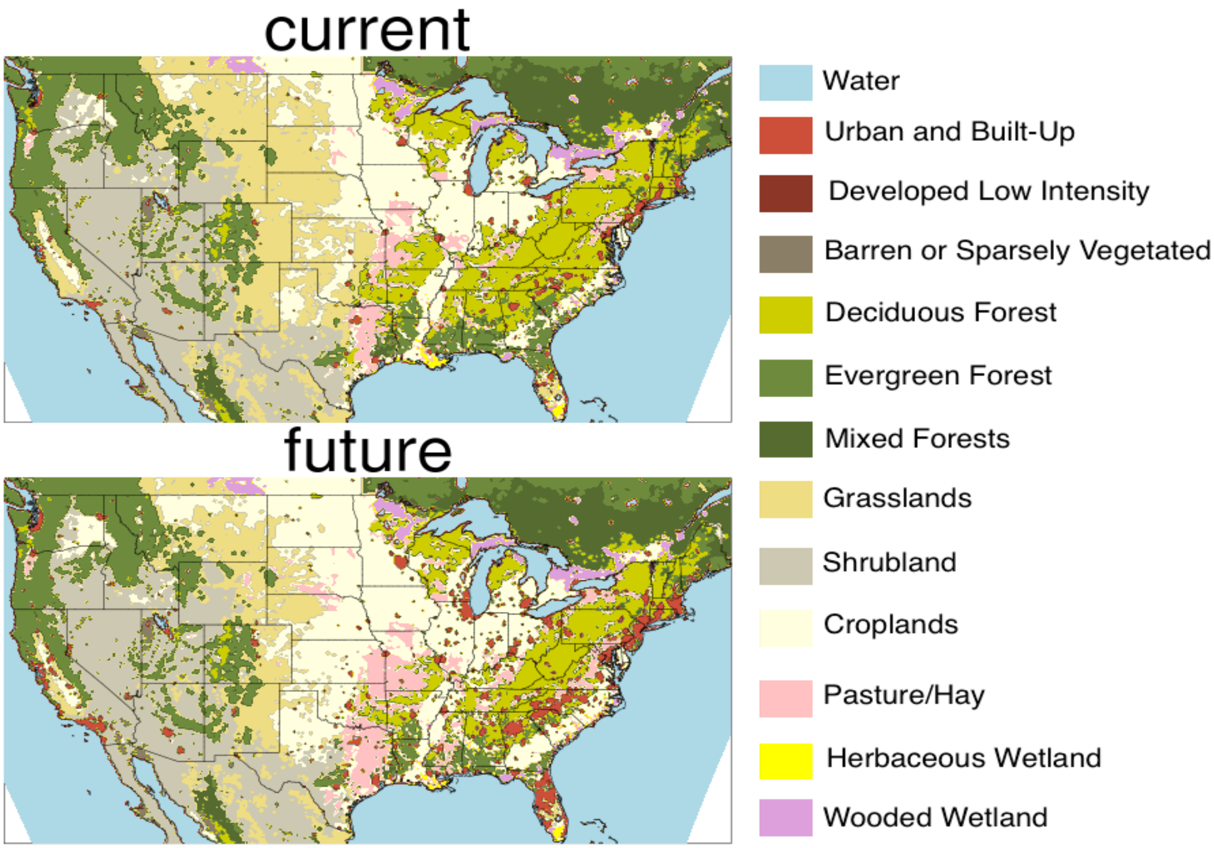

Figure 4.1. Spatial distribution of current (year 2011, top panel) and expected future (year 2100, bottom panel) LULC pattern.

In this study, we analyze LULCC-induced changes in wind density field at 50 m above ground level (AGL). The 50-meter wind is calculated following the power law

$$U_{50} = U_{10}\left(\frac{50m}{10m}\right)^{\alpha}$$

where U_{10} are wind speeds at 10 m AGL, which is a direct model output, and α, commonly assumed to be constant in wind resource assessments, is equal to $\frac{1}{7}$. Since wind energy density is a function of the cube of the wind speed, a small change in the wind speed will have a significant impact to the energy density and the wind energy resource (change in wind speed of 10% will result in 30% change in wind energy density).

Finally, wind power classes are defined based on the mean wind speed at the 50 m AGL and wind energy density (Table 4.1). It should also be noted that there are “cut-in” and “cut-out” wind speeds that define optimal wind speed range for a maximum wind energy production. Wind energy production is zero below approximately 4 m s^{-1}, after which it increases and reaches its maximum in production around 15 m s^{-1}, and then is usually constant until approximately 25 m s^{-1}, which is a “cut-out” wind speed for the energy production (Pryor and Barthelmie 2011).

Table 4.1. Wind power classes defined by 50-m mean wind speed and wind energy density

Wind Power Class	Wind Energy Density (W^2/m)	Wind Speed (m/s)
1	<200	0 – 5.6
2	200 – 300	5.6 – 6.4
3	300 – 400	6.4 – 7.0
4	400 – 500	7.0 – 7.5
5	500 – 600	7.5 – 8.0
6	600 – 800	8.0 – 8.8
7	>800	8.8 – 11.9

4.3 Results

To understand how expected changes in LULC patterns may affect wind resources over the CONUS, we compare the simulated annual means of the 50 m wind speed, wind energy density and wind power classes across different regions of CONUS. We also examine how the LULCC-induced change vary with season by compare seasonal means.

4.3.1 Annual and seasonal mean 50 m wind speed

For both the current and future LULC simulations and their differences, the 50 m wind speeds show a clear dependency on location (Figure 4.2). Regardless of the seasons, lower wind speeds are simulated in the Southeast and across much of the West, except over high terrains, while higher wind speeds are found over the Great Plains, in parts of Midwest, and at higher elevations.

There is some seasonal variation. For example, for most locations, particularly in high terrains and in the Great Lakes region, winter has the strongest seasonal mean winds, while over the Great

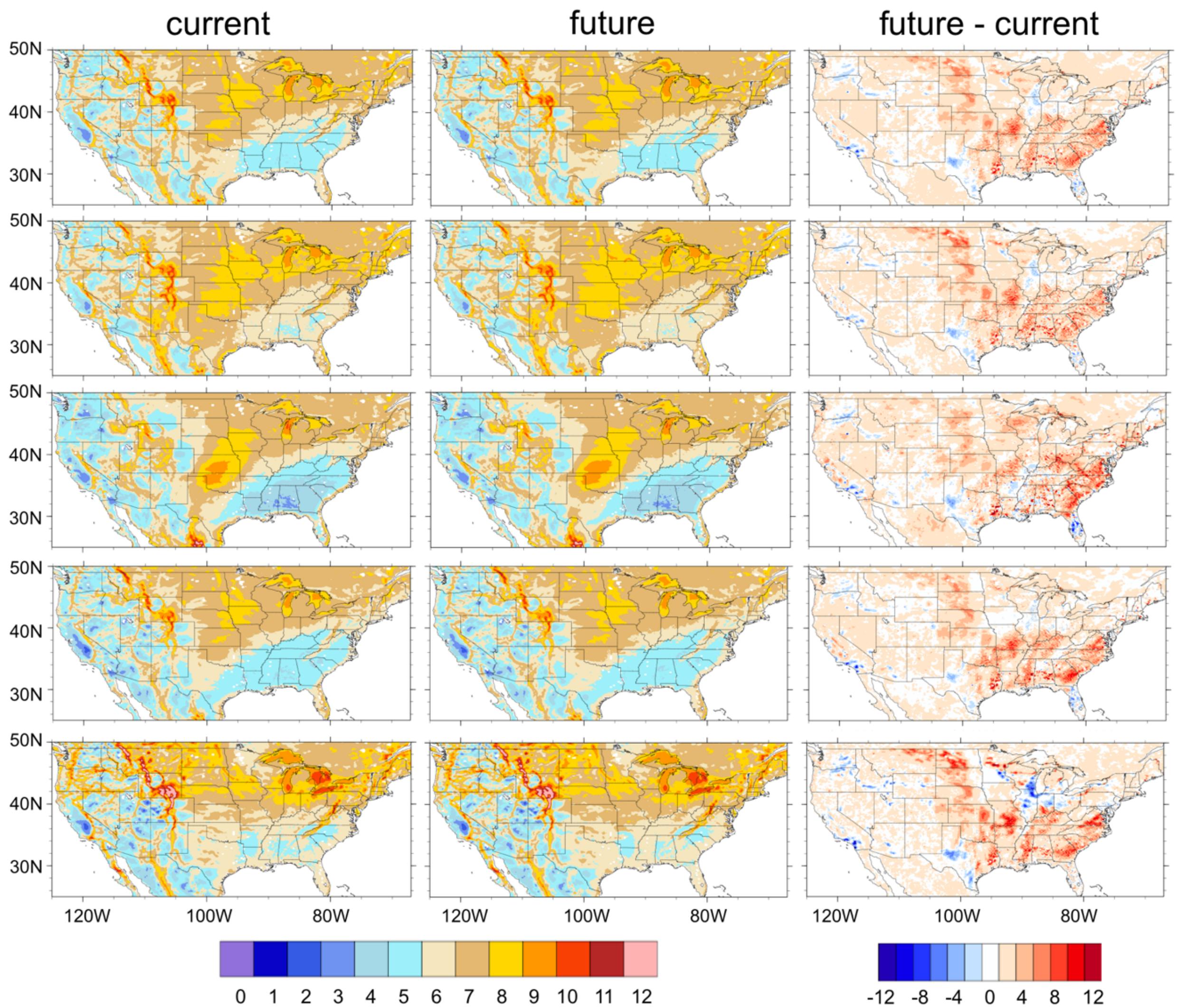

Figure 4.2. Spatial distribution of 50 m wind speeds averaged over the year (top panel), and over spring (second row), summer (third row), fall (fourth row), and winter (bottom row) under current (left column) and future (middle column) LULC patterns and the percent change between the two (right column).

Plains strongest seasonal winds occur in summer due to the existence of summer time low-level jet that has its core in the south-central Great Plains (Walters et al. 2008).

Although the changes in the underlying LULC types are not sufficient enough to alter this spatial distribution and seasonal variation pattern, there is a general increase in the seasonal and annual mean 50 m wind speed across most of the CONUS, with exception for some areas in the Intermountain West, Midwest, southwest Texas and Florida, where LULCC resulted in a decrease in wind speeds. Larger percent increase happens in areas of the Southeast, the Ohio and Mississippi Valley, and the Great Plains. A decrease in wind speed is projected for Florida, parts of Midwest, west Texas and southern California. The percent changes are the largest in winter and smallest in summer. An examination of the relationship between wind speed change and LULC change shows that a wind speed increase generally occurs over areas where forests are expected to be replaced by croplands, and a decrease is associated with urban expansion.

4.3.2 Annual and seasonal mean wind energy density

Because of the strong dependency (cube power) of wind energy density on the mean wind speed, it is no surprise to see that wind energy density has a similar spatial pattern as wind speed, but stronger spatial gradients (Figure 4.3). Maximum energy density is found over the high mountain ranges since wind speed increases with altitude away from the earth surface's friction. This is particularly true over the Rockies Mountains and the Sierra Nevada Range, and is slightly less over the Cascades and the Appalachians. Maximum wind energy density is also seen over the Great Lakes, resulting once again from less friction of lake surfaces compared to land surfaces. Lowest wind energy density occurs in low lying basins or valleys in western U.S., such as the Columbian Basin in eastern Washington and Oregon and the Central Valley of California. Wind energy density is also lower in the Gulf of Mexico States. On average, summer season has the lowest wind energy density except for a distinct local maximum in south-central Great Plains, while winter has higher values. Similar to wind speed, LULCC is likely to cause as much as 20%

increase in energy density over the Great Plains, the Ohio Valley and the Southeast, except for Florida where there is likely a decrease. A decrease in wind energy density up to 20% is also likely to occur in parts of Midwest, Texas and southern California. The percent change, whether increase or decrease, is the largest in winter. The largest decrease in wind energy density change is projected over large urban areas in the Midwest and western Texas in winter, as well as over Florida in all seasons.

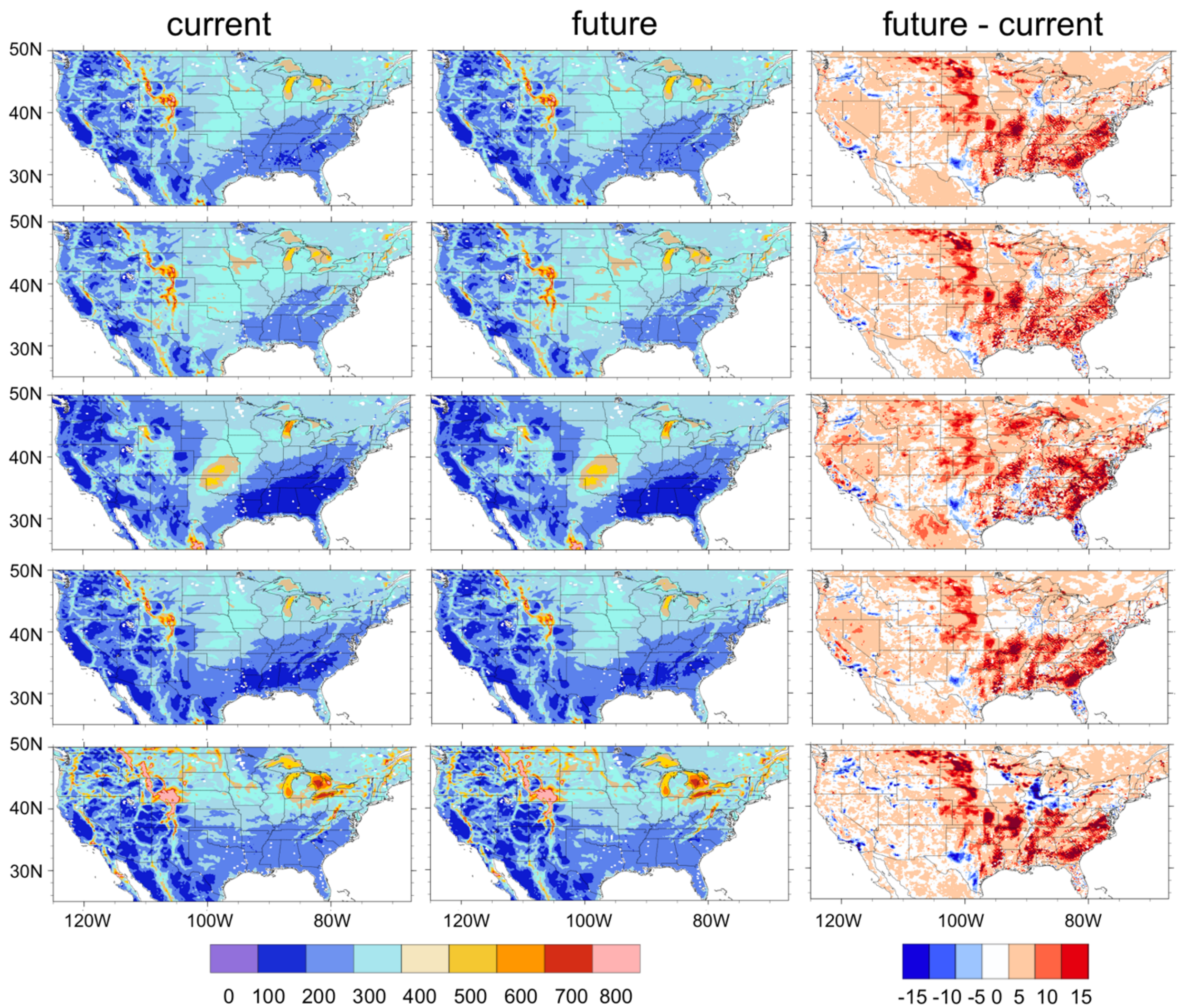

Figure 4.3. Same as Figure 4.2, but for wind energy density.

4.3.3 Implication to wind energy resource

Wind energy potentials can be estimated using wind power classes (Table 4.1). Class 3 and above are suitable for wind energy generation, Class 2 is marginal, and Class 1 is not suitable. So, the LULCC-induced changes to wind energy resources would make the most difference in currently lower class (1-3) locations, where a drop of 1 class from 3 to 2 (or 2 to1) would change the location from suitable to marginal (or marginal to unsuitable), and vice versa. Although the LULCC-induced wind speed increase or decrease tend to occur on regional scale, some of the change is not sufficient to alter wind power by one class and as a result, the changes in wind power class tend to occur in localized areas. In general, a drop in 1 class is seen in small areas of Florida, areas around major metropolitan centers in the Midwest, Texas and California. On the other hand, a raise in one class occur in areas of the Great Plains, the Great Lakes region and Indiana.

The changes in wind power classes show slight seasonal variability. An increase in wind power classes is simulated for the Great Plains in all seasons, with some areas of increase in Ohio Valley, parts of the Midwest and the mid-Atlantic states occurring mostly in spring and fall. A decrease is simulated in west Texas in all seasons, with secondary decrease areas in Florida in fall and some metropolitan areas of the Midwest in winter.

4.4 Conclusion and discussion

In this study, we analyzed results from two 10-year (2006-2015) simulations using a regional climate model driven at the lateral boundaries by reanalysis data and at the lower boundary by the current and future LULC patterns, to characterize potential response of winds at 50 m above ground to LULCC and its implication for wind energy production over the CONUS. The results show that although the changes to 50 m wind mean wind speed caused by LULCC is not enough to alter the overall spatial distribution across CONUS and seasonal variations, there will be a general wind speed increase across much of the CONUS especially in the Great Plains, the Southeast, the Mississippi and Ohio River Valleys. A decrease in wind speed is simulated in some areas in Florida, Northwest Texas, parts of the Midwest, as well as in the Pacific Northwest and southern California. The areas of increase or decrease remain independent of season, but the magnitudes of the LULCC-induced changes are larger in winter and smaller in summer.

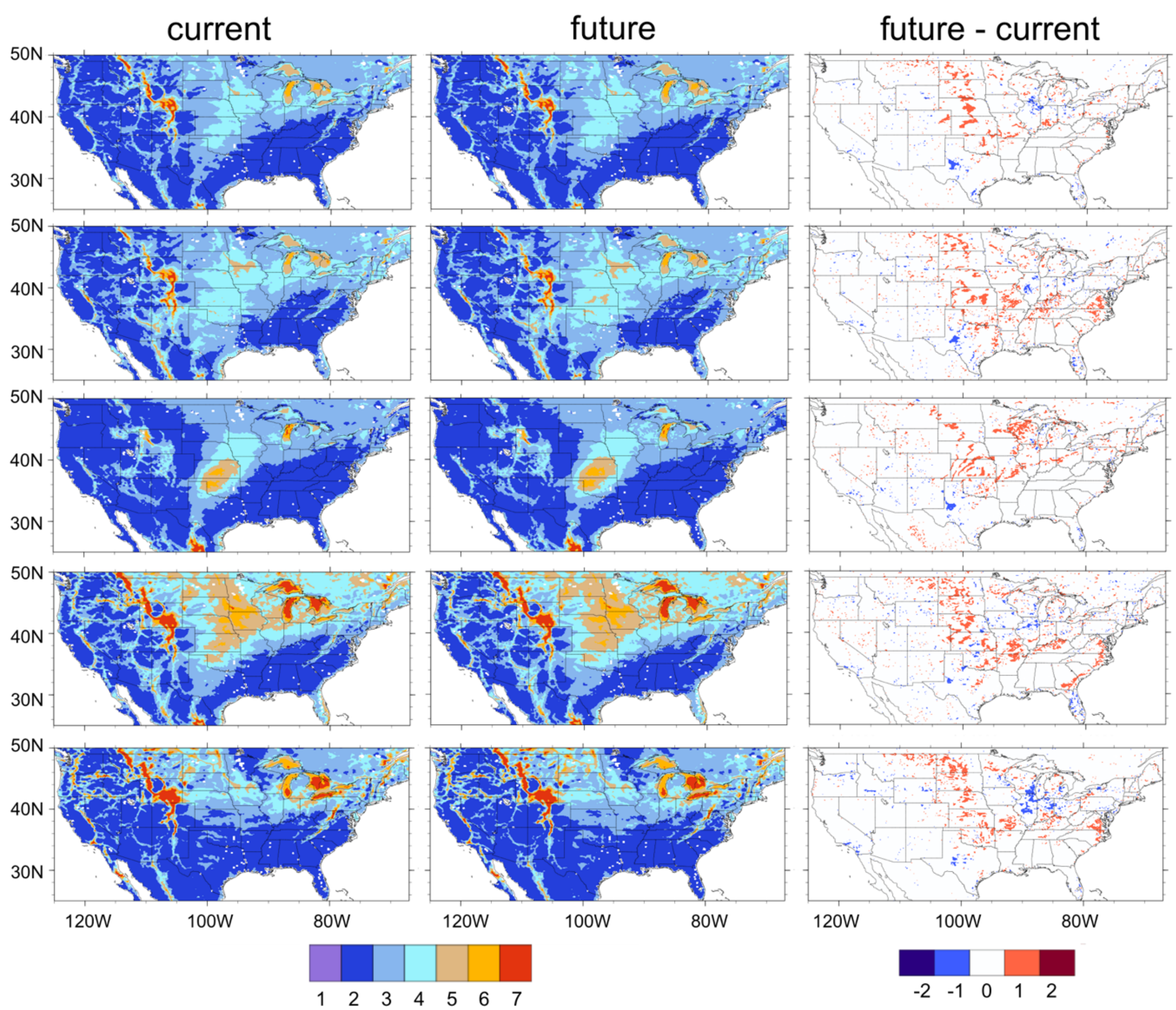

Figure 4.4. Same as Figure 4.2, but for wind energy classes larger than 3.

The response of wind energy density exhibits a similar spatial and seasonal variation pattern. An increase in wind power classes is simulated over the Great Plains and parts of the Ohio Valley in all seasons, while decrease is simulated for west Texas, parts of the Midwest and Florida. These results can have important implications for energy policy and future wind farm sitting.

The increase or decrease in wind speed and wind energy density can be largely attributed to the decrease or increase in surface roughness lengths, as the underlying LULC patterns change by both natural and anthropogenic forces. As shown in Figure 4.5, in which an increase or a decrease in roughness lengths is overlain on wind speed change, the areas projected to experience an increase in wind speed in the future in the Ohio and Mississippi River Valleys and in the Southeast coincide with the areas of decreasing roughness length as a result of conversion from forests to croplands (Figure 4.1), and areas expected to see an increase in roughness length (e.g., Florida, as a result of urban expansion) overlap with those of decreased wind speed. These results are in good agreement with previous studies that indicated a direct response of surface wind speed to changes in surface roughness lengths (Tao et al. 2013).

An exception to this lies in some areas in the central and northern Great Plains, where an increase of wind speed appears to coincide with an increase in roughness lengths. The LULC type change in these areas is mainly characterized by conversion from grassland to cultivated land (cropland and pasture/hay), with a slight increase in roughness lengths (Figure 4.1). A direct response of wind speed to roughness length would result in a slightly lower wind speed, but wind speeds in these regions appear to increase in the future. A possible explanation for this is that the seasonal or annual mean winds in these regions are dominated by synoptic and regional scale forcing instead of local forcing. During the cold seasons, winds in these regions are frequently associated with frontal movements, and in warm seasons they are enhanced by the frequent occurrence of low-level jets. Low-level jets are driven by large-scale pressure gradient related to the strength and location of Bermuda High (Uccellini 1980), mesoscale pressure gradient produced by differential heating over the high plains (Holton 1967) and by inertial oscillation related to the formation of surface-based temperature inversions (Zhong et al. 1996). Although the frequency and strength of surface inversions are influenced by surface energy budget that directly responds to LULCC, the effect is small compared to regional and synoptic scale influence on winds in this region.

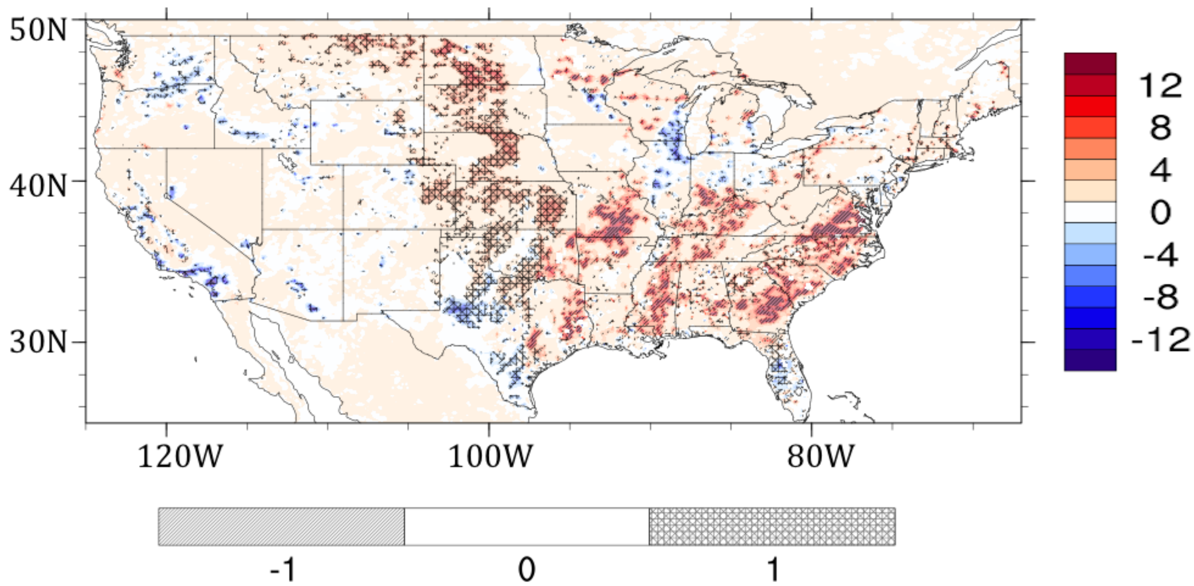

Figure 4.5. Spatial pattern of expected change in roughness length over the CONUS overlaid over spatial pattern of simulated change in 50 m wind speed.

It is worth noting that the simulated changes in wind speed due to LULCC are comparable to those due to increased greenhouse gasses (GHG) emissions. Therefore, LULCC-induced changes should be included as an important factor in local and regional-scale climate change and energy assessments together with increasing GHG emissions. Finally, the RCM simulations are driven by the same lateral boundary forcing derived from reanalysis data. In reality, the lateral boundary conditions, a reflection of larger-scale atmospheric circulations, should also change as a result of LULCC-atmosphere feedback. Such feedback needs to be taken into consideration for a complete assessment of future distribution of wind energy density and class across the CONUS.

Chapter 5 Conclusion

The dissertation research is aimed at quantifying the potential impact of LULCC between now and the end of the 21st century on selected processes and climate variables in the CONUS: the LLJ, frost indices, and wind energy resources. These processes and climate variables are chosen because of their broad impact on different sectors of the U.S. economy, such as agriculture and renewable energy. The assessment is based on high-resolution RCM simulations driven by the current climate conditions between 2006 and 2015 at the model's lateral boundaries, but with different surface forcing corresponding to the USGS's national estimates of the current (2011) and future (2100) LULC patterns at the model's lower boundary. The results from the two 10-year RCM simulations are used to produce the current and future climatology of the processes and three variables, and their differences caused only by the changes in the LULC patterns are analyzed along with possible explanations of the physical mechanisms for the differences.

For the LLJ climatology, the results indicate that the sensitivity of the LLJ characteristics (jet frequency, strength and elevation of the maximum wind) vary considerably with season and time of the day. Winter season jets and daytime jets, which are mostly associated with synoptic weather systems, are less sensitive to the local and regional changes in LULC patterns, compared to summer season jets that are forced primarily by boundary-layer processes and thus more sensitive to changes in surface conditions. It is simulated that in the future, summer jets are likely to be more frequent over the Great Plains, the core region of the jet, and less frequent in parts of the Ohio River Valley and the Southeast, particularly Florida. Although there appears to be some connection between urban expansion and less frequent, slightly weaker and more elevated jets, the direct connection between local changes in jet characteristics and changes in underlying LULC is weak.

In contrast to the LLJ, the response of frost indices – dates of last spring frost (LSF) and first fall frost (FFF) and the length of frost free season (FFS) – is more sensitive to local changes in LULC patterns. The results suggest that LULCC-induced changes to frost indices could be beneficial to agricultural production in some regions while harmful in others. A LULCC-induced decrease in FFS length, from a day to a week, is projected over some regions in the Great Plains and along the lower to mid-Atlantic states, where grass or forested lands are expected to be converted to cultivated lands in the future. An increase in FFS length from a few days to two weeks, however, will likely to occur in areas influenced by future urban expansion - particularly around the major cities in Florida, the lower and mid-Atlantic states, the Central Valley of California and the Midwest. Similar to frost indices, the projected LULCC-induced changes to wind energy resources also vary spatially, with generally larger percent changes in eastern U.S.. Future wind energy potentials are expected to be enhanced by LULCC in some areas of the Southeast (except Florida), the Great Plains and the Ohio and Mississippi River Valleys, and reduced in parts of the Midwest, west Texas, Florida and Pacific Northwest. Changes in wind resources also vary with season, with generally largest changes in winter and smallest in summer. There is a direct connection between changes in wind energy potential and underlying LULCC, where a decrease in surface roughness length resulting from the conversation from forests to croplands in the future, correspond to an increase in wind energy potential, and vice versa. An exception to this appears over areas of Great Plains where a general increase in wind energy potential is accompanied by a slight increase in surface roughness length. This may be explained by the fact that winds over the Great Plains are strongly influenced by the LLJ, and as concluded from the study in Chapter 2, the LLJ characteristics are not very sensitive to the local changes in LULC over the same area.

Several common features are shared by all three studies. First, impact of LULCC is not strong enough to alter the overall spatial distributions and seasonal variation of LLJ, frost indices and wind energy resources across the CONUS. Second, the modifications are generally more significant in eastern (particularly southeastern) than western regions in the CONUS. Florida appears to stand out from the rest of the Gulf States. Third, and also more important, the magnitudes of the changes due to LULCC, although may appear small, are comparable to the magnitudes of changes caused by increasing greenhouse gas (GHG) emissions. In other words, the local and regional climate response to LULCC are of similar magnitude as climate change signal induced by changes in GHG emissions (Diffenbaugh 2009). In some areas, such as those over the Great Plains and along the lower and mid-Atlantic coast, LULCC is likely to result in a decrease in minimum temperature, as shown in the second study, that may compensate the increase in minimum temperature caused by increasing GHG emissions. Therefore, it is necessary to take LULCC-induced climate change into account in decision making regarding regional climate change adaptation and mitigation.

It is worth pointing out that the results presented in this dissertation are products of RCM simulations. The RCM simulations are limited by the accuracy of model physical parameterizations, as well as the accuracy in the initial and boundary conditions, which in this case, are derived from the NARR reanalysis dataset. In addition, although the model horizontal resolution of 15 km is much finer than the resolution used by most general circulation models used for climate change studies, it is still unable to adequately resolve the spatial variability of LULC types and the changes. Higher resolution simulations at O(1 km) are necessary to capture small scale features in LULC patterns. Another major limitation is that the two simulations are forced at the lateral boundaries by current climate conditions. In other words, it is assumed that changes in LULC patterns within the modeling domain would not affect large-scale atmospheric circulations. In reality, the interaction and feedback between LULCC and climate change would occur not only at local and regional scales, as considered in these studies, but also at synoptic scale and beyond. Fully coupled climate modeling approach is needed to have a better understanding of LULCC-climate interactions.

The three studies presented in Chapters 2, 3 and 4 indicate that future climate change is sensitive to changes in LULC patterns and thus any possible future changes in climate of different variables cannot be fully assessed without the inclusion of more detailed representation of LULCC. Changes in LULC occur in response to both human and climate factors and are usually estimated based on economic factors. As shown by this research, LULCC and the changes in the processes and climate variables, LLJ, frost indices and wind energy resources, have important implications for economic sectors (agriculture, renewable energy) and should be included in future climate assessments.

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