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ELIZABETH NICOLE SMITH

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SCHOOL OF METEOROLOGY

BY

Dr. Petra Klein, Co-Chair

Dr. Evgeni Fedorovich, Co-Chair

Dr. Alan Shapiro

Dr. Jeremy Gibbs

Dr. Kieran Mullen

Dedication

For my childhood self, who always asked "why?" I still don't know all the 'whys', but that's the fun of it.

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Abstract

The nocturnal low-level jet (NLLJ) is a maximum in the vertical wind profile often occurring in the lowest 1-km of the atmosphere during the overnight hours in the Great Plains of the United States. This wind maximum has many implications including wind energy impacts, aviation hazards, and convection and precipitation forecasting. In broad terms, this dissertation set out to expand the current understanding of the mechanisms that lead to the development of NLLJs in the Great Plains. Using high resolution observations and numerical simulations together, this dissertation documents, describes, and analyzes spatial and temporal characteristics of the Great Plains nocturnal low-level jet.

The first part of the dissertation focuses on identifying the optimal configuration in which to run the Weather Research and Forecasting (WRF) model for NLLJ studies. Horizontal spacing finer than 4-km did not offer enough improvement to the resulting simulation to justify computational expense. Using finer vertical spacing did improve simulations of NLLJs. Sensitivity to planetary boundary layer parameterization scheme was generally small. Based on the conducted sensitivity tests, the optimal WRF model configuration for NLLJ studies was identified as based on a grid with 4-km horizontal spacing, 40-m vertical constant spacing, and employing the Quasi-Normal Scale Elimination planetary boundary layer parameterization scheme.

Next, data were collected during three Plains Elevated Convection at Night (PECAN) field campaign NLLJ cases and used alongside optimally configured simulations to identify and describe the spatial and temporal characteristics of Great Plains NLLJs. This analysis showed that the NLLJ is heterogeneous with respect to depth, wind speed, and wind direction. Additionally, the spatially heterogeneous NLLJ was shown to be moving across the slope of the Great Plains through the night. As such, the spatial and temporal characteristics of the nocturnal low-level jet are inherently connected and should not be considered independently.

This spatial-temporal evolution of the NLLJ has multiple implications for our understanding of local NLLJ features. The typical spatial and temporal evolution of the NLLJ was described using PECAN observed cases. A set of fourteen cases (including both PECAN and Lower Atmospheric Boundary Layer Experiment, LABLE, cases) were used to document and describe features of this evolution. Two buoyancy-related driving mechanisms were investigated to explain the spatial-temporal variability of the NLLJ. The consideration of this motion and spatial heterogeneity showed that sudden changes in the nocturnal boundary layer structure could be induced by the advection of spatial jet characteristics.

Chapter 1

Introduction

1.1 The boundary layer

The boundary layer is the lowest portion of the atmosphere resting just above the surface of the Earth which intensively exchanges heat, mass, and momentum with the surface. The vast majority of life on our planet takes place in this layer, yet the boundary layer is one of the least understood portions of the atmosphere. Our poor understanding is due in large part to boundary-layer motions ranging from the molecular scales to the mesoscale. Atmospheric flow in the boundary layer is essentially turbulent motion. This turbulence is crucial to the transport of physical substances from the surface into the atmosphere. Conditions in the boundary layer have far reaching impacts. From air quality concerns to agriculture to human impacts of extreme weather, knowledge of boundary layer processes is of paramount importance. In the context of weather research and forecast applications, boundary layer processes are one of the largest sources of uncertainty and forecast error (Sandu et al. 2013; Bauer et al. 2015).

The boundary layer's diurnal evolution is sketched in Fig. 1.1. During the day, the sun warms the surface of the Earth which gains thermal energy. This energy can then be transferred to the soil, to the atmosphere, or used in latent heating processes like evaporation. Transfer of sensible heat energy from the surface to the air during the daytime leads to turbulent convective motions that mix momentum, heat, and mass throughout the depth of the boundary layer. The sensible and latent heat fluxes control the vertical distribution of temperature in the boundary layer.

The resulting potential temperature distribution can be classified into stratification categories: stable (where the air aloft is warmer in terms of potential temperature than the air below), neutral (where the potential temperature is nearly constant), and unstable (where

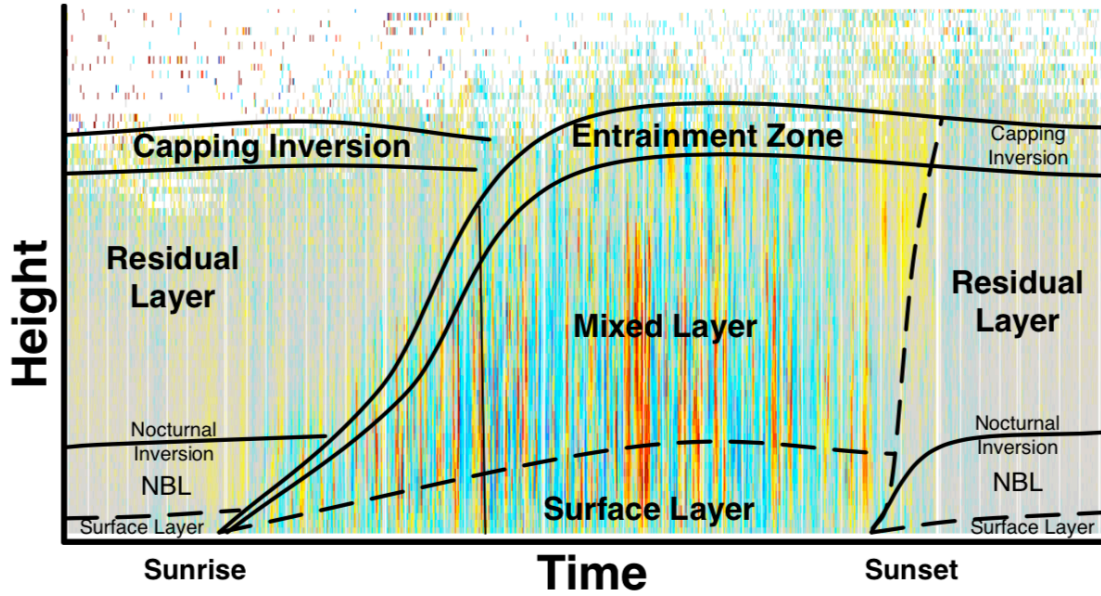


Figure 1.1: Schematic of the diurnal evolution of the boundary layer with Doppler lidar vertical velocity observations. Warm (cool) colors indicate rising(sinking) motions. Boundary layer regions are marked and labelled in an adaptation of a similar figure in Stull (2012).

air aloft is cooler than the air below). Unstable conditions, often observed during the day, are indicative of vertical parcel accelerations. Neutral conditions are often observed during transition periods between night and day and are typically characterized by decaying buoyancy forces. Stable conditions – thus stable boundary layers (SBLs) – typically exist at night within the nocturnal boundary layer (NBL), although they are not necessarily restricted to overnight hours. For example, Canter et al. (2018) observed the development of a daytime SBL during the 2017 solar eclipse in Kentucky. Additional examples of non-nocturnal SBLs include persistent SBLs that can form in polar regions or over ice, or cases where a stable air mass is advected into a region during the day. In this dissertation, the terms NBL and SBL will often be used interchangeably since most discussion will focus on overnight periods.

As the sun sets, the evening transition of the boundary layer begins. Unstable conditions near the surface give way to near-neutral conditions. Buoyancy-driven turbulence

decays, and the structure of the boundary layer becomes more complex than during the day (Acevedo and Fitzjarrald 2001). In a shallow layer near the surface, the temperature rapidly decreases and a temperature inversion forms: this is the onset of NBL/SBL development. This layer rests below the residual layer, which is a remnant of the mixed layer from the previous day. Under many circumstances the turbulent exchange between the residual layer and the NBL is limited, but this situation may be altered in the presence of turbulence. One such driver of turbulence in the NBL is the nocturnal low-level jet (NLLJ), which can produce shear turbulence. This dissertation focuses on the NLLJ, which is a typical feature of the NBL over the Great Plains.

1.2 Nocturnal low-level jets

The NLLJ is defined as a wind maximum occurring overnight in the lowest kilometer of the atmosphere. The NLLJ is frequently observed in the United States (Blackadar 1957; Hoecker Jr 1963; Bonner 1968; Parish et al. 1988; Mitchell et al. 1995; Stensrud 1996; Zhong et al. 1996; Whiteman et al. 1997; Banta et al. 2002; Song et al. 2005; Banta 2008; Walters et al. 2008), Australia, Europe, North Africa, and elsewhere in the world (Beyrich et al. 1997; Baas et al. 2009; Stensrud 1996). In the most general sense, the NLLJ is the result of the disruption of the daytime force balance between the Coriolis, pressure-gradient, and frictional forces. Once the sun sets, thermally-generated turbulence decays, and the SBL forms. The frictional force weakens above the surface, which destroys the force balance and leads to increased wind speed in the boundary layer (e.g., Markowski and Richardson 2011).

While NLLJs are observed in many locations around the globe such as the Koorin Jet (e.g., Brook 1985) and Southerly Buster (e.g., Baines 1980) in Australia and the Somali Jet of East Africa (e.g., Ardanuy 1979), this study will focus on NLLJs that commonly form over the Great Plains of the United States, especially in the warm months, and are usually southerly (e.g., Blackadar 1957; Bonner 1968; Zhong et al. 1996; Whiteman et al. 1997;

Banta et al. 2002; Song et al. 2005; Banta 2008; Klein et al. 2016). Early climatology from Bonner (1968) used 6-hourly radiosonde data over the Great Plains during a 2-year period to describe NLLJ features. The study showed that NLLJs occur most frequently over northwestern Oklahoma and reach their maximum speed around midnight local time with an average height around 800 m. NLLJs were shown to be most often southerly or southwesterly and most prevalent in the summer months, but jets occurring in other seasons and with different wind directions were also observed (Bonner 1968). Later, Mitchell et al. (1995) used hourly wind profiler network data to update the NLLJ climatology. A similar spatial maximum was found over northwestern Oklahoma, but the average NLLJ height was closer to 1-km. It is worth noting that wind profiler data used in this study were more coarse than radiosonde data, and the lowest range gate was 500-m meaning low jet maxima may not be detected. The plethora of atmospheric observations available from the Atmospheric Radiation Measurement Southern Great Plains (ARM-SGP) site was leveraged by both Whiteman et al. (1997) and Song et al. (2005). These studies showed the NLLJ height was frequently observed between 250-500 m above ground level (AGL). Using 40 years of twice daily radiosonde data, Walters et al. (2008) found the summertime NLLJ spatial maximum to be similar to that of Bonner (1968), but the annual spatial maximum further south in Texas. Most recently, Rife et al. (2010) employed global reanalysis data to produce a worldwide jet climatology. This study showed a seasonal dependence with NLLJs occurring most often in summer months and highlighted the United States' Great Plains as a hot spot of NLLJ activity.

These NLLJs can modulate the atmosphere in many ways resulting in weather and climate impacts for the region (Stensrud 1996). The southerly NLLJ can transport moisture from the Gulf of Mexico over the central United States. This transport has been connected to the observed nocturnal maximum in warm-season precipitation in this part of the country (Markowski and Richardson 2011). The strong poleward transport of moisture by the NLLJ can lead to significant flooding causing property and agricultural damage (Arritt et al.

1997). The NLLJ can modify the thermodynamic and dynamic structure of the lower atmosphere in support of convection initiation and severe weather (Pitchford and London 1962; Bonner 1966; Maddox 1983; Astling et al. 1985; Trier et al. 2006; Fedorovich et al. 2017). The NLLJ can act to redistribute atmospheric pollutants such as ozone and carbon dioxide (e.g., Hu et al. 2013; Klein et al. 2014). Long range transport and downward mixing via NLLJ-related turbulence were identified in a study of ozone concentrations by Corsmeier et al. (1997). Similar vertical mixing associated with the NLLJ was shown to be related to ozone concentrations jumps by Hu et al. (2013). NLLJ flow has also been shown to modulate carbon dioxide exchange above agricultural fields and forest canopies (Karipot et al. 2006).

Beyond its atmospheric effects, NLLJs can have direct impacts on several industries. The importance of the NLLJ to aviation is one obvious example (National Research Council 1983). Cross-runway NLLJ winds can lead to differential transport of the wake vortices created by aircraft, which impacts how closely consecutive aircraft can safely take off and land (Kaplan et al. 2000). NLLJ-related vertical wind shear can also pose risks to aircraft on approach or during ascent (National Research Council 1983). NLLJs are also relevant to the wind energy industry. NLLJ winds can provide increased renewable energy generation, but associated turbulence and shear can damage wind turbines (Storm et al. 2009).

The dynamics of NLLJs have been described by various theories in the literature. While each theory attempts to explain particular features of the NLLJ, a theory fully describing this phenomenon as observed has yet to be developed. There are three main mechanisms detailed in the literature. The first mechanism is the inertial oscillation. Blackadar (1957) detailed the NLLJ as an inertial oscillation in the lower atmosphere occurring once frictional restraint from the surface is released after sunset. This oscillation results in the nocturnal wind vector turning around the geostrophic wind vector. The period of this oscillation is dependent upon latitude, ϕ (positive for the Northern Hemisphere), as $\frac{\pi}{f}$, where $f = 2\Omega \sin \phi$ is the Coriolis parameter, with Ω as the angular velocity of the Earth's rotation.

In order to facilitate a more complete understanding of the inertial oscillation mechanism and the roles of vertical momentum transport and intra-layer friction in the NLLJ, Shapiro and Fedorovich (2010) extended the Blackadar theory by considering the NLLJ as an inertial oscillation initiated by the sudden reduction of frictional constraint rather than the full release. The resulting oscillation tends toward a steady-state nocturnal Ekman wind profile with reduced eddy viscosity instead of the geostrophic wind. The second mechanism is slope-associated baroclinity. Holton (1967) and Shapiro and Fedorovich (2009) linked the NLLJ forcing to the sloping terrain of the Great Plains. Holton (1967) proposed a periodic radiative forcing term to explain the diurnal variation in boundary layer wind, but his theory did not replicate the observed strength of the nocturnal wind maximum. Shapiro and Fedorovich (2009) considered the horizontal distribution of temperature in the lower atmosphere over gently sloped terrain with a tilted residual layer. The tilted residual layer results in buoyancy gradients that support flow acceleration in a gravity-inertial oscillation. The Shapiro and Fedorovich (2009) theory's jet does qualitatively match the observed evolution, but the position of NLLJ prevalence is shifted slightly too far west. The third mechanism deals with flow blocking by a mountain range. Wexler (1961) presumed that Great Plains NLLJs could be connected to large-scale blocking of low-level flow by the Rocky Mountains stretching south to north across the country. This blockage is proposed to deflect the easterly trade winds northward as they approach the mountain region in analogy to intense ocean currents along eastern coastlines. This theory alone cannot describe the diurnal pattern of the NLLJ but does support prevalence of the net southerly flow over the central United States. In recent years, efforts have turned to combine different mechanisms into a unified theory (Shapiro et al. 2016). This unified theory broadly represents the observed NLLJ but still has a places the location of highest NLLJ frequency too far west and tends to underpredict the magnitude of strong jets. This is not entirely surprising since the 1-dimensional theory cannot represent important spatial features of the NLLJ. However, results from Shapiro et al. (2016) suggest that variations in buoyancy may be an

important mechanism in NLLJ formation and evolution. The 1-dimensional theory leads to weak NLLJs when considering buoyancy alone, but buoyancy was shown to strengthen NLLJs caused by the inertial oscillation. The impacts of buoyancy will be considered in more detail in Chapter 5.

1.3 Modeling studies

In boundary layer studies, there are several approaches to model-based analysis. As computing technology advances, more computationally expensive numerical simulation methods such as large-eddy simulation (LES) and direct numerical simulation (DNS) have become feasible. In a general sense, DNS is the most straightforward approach to numerical simulation. The governing equations are solved without any simplifying assumptions, resolving motions of all scales in the flow. However, the computational expense of DNS is high and increases with Reynolds number (dimensionless ratio of the inertial force to the viscous force, $Re = \frac{UL}{\nu}$, where U is a characteristic velocity, L is a characteristic length, and ν is the kinematic viscosity of the fluid). As such, DNS applications are typically limited to flows with low Re . Either atmospheric air is represented in a very small box or a viscous fluid is represented in a box with atmospheric scales. For boundary layer flows, DNS has become a valuable tool to study idealized flow under various forcing and stratification conditions. This approach allows for the evaluation of specific drivers and physical interactions and feedbacks within an idealized setup, but does not allow for a realistic simulation of full atmospheric conditions (Moin and Mahesh 1998; Fedorovich et al. 2017).

LES approaches allow for the simulation of more realistic atmospheric scales compared to DNS methods. These techniques filter the governing equations such that the flow field is separated into large-scale eddies and smaller sub-filter scale eddies. The large-scale eddies are explicitly computed on the computational mesh while the smaller ones are parameterized via a sub-filter scale closure model. In this method, the large-scale eddies are assumed to comprise the energy-containing scales of motion while the sub-filter eddies are assumed

to mostly exist in the dissipation range (Smagorinsky 1963; Deardorff 1970). While not restricted by Re like DNS, LES approaches are typically limited to small domains and large-scale forcings (e.g., synoptic environments, terrain conditions) may thus not be represented, which can limit the realism of the simulation output. Some techniques allow for LES grids to be nested within or driven by mesoscale numerical model data, but the method of downscaling data and generating the full spectrum of turbulence at the boundaries remains an active area of research (Mazzaro et al. 2017).

Mesoscale modeling can most realistically reproduce atmospheric conditions from real cases without the limitations that DNS and LES pose. However, these models cannot represent turbulent flow in the boundary layer and instead rely on parameterizations of contributing small-scale physical processes. Studies with mesoscale models have helped improve the understanding of NLLJ phenomena. In particular, Zhong et al. (1996) showed that soil moisture changes impacted jet amplitudes with drier soils leading to stronger NLLJs. Pan et al. (2004) described the role of slope-induced horizontal temperature gradients in the formation of the NLLJ. It has been shown that the evolving SBL and embedded NLLJs are generally not well captured by numerical models. Consistent underestimation of the magnitude and depth of the NLLJ and minimal sensitivity to planetary boundary layer (PBL) parameterization schemes was reported by Storm et al. (2009) in a study using the Weather Research and Forecasting (WRF; Skamarock et al. 2008) model on a 4-km horizontally spaced grid with ten grid points below 1 km in the vertical. Steeneveld et al. (2008) found similar effects in their simulations of the NLLJ using three state-of-the-art mesoscale models. On the other hand, recent studies have shown improved agreement between observed and simulated NLLJ features using the WRF model (e.g., Vanderwende et al. 2015; Klein et al. 2016). In particular, Mirocha et al. (2016) found the prediction of wind speed near wind turbine height by the WRF model to be sensitive to PBL scheme choice, but noted that the degree of sensitivity was also related to the choice of other model options such as the grid configuration.

While much progress has been made in recent decades, modeling the SBL remains difficult. Such difficulties include the applicability and validity of Monin-Obukov similarity theory, limited vertical resolution causing issues with thin surface layers and flux-gradient relationships, and interactions with mesoscale motions such as gravity waves and cold air drainage flows (Mahrt 1998). A review of boundary layer representation in modern weather models by Holtslag et al. (2013) points toward complexity of PBL parameterization approaches being further muddled by differing schools of thought and historical influences. Current PBL and turbulence parameterization schemes are often inadequate, especially when applied to the SBL. These deficiencies are attributed, at least in part, to insufficient understanding of turbulent exchange processes in the SBL (Steenefeld et al. 2008). The literature suggests that simulations of the SBL and NLLJs can be improved if model settings are chosen carefully with the relevant application in mind. As such, horizontal grid spacing, vertical grid spacing, and PBL parameterization approaches are explored in more detail in Chapter 2.

1.4 Goals

This dissertation aims to extend the knowledge of Great Plains NLLJ characteristics. Previous studies have identified the NLLJ to be important to the Great Plains and regions beyond via weather, climate, and industry impacts. The literature has defined the NLLJ and described its basic features and climatology. The literature has also shown that simulating the SBL, and thus the NLLJs that form within it, poses particular challenges. As such, this dissertation evaluates the ability of the WRF model to represent the Great Plains NLLJ and identifies the optimal WRF model configuration in which to do so using high-resolution Lower Atmospheric Boundary Layer Experiment (LABEL, Klein et al. 2015) observations (Chap. 2, published in Smith et al. 2018a). Using the optimal configuration, simulations of cases from the Plains Elevated Convection At Night (PECAN, Geerts et al. 2016) field experiment are evaluated (Chap. 3, in review as part of Smith et al. 2019).

These simulations are then used alongside high-resolution PECAN observations to identify Great Plains NLLJ characteristics, in particular, spatial and temporal evolution (Chap. 4, in review as part of Smith et al. 2019). Based on findings from the PECAN cases, the full set of fourteen LABLE and PECAN NLLJ cases are revisited to understand how common the identified spatial and temporal NLLJ characteristics are and why they may occur (Chap. 5, in preparation for publication).

Chapter 2

The Optimal WRF Configuration

2.1 Introduction

While the use of horizontal grid spacing at or below 1 km is increasingly feasible as computational resources improve, such scales often fall into the so-called *terra incognita*, where refined spacing can result in unrealistic flow structures in the daytime boundary layer (Wyngaard 2004; LeMone et al. 2013; Zhou et al. 2014). Since sensitivities to horizontal grid spacing are most likely related to partially resolving the largest eddies in the daytime boundary layer, such sensitivities may not be as pronounced in the overnight period when eddies are smaller. However, the availability of computational resources coupled with the natural assumption that more grid points add more information means that the impact of horizontal grid spacing is still worth testing. Improvements in the vertical grid resolution may be more important for simulating NLLJs since sharp gradients are difficult to resolve with coarser grids (Mirocha et al. 2016). The optimal grid configurations may be sensitive to PBL scheme choice.

PBL schemes parameterize the turbulent transport of momentum, heat, and scalars in the vertical direction within and beyond the PBL. Different PBL parameterization approaches may produce different characteristic SBLs and thus impact NLLJ simulations. Known deficiencies in the performance of PBL schemes in the SBL environment can be attributed to our incomplete knowledge of turbulent exchange processes in the SBL (e.g., Salmond and McKendry 2005; Steeneveld et al. 2008; Fernando and Weil 2010; Steeneveld 2014). The PBL schemes used in the WRF model may be conventionally categorized as local or non-local (e.g., Stull 2012, Chapter 6). Local closure schemes only allow the vertical levels that are in the immediate vicinity of a particular level to directly impact the variables at that level. Conversely, non-local closure schemes allow for interactions between remote

vertical levels. Local schemes are often thought to offer some disadvantage for application to the PBL since local gradients of meteorological variables are not always representative of the processes that extend throughout the entire layer. Non-local schemes are generally assumed to better represent the effect of the large turbulent eddies than local schemes, and thus to better account for deep PBL circulations that are typical under convective conditions. However, such characterizations of each closure type may not be relevant for SBLs since in stable conditions all schemes act as local schemes. This study aims to address some of the outstanding challenges described above by performing tests that include a local transport scheme (Mellor-Yamada Nakanishi Niino - MYNN, Nakanishi and Niino 2009), a non-local transport scheme (Yonsei University - YSU, Hong et al. 2006), and a scale elimination scheme (Quasi-Normal Scale Elimination - QNSE, Sukoriansky et al. 2005), which acts locally.

Our study is motivated by initial experimental findings from the PECAN (Geerts et al. 2016) experiment, which indicate that the spatial evolution of the NLLJ throughout the PECAN domain may be important for modulating the turbulence and thermal structure in the boundary layer (e.g., Gebauer et al. 2018). Sudden local changes in stability and turbulent mixing may be primarily triggered by veering and advection of the NLLJ from west to east (Smith et al. 2018b). Combining the sparse observations of NLLJs collected during PECAN with numerical model output is critical for investigating these effects in more detail. Our objective was thus to find an optimal WRF model configuration for simulating NLLJs in the Great Plains. For this model evaluation study, we focused on selected cases from the LABLE campaign. LABLE took place at the ARM-SGP site near Lamont, Oklahoma during the fall of 2012 and the summer of 2013 to investigate the dynamic, thermal, and turbulence characteristics in the atmospheric boundary layer (Klein et al. 2015). LABLE datasets provided detailed continuous observations that captured the NLLJ evolution throughout the entire night, while PECAN NLLJ observations are limited to only four nights, and often ended before the early morning transition impacted the NLLJ. To

find an optimal configuration in which to run the WRF model for NLLJ studies, we chose ten LABLE cases during which NLLJs were observed. These ten cases were classified following Bonin (2015) as either strongly or weakly turbulent NLLJs. Two example cases (one weakly and one strongly turbulent NLLJ) and model setup are described first in the subsequent sections. These two cases are then used to explore the sensitivity of the model to horizontal grid spacing, vertical grid spacing, and PBL scheme. After detailed results are shown for the two selected cases, the results are verified using the ten-case dataset. Conclusions are presented in the final section of the chapter.

2.2 LABLE Cases

Ten LABLE cases of observed NLLJs were considered in this study. While more cases would have been desirable, we choose to retain only these ten cases as they were not directly impacted by boundaries or other mesoscale features and to prevent any complications from including different seasons or locations in the analysis. Fig. 2.1 shows the maximum ten-case mean normalized NLLJ magnitude in the lowest 1 km at three different times from North American Mesoscale Forecast System (NAM) analysis data. For these cases, the LABLE observation site was located within the core region of the NLLJ. Among many other instruments, LABLE deployed a Doppler lidar and an Atmospheric Emitted Radiance Interferometer (AERI) to observe temperature and wind profiles. Conical Doppler lidar scans occurred every 15 minutes using 18-m range gates and a 70-degree scan elevation. Velocity azimuthal display analysis permitted retrieval of the horizontal wind from these data. Between other scans, the Doppler lidar collected continuous vertical stare data to measure vertical velocity. The AERI observations allowed for retrieval of vertical thermodynamic profiles with 5-min temporal resolution (Turner and Löhnert 2014). More details on the instrument operations during LABLE can be found in Klein et al. (2015). For reference, the local time at the observation site was CDT (UTC-5 h). These observations provide high resolution information about NLLJs throughout the night, which allows

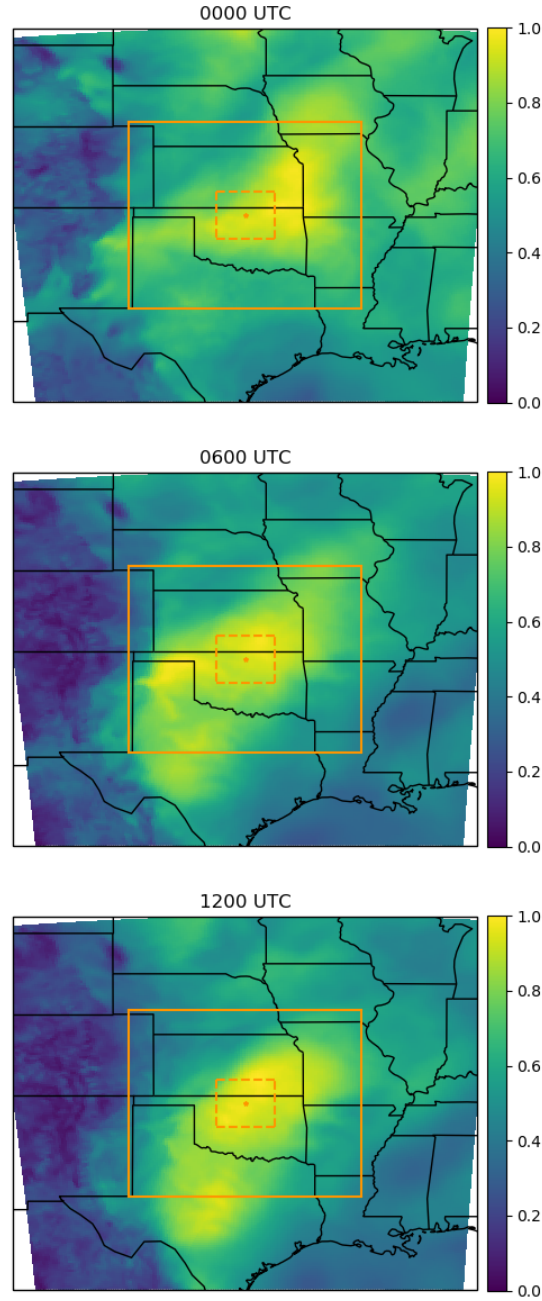


Figure 2.1: Color fill shows the maximum mean normalized NAM analysis NLLJ magnitude in the lowest 1-km for all ten cases at three times, where a value of one indicates the maximum wind speed. The solid orange box shows the 1024-km $\times$ 1024-km simulation domain and the dashed orange box shows the 256-km $\times$ 256-km simulation domain. The star marks the location of the ARM-SGP site where LABLE observations were collected.

evaluation of model representation of processes relevant to NLLJs (e.g., NLLJ magnitude, NLLJ evolution, SBL structure, etc.). In analyses completed by Bonin (2015), LABLE NLLJs were classified based on the observed near-surface turbulence, which was quantified in terms of the vertical velocity variance (σ_w) retrieved from the vertical stare Doppler lidar data. The turbulence regime is defined by the mean measured value of σ_w below 100 m ($\overline{\sigma_w}_{100m}$). It is important to note that the lowest usable range gate is near 63 m, so the effective mean is from 63-100 m. Bonin et al. (2015) identified a threshold of $\overline{\sigma_w}_{100m} = 0.2 \text{ m s}^{-1}$, above which a weakly stable boundary layer existed and below which a very stable boundary layer existed. Bonin (2015) then used the nighttime (0200-1200 UTC) mean $\overline{\sigma_w}_{100m}$ to categorize NLLJs as weakly turbulent ($\overline{\sigma_w}_{100m} < 0.2 \text{ m s}^{-1}$) or strongly turbulent ($\overline{\sigma_w}_{100m} > 0.2 \text{ m s}^{-1}$). The ten LABLE cases and their classifications are shown in Table 2.1. Six cases were classified as strongly turbulent while four cases were classified as weakly turbulent ¹.

In addition to the difference in near-surface turbulence, Bonin (2015) found that weakly and strongly turbulent NLLJs have other defining features. Weakly turbulent NLLJs generally form under more weakly synoptic forced conditions, with shortwave troughs at 850-hPa often positioned a few hundred kilometers west, and do not form until a strong surface-based inversion forms. Strongly turbulent NLLJs often form with large-scale 500-hPa troughs over the west coast of the United States. The strong large-scale synoptic forcing and associated southerly winds are present before sunset preventing strong surface based inversions from forming. Furthermore, the large-scale troughs propagate more slowly than shortwaves and can thus result in several consecutive nights of strongly turbulent NLLJs. The NLLJ height and maximum wind speed also evolve differently for strongly and weakly turbulent cases. Strongly turbulent NLLJs have a relatively constant

¹The case on 15 October 2012 was classified based on data from the ARM Doppler lidar rather than the OU Doppler lidar because the OU Doppler lidar data was too noisy. The ARM Doppler lidar range gate was longer and thus averages out smaller scales of turbulence resulting in lower $\overline{\sigma_w}_{100m}$ values than those from the OU Doppler lidar. However, this value is so small that mis-classification is unlikely.

Table 2.1: Ten LABLE cases classified based on Bonin (2015). The case marked by an asterisk was classified based on data from the ARM Doppler lidar rather than the OU Doppler lidar. See footnote in Sect. 2.2.

Date	$\overline{\sigma}_{w100m}$ [m ² s ⁻²]	Classification
2012 Oct. 09	0.10	Weakly Turbulent
2012 Oct. 13	0.27	Strongly Turbulent
2012 Oct. 15	0.01*	Weakly Turbulent
2012 Oct. 16	0.47	Strongly Turbulent
2012 Oct. 21	0.07	Weakly Turbulent
2012 Oct. 22	0.52	Strongly Turbulent
2012 Oct. 23	0.47	Strongly Turbulent
2012 Oct. 24	0.54	Strongly Turbulent
2012 Nov. 08	0.07	Weakly Turbulent
2012 Nov. 09	0.50	Strongly Turbulent

height and reach a maximum magnitude by about 0500 UTC. On the other hand, weakly turbulent NLLJs tend to follow isentropic surfaces with the height changing in time and slowly strengthen throughout the night reaching a maximum shortly before sunrise. More details about strongly and weakly turbulent NLLJs are available in Bonin (2015).

The NLLJ that formed on 09 October 2012 was classified as weakly turbulent. At 0000 UTC on 09 October 2012, a surface low pressure system was positioned in the northern United States over northern Minnesota connected to a 500-hPa trough. An associated cold front draped southwest through the center of Nebraska. Near the observation site, 700-hPa and 500-hPa flows were approximately zonal. A shortwave trough was located at 850-hPa over eastern New Mexico and Colorado. As the shortwave trough propagated east during the overnight hours, a secondary low pressure formed in western Kansas by 1200 UTC. The approaching trough and surface-low increased the pressure gradient force and resulted in stronger synoptic scale forcing overnight at the observation site. The observed wind speed is shown in Fig. 2.2a and observed potential temperature is shown in Fig. 2.2c. The NLLJ strengthened throughout the night until about 1000 UTC, while the stability increased at the levels where the NLLJ formed. The core region of the NLLJ (the region where wind speed is at least 90% of the maximum value, shown by the thin black lines in Figs. 2.2a,c) became narrower with time. The height of the NLLJ also tended to follow isentropic surfaces through the night, with the height of the NLLJ increasing as the inversion grew deeper.

On 24 October 2012, a strongly turbulent NLLJ formed. This night was the third night of consecutive strongly turbulent NLLJs associated with a large-scale 500-hPa trough over the western United States. A closed-low propagated from northeastern Colorado to Western Kansas between 0000 and 1200 UTC as a cold front moved south into northwestern Kansas. The observed wind speed is shown in Fig. 2.2e, and observed potential temperature is shown in Fig. 2.2g. The NLLJ formed early in the period, strengthened until it reached a maximum just before 0400 UTC, and stayed at or near that magnitude until about 1000 UTC when the NLLJ began to weaken. The height of the NLLJ remained fairly constant

through the night, but the core region (thin black lines in Figs. 2.2e,g) of the NLLJ did get narrower after the NLLJ reached maximum magnitude.

These two cases were selected as examples of a weakly and a strongly turbulent NLLJ for which model evaluation will be presented in detail. Once the results based on these two cases are described in detail, the model evaluation study is expanded using the results of the full ten-case dataset.

2.3 Model Setup

In this study, the WRF model (WRF-ARW, version 3.8.1) was applied to study the Great Plains NLLJ. The model domain was centered over the ARM-SGP site in Lamont, Oklahoma. The ARM-SGP site and the $1024\text{-km} \times 1024\text{-km}$ and $256\text{-km} \times 256\text{-km}$ model domains are shown in Fig.2.1. Numerical experiments were run for the ten LABLE cases presented in Table 2.1. Detailed descriptions of the model experiments are presented for the cases observed on 09 October 2012, a weakly turbulent NLLJ, and 24 October 2012, a strongly turbulent NLLJ (Figs. 2.2-2.4).

Each simulation was run for a 24-h period starting at 1200 UTC on the day preceding the NLLJ. The first 12 h of each simulation were used to accommodate model spin-up effects. Simulations with additional spin-up time were tested, but differences were found to be negligible beyond 12 h. The WRF model was initialized using reanalysis data from the NAM with 12-km grid spacing. These NAM data were also used to generate lateral boundary conditions for the model every six hours. While previous studies included land surface model physics in sensitivity tests (e.g., Mirocha et al. 2016), impacts of degraded land surface representation are likely minimized during nighttime conditions due to decoupling from the surface (Mahrt 1998). It is important to note that the WRF model is a limited area model, allowing the initial and boundary conditions to reflect the larger scale conditions. Model settings are summarized in Table 2.2. Only the PBL parameterization

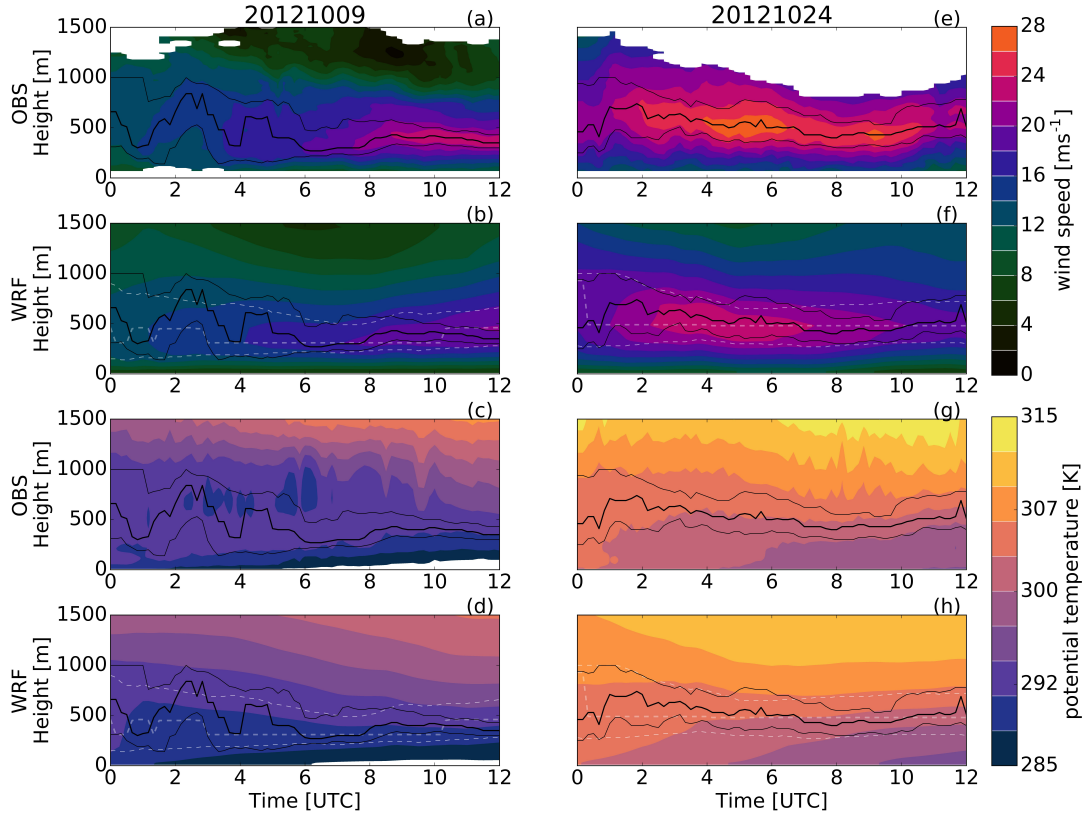


Figure 2.2: Time-height cross sections of observed and **YSU4kmDef** WRF simulated data for 09 October 2012 (a-d) and 24 October 2012 (e-h). Observed (a and e) and simulated (b and f) wind speeds are shown together with observed (c and g) and simulated (d and h) potential temperatures. The heavy solid black (dashed white) lines show the height of the observed (simulated) NLLJ maximum, while the lighter solid black (dashed white) lines encompass the region in which the observed (simulated) wind speed is at least 90% of the NLLJ maximum wind speed. Local time at the observation site was CDT (UTC-5 h).

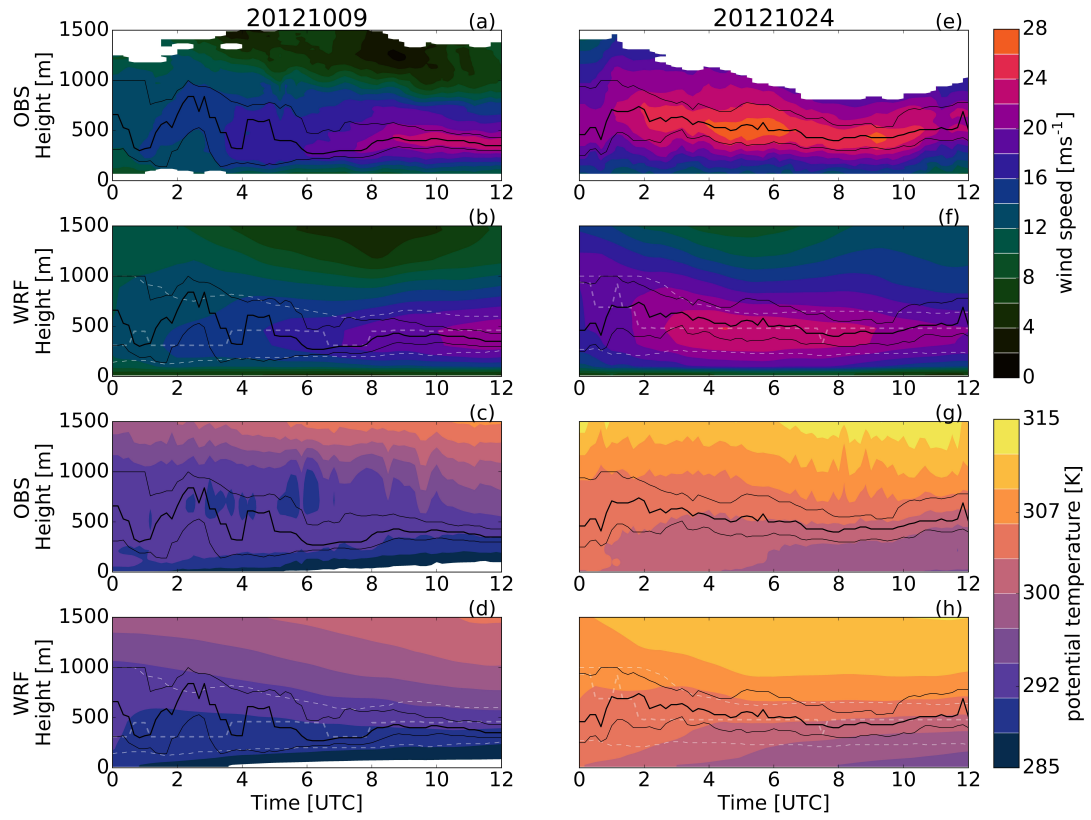


Figure 2.3: As in fig. 2.2, except the WRF simulation used the **MYNN4kmDef** configuration.

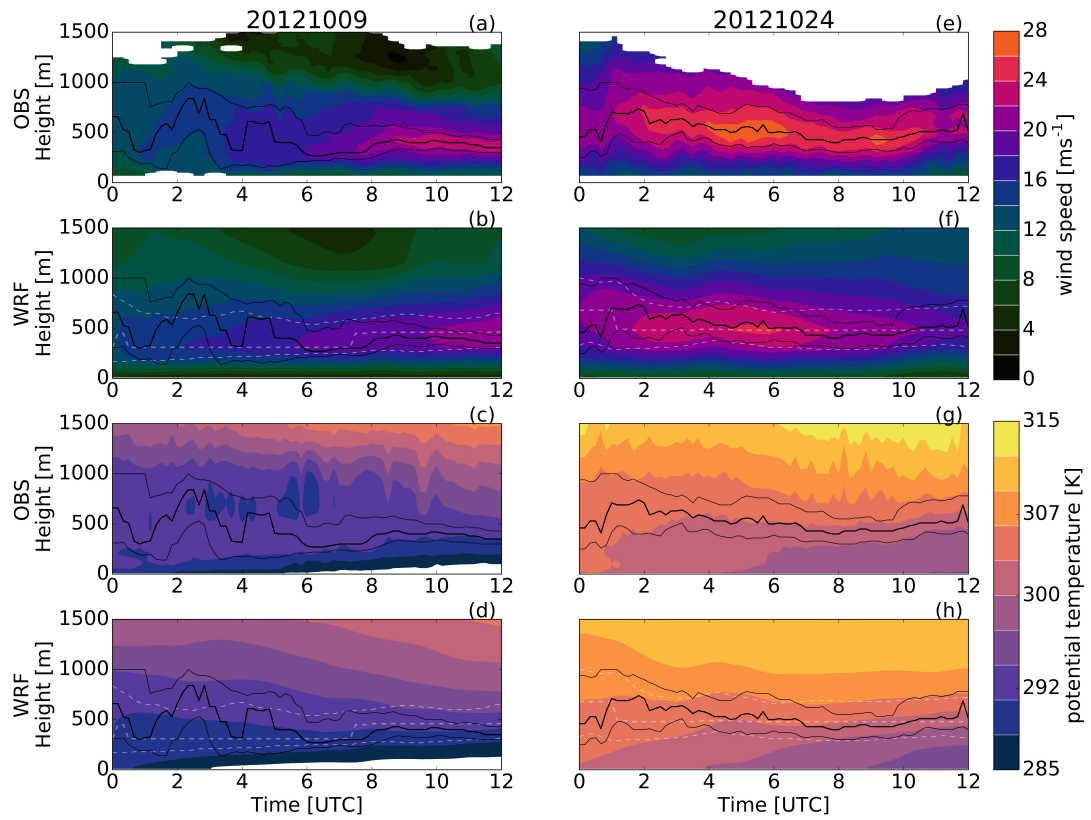


Figure 2.4: As in fig. 2.2, except the WRF simulation used the **QNSE4kmDef** configuration.

Table 2.2: WRF model physics options used in this study.

Setting	Choice
Land surface model	NOAH Land Surface Model (Tewari et al. 2004)
Microphysics	WRF Single-Moment 5-Class Scheme (Hong et al. 2004)
Shortwave radiation	5th-Generation Penn. State/NCAR Mesoscale Model (MM5) Shortwave Radiation Scheme (Dudhia 1989)
Longwave radiation	Rapid Radiative Transfer Model (Mlawer et al. 1997)
Horizontal diffusion	Horizontal Deformation First-Order Closure Scheme (Smagorinsky 1963)
PBL/SL	YSU PBL/Revised MM5 Monin-Obukhov SL; MYNN PBL/MYNN SL; QNSE PBL/QNSE SL

and associated surface layer (SL) scheme, vertical grid spacing, horizontal grid spacing, and horizontal grid expanse were varied in this study.

The default vertical grid in the WRF model employs 41 terrain-following normalized pressure levels, the so-called eta-levels. These levels are stretched vertically in such a manner that the grid spacing increases with distance from the surface. For this study, the default vertical grid was chosen using “out-of-the-box” settings making as few changes to the input settings of the model as possible. In the simulations with the default grid configuration, the WRF stretching algorithm produced ten vertical levels located within the lowest 2 km, as shown in the leftmost panel of Fig. 2.5. The first model level was located approximately 30 m above the ground and the model top was near 16 km. This default vertical grid is intended to act as a control configuration against which adjustments to the vertical grid spacing can be compared.

As discussed in Sect. 2.1, three PBL schemes were evaluated for their ability to reproduce NLLJs: a local scheme (MYNN), a non-local scheme (YSU), and a scale-elimination scheme (QNSE), which can be classified as local. The MYNN level 2.5 parameterization is a scheme with a prognostic turbulence kinetic energy (TKE) equation and parameterized equations for turbulent variances/fluxes. Through the use of various length scales, MYNN induces extra mixing to account for the poor local approximation of fluxes based on eddy diffusivity. The YSU scheme is based on a first-order turbulence model that directly specifies the eddy diffusivity and explicitly treats turbulent entrainment, which is



Figure 2.5: The vertical spacing below 2 km for default vertical spacing (left), 40-m vertical spacing (right).

particularly important for convective conditions. Lastly, QNSE is a local closure with a prognostic TKE equation. The scheme uses the scale elimination approach to approximate exchange by interacting turbulent eddies, and was designed specifically for the SBL. The scale elimination approach uses successive averaging over small intervals of the turbulence spectrum providing expressions for turbulent viscosity and diffusivity as functions of local Richardson number.

WRF model output was saved in the same time increments as Doppler lidar observations (i.e, every 15 minutes) to facilitate comparisons between the two. The first two range gates of the lidar were removed along with any other suspicious data after applying a signal-to-noise ratio filter to the data. AERI observations were interpolated to the same 15-minute temporal resolution as Doppler lidar and WRF data. WRF model data were extracted from the four grid cells nearest to the observational site and then spatially averaged in order to facilitate a comparison of the simulated and observed data. This method was chosen since the WRF model uses a staggered grid. Averaging the four nearest boxes provides a way to include effects from each cell and to account for any small translation errors. Additionally, for the computation of performance metrics, the data were vertically interpolated to match the lidar levels. Performance metric comparisons between observations and simulations were limited to the lowest 800 m. The lidar data are not as trustworthy above this level and are often removed by data quality filters as lidar returns are dependent on aerosol load.

The investigated performance metrics include normalized bias,

$$BIAS_N = \frac{\frac{1}{N} \sum_{i=1}^N (U_{WRF_i} - U_{lidar_i})}{0.5(\bar{U}_{WRF} + \bar{U}_{LIDAR})}, \quad (2.1)$$

normalized mean absolute error,

$$MAE_N = \frac{\frac{1}{N} \sum_{i=1}^N |U_{WRF_i} - U_{lidar_i}|}{(\bar{U}_{WRF} + \bar{U}_{LIDAR})}, \quad (2.2)$$

and normalized centered root mean square error,

$$CRMSE_N = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N [(U_{WRF_i} - \bar{U}_{WRF}) - (U_{lidar_i} - \bar{U}_{lidar})]^2}}{\sqrt{\sigma_{WRF} \sigma_{LIDAR}}}, \quad (2.3)$$

where index i loops over N , the number of points in the time/height domain, U_{WRF} and U_{lidar} refer to the WRF-simulated and lidar-observed wind speed, respectively, and overbars denote mean quantities. Standard deviations are represented by σ . *BIAS* shows, on average, whether the WRF model over- or underestimates wind speed compared with observations, *MAE* represents the average difference between the WRF model solutions and lidar data, and *CRMSE* describes the random component of the error since the mean *BIAS* has been removed. To facilitate comparison between cases, each metric is shown as a normalized quantity. The normalization method employed here is similar to that in Chang and Hanna (2004). To summarize the performance metrics, the mean metric is defined as

$$MM = \frac{BIAS_N + MAE_N + CRMSE_N}{3}. \quad (2.4)$$

Performance metric data for the 09 October 2012 and 24 October 2012 cases are visualized in Fig. 2.6 with each value presented in Tables 2.3 and 2.4.

The model configurations are labeled as $\text{PBL}\Delta h\Delta z$, where PBL indicates the PBL scheme (MYNN, YSU, or QNSE), Δh indicates the horizontal spacing (1km, 2km, or 4km), and Δz indicates the vertical grid spacing (40-m or Def – meaning default). For instance, a model run using the YSU PBL scheme with $\Delta h = 1$ km and the default stretched vertical grid is labeled **YSU1kmDef**.

2.4 Results

First, observations of wind speed and potential temperature for the two selected LABLE cases were compared with WRF simulations using 4-km horizontal spacing, the default stretched vertical grid, and varying PBL schemes (Figs. 2.2, 2.3, and 2.4). These WRF simulations represent the expected simulation of the NLLJ and SBL from a typical mesoscale model with a standard grid configuration like those found in previous studies. While a

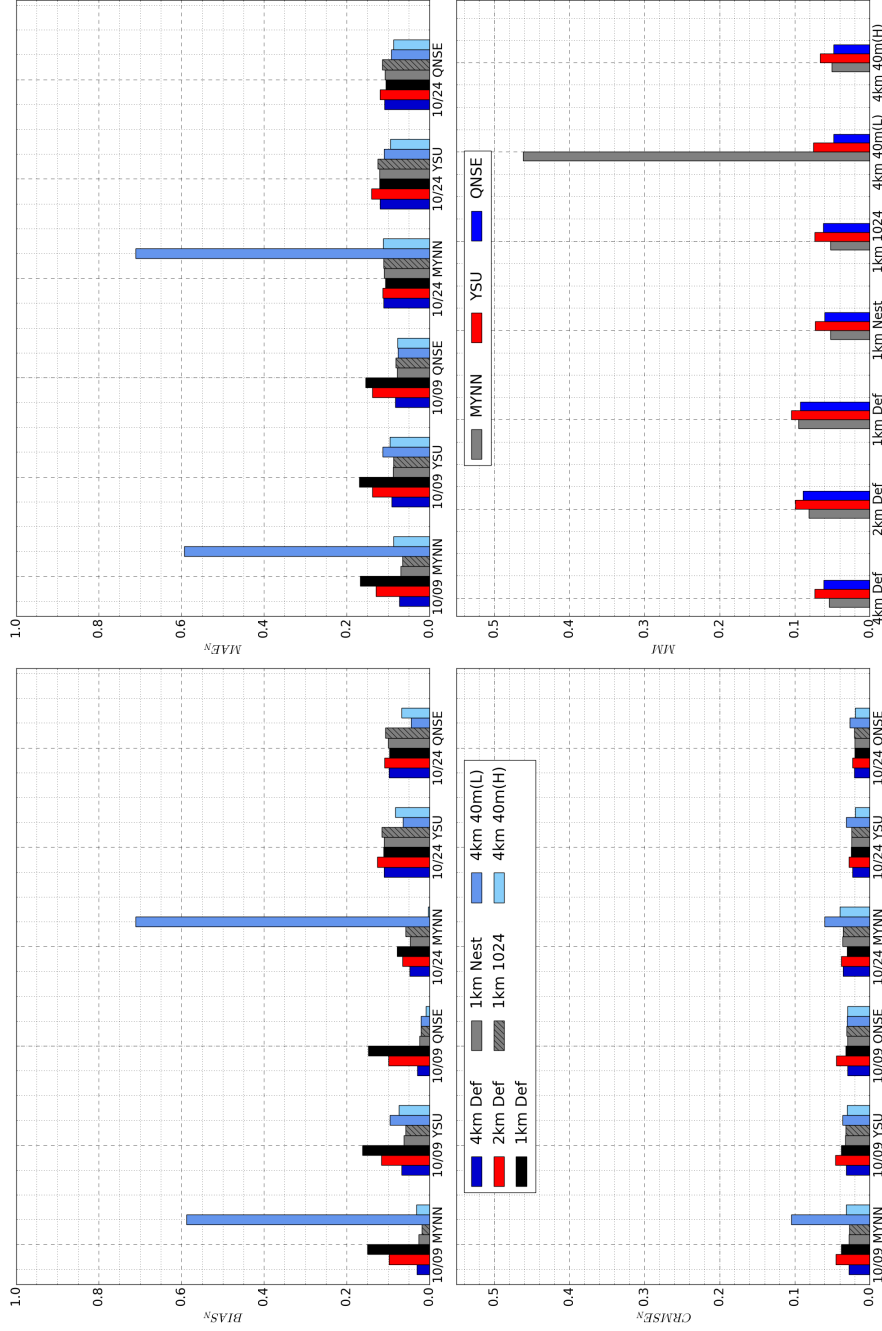


Figure 2.6: Bar plots show the values of $BIAS_N$ (upper left panel, displayed as an absolute value), MAE_N (upper right panel), and $CRMSE_N$ (lower left panel) for 09 October 2012 and 24 October 2012. The lower right panel shows MM including both cases for each grid configuration. Lower values indicate better performance.

Table 2.3: Performance evaluating each WRF model configuration are presented for 09 October 2012, where Δh is horizontal grid spacing, $npts$ is the number of grid points in the horizontal model domain, Δz is vertical grid spacing, $BIAS_N$ is the normalized mean error, MAE_N is normalized mean absolute error, and $CRMSE_N$ is normalized centered root mean square error. For vertical grid spacing, **default** refers to the traditional stretched vertical grid used in the WRF model.

PBL Scheme	Δh [km] (npts)	Δz [m] (npts)	$BIAS_N$	MAE_N	$CRMSE_N$
YSU	1 (256 ²)	default (41)	−0.16	0.17	0.04
	1 (256 ² , nest)	default (41)	−0.06	0.09	0.03
	1 (1024 ²)	default (41)	−0.06	0.09	0.03
	2 (256 ²)	default (41)	−0.12	0.14	0.05
	4 (256 ²)	default (41)	−0.07	0.09	0.03
	4 (256 ² , low model top)	40 (101)	−0.10	0.11	0.04
	4 (256 ² , high model top)	40 (126)	−0.07	0.10	0.03
MYNN	1 (256 ²)	default (41)	−0.15	0.17	0.04
	1 (256 ² , nest)	default (41)	−0.03	0.07	0.03
	1 (1024 ²)	default (41)	−0.02	0.07	0.03
	2 (256 ²)	default (41)	−0.10	0.13	0.04
	4 (256 ²)	default (41)	−0.03	0.07	0.03
	4 (256 ² , low model top)	40 (101)	−0.59	0.59	0.10
	4 (256 ² , high model top)	40 (126)	−0.03	0.09	0.03
QNSE	1 (256 ²)	default (41)	−0.15	0.15	0.03
	1 (256 ² , nest)	default (41)	−0.02	0.08	0.03
	1 (1024 ²)	default (41)	−0.02	0.08	0.03
	2 (256 ²)	default (41)	−0.10	0.14	0.04
	4 (256 ²)	default (41)	−0.03	0.08	0.03
	4 (256 ² , low model top)	40 (101)	−0.02	0.08	0.03
	4 (256 ² , high model top)	40 (126)	−0.01	0.08	0.03

Table 2.4: As in Table 2.3, but for 24 October 2012.

PBL Scheme	Δh [km] (npts)	Δz [m] (npts)	$BIAS_N$	MAE_N	$CRMSE_N$
YSU	1 (256 ²)	default (41)	−0.11	0.12	0.03
	1 (256 ² , nest)	default (41)	−0.11	0.12	0.02
	1 (1024 ²)	default (41)	−0.11	0.12	0.02
	2 (256 ²)	default (41)	−0.13	0.14	0.03
	4 (256 ²)	default (41)	−0.11	0.12	0.02
	4 (256 ² , low model top)	40 (101)	−0.06	0.11	0.03
	4 (256 ² , high model top)	40 (126)	−0.08	0.09	0.02
MYNN	1 (256 ²)	default (41)	−0.08	0.11	0.03
	1 (256 ² , nest)	default (41)	−0.05	0.11	0.04
	1 (1024 ²)	default (41)	−0.06	0.11	0.04
	2 (256 ²)	default (41)	−0.07	0.11	0.04
	4 (256 ²)	default (41)	−0.05	0.11	0.04
	4 (256 ² , low model top)	40 (101)	−0.71	0.71	0.06
	4 (256 ² , high model top)	40 (126)	−0.01	0.11	0.04
QNSE	1 (256 ²)	default (41)	−0.10	0.11	0.02
	1 (256 ² , nest)	default (41)	−0.10	0.11	0.02
	1 (1024 ²)	default (41)	−0.11	0.11	0.02
	2 (256 ²)	default (41)	−0.11	0.12	0.02
	4 (256 ²)	default (41)	−0.10	0.11	0.02
	4 (256 ² , low model top)	40 (101)	−0.04	0.09	0.03
	4 (256 ² , high model top)	40 (126)	−0.07	0.09	0.02

NLLJ is predicted with all three PBL schemes, details of SBL and NLLJ evolution are generally not well captured, and the magnitude and depth of the NLLJ is poorly represented compared with the observations. Similar results hold across all ten LABLE cases shown in Fig. 2.7. Runs using 4-km horizontal spacing and the default vertical grid tended to underestimate the wind speed maxima and evolved much more smoothly, missing sudden increases and decreases in the NLLJ maximum wind speed. With this standard grid configuration, no single PBL scheme can be qualified as the best to use for simulating the NLLJ. All schemes struggle more with the late forming weakly turbulent NLLJ on 09 October 2012 than with the strongly turbulent NLLJ on 24 October 2012. Tests conducted in our study have been designed to examine changes to this baseline configuration that would be beneficial for simulating the NLLJ and to find out if associated improvements are consistent for each PBL scheme. The overarching goal was to identify a suitable WRF model configuration for NLLJ research applications.

2.4.1 Horizontal grid spacing

Simulations were conducted on numerical grids of size $256 \times 256 \times 41$ with 1-, 2-, and 4-km horizontal spacing in order to test the sensitivity of model results to horizontal resolution. Runs were conducted for each SL/PBL combination described in Sect. 2.3. First, our discussion focuses on results from runs using the YSU scheme.

For the weakly turbulent 09 October 2012 case, the **YSU4kmDef** (Fig. 2.8d) configuration underestimated the magnitude of the NLLJ as mentioned previously, but the temporal evolution of the wind field overnight resembled the observed evolution. Errors were most obvious in the NLLJ core region. The **YSU2kmDef** (Fig. 2.8c) configuration resulted in a simulated wind field that was less representative of the observations than the simulation with 4-km horizontal spacing. The magnitude and structure of the NLLJ were poorly captured, and there was little detail provided about the temporal evolution of the wind field. Finally, the **YSU1kmDef** (Fig. 2.8b) configuration captured the timing of the NLLJ, but

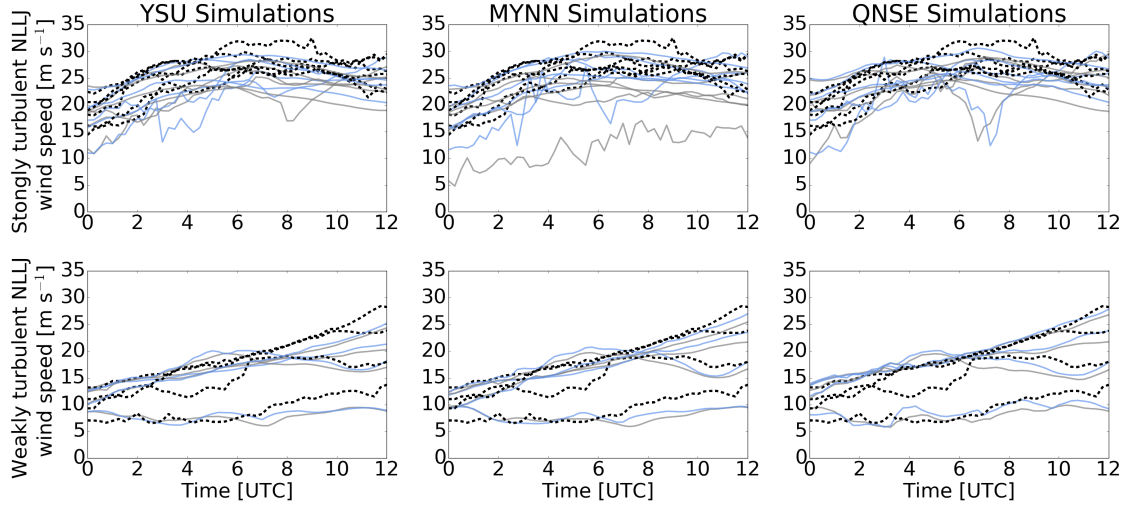


Figure 2.7: NLLJ wind speed maxima plotted in time for the strongly turbulent (upper row) and weakly turbulent (lower row) NLLJ cases listed in Table 2.1. Black dashed lines show the observed wind speed maxima. Grey lines show NLLJ wind speed maxima from simulations using 4-km horizontal spacing and the default vertically stretched grid. Blue lines show NLLJ wind speed maxima from simulations using 4-km horizontal spacing and the 40-m non-stretched vertical grid (with a high model top). Each column shows simulations using a different PBL scheme.

failed to predict a NLLJ with structure and magnitude comparable to the observed NLLJ. The predicted height of the NLLJ maximum also appeared too low compared with the observations. Simulations with 4-km spacing generally predicted the magnitude of the NLLJ better than the simulations with 1- or 2-km spacing, but large errors were still observed in the core region. $BIAS_N$ and MAE_N values in Table 2.3 and Fig. 2.6 agree with this analysis since each value decreases as horizontal spacing increases.

For the strongly turbulent 24 October 2012 case, the **YSU4kmDef** (Fig. 2.8h) configuration predicted a NLLJ that is visually most similar to observations. The NLLJ magnitude was still underestimated, but the jet was generally stronger, and its temporal evolution was better captured than in the **YSU1kmDef** or **YSU2kmDef** simulations. The performance metrics were slightly improved compared with metrics of other considered configurations (Table 2.4 and Fig. 2.6). The **YSU2kmDef** (Fig. 2.8g) run offered some information about temporal evolution by depicting a slight descent of the jet at 0700 UTC and realistic flow structure early in the simulation window. However, it is clear that the jet strength was still underestimated, which is especially true for the region around the jet maximum. Increased values of $BIAS_N$, MAE_N , and $RMSE_N$ (Table 2.4 and Fig. 2.6) suggested a degradation of the **YSU2kmDef** modeled jet as compared with the **YSU4kmDef** run. The **YSU1kmDef** (Fig. 2.8f) configuration generally captured the timing and vertical extent of the jet. However, the model failed to reproduce the slow descent and subsequent ascent of the jet between 0700 and 0900 UTC. In addition, the **YSU1kmDef** configuration delayed the erosion and lifting of the jet. Metrics in Table 2.4 and Fig. 2.6 show that the **YSU1kmDef** run was slightly improved over the **YSU2kmDef**, but the **YSU4kmDef** run still fared the best.

Each simulation discussed in the previous tests of horizontal spacing used numerical meshes with 256×256 points in the horizontal. Accordingly, the mesh with 1-km horizontal grid spacing spanned a 256-km region (dashed box shown in Fig. 2.1), while the mesh with 4-km horizontal grid spacing covered a 1024-km domain (solid box shown in Fig. 2.1). It is possible to suppose that allowing flow features more space to develop within

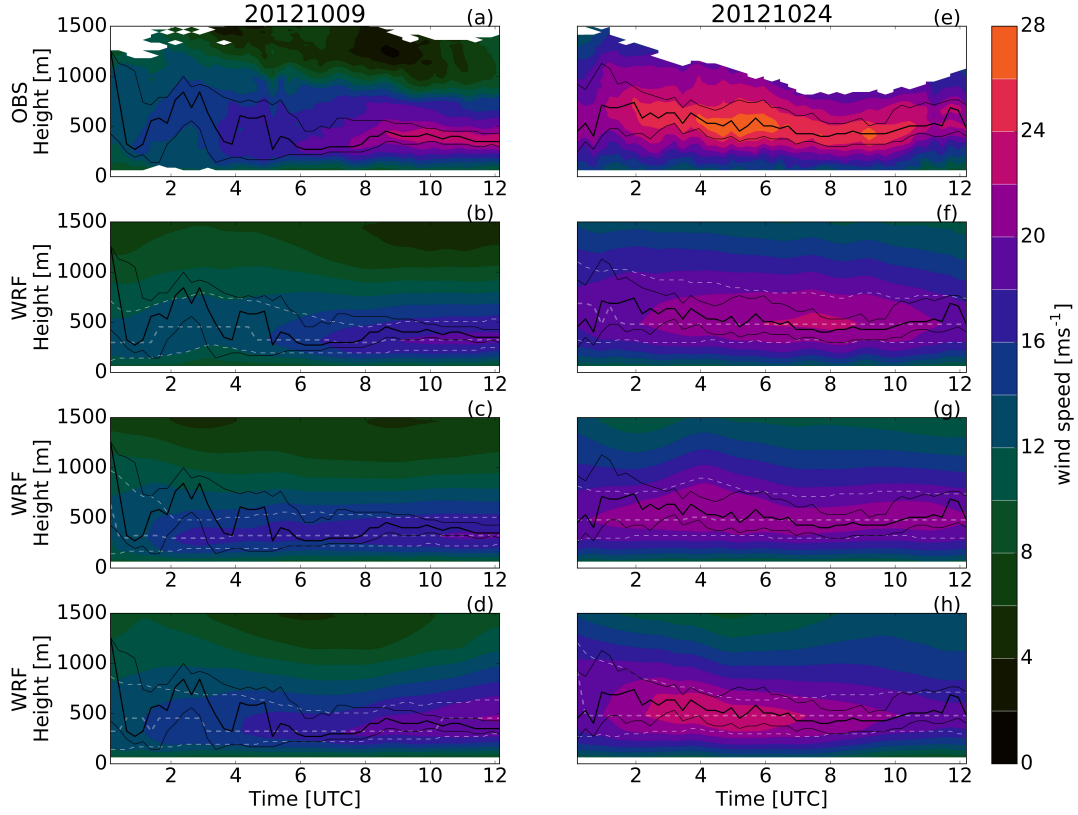


Figure 2.8: Time-height cross sections of observed and WRF simulated data from 09 October 2012 (panels a-d) and from 24 October 2012 (panels e-h). Panels a and e show the observed wind speed. Simulations are shown with 1-km horizontal spacing (b and f), 2-km horizontal spacing (c and g), and 4-km horizontal spacing (d and h), all using the default stretched vertical grid and the YSU PBL scheme. Heavy solid black (dashed white) lines show the height of the observed (simulated) NLLJ maximum. Lighter solid black (dashed white) lines encompass the region in which the observed (simulated) wind speed is at least 90% of the NLLJ maximum wind speed.

the model domain may improve the performance of the simulations with 1-km horizontal grid spacing. In order to investigate whether the mesh size, and thus also the proximity of the interior grid cells to the boundaries, had an impact on the modeled NLLJ, results of model runs in two domains with a horizontal expanse of 1024 km were compared: in the domain of size 256×256 using 4-km horizontal grid spacing, and in the domain of size 1024×1024 with 1-km horizontal grid spacing. The use of one-way nesting was also investigated. As stated previously, data from the 12-km NAM provided boundary conditions to the WRF model every 6 hours. This means that the 12-km NAM reanalysis data used for setting the initial and boundary conditions were downscaled differently to match the 4-km grid than they were to match the 1-km grid. To evaluate the impact that this downscaling difference had on the resulting wind fields, a grid with 1-km horizontal spacing was nested within a grid with 4-km spacing. Thus, the boundaries of the 256×256 grid with 1-km horizontal spacing (dashed box shown in Fig. 2.1) were driven by 4-km spaced data rather than 12-km spaced data.

Results for the 09 October 2012 case (see Table 2.3 and Fig. 2.6) indicate that the 1-km 1024-point simulation performed comparably with the model runs using the 4-km 256-point domain and offered some improvement over the 1-km, 256-point domain. For example, bars depicting $BIAS_N$ in Fig. 2.6 show a modest difference between the 1-km 1024-point simulation and the 4-km 256-point, but a much larger difference exists between the 1-km 256-point domain and the 1-km 1024-point domain. This implies that choosing an appropriate horizontal grid size and considering a location's proximity to the simulation domain boundaries can be just as important as selecting an appropriate horizontal grid spacing when reproducing the NLLJ over U.S. Great Plains. However, results for the 24 October 2012 case (see Table 2.4 and Fig. 2.6) did not necessarily agree with the above conclusion. In this case, the 1-km 1024-point, 4-km 256-point, and 1-km 256-point simulations all performed similarly. For both cases, the 1-km 256-point nested domain performed similarly to the 1-km 1024-point and 4-km 256-point domains. In summary, any possible

advantages of using 1-km spacing on the 256-point domain without nesting was likely washed out by the relatively coarse representation of the NLLJ from the 12-km NAM lateral boundary conditions. In this study, using 1-km spacing in the NLLJ only (i.e., the 1-km 256-point simulations) and using 1-km spacing in the NLLJ and in the surrounding region (i.e., the 1-km 1024-point simulations) to represent additional features that could influence the jet had similarly small impacts on the considered performance metrics. The differences between the simulations using 1-km and 4-km horizontal grid spacing did not justify the sixteen-fold increase in computational burden associated with the finer-resolution simulation, and did not motivate further study of larger nested domains. While we could envision additional tests of grid extent and nesting applications, we felt that investigating vertical grid spacing would be generally more important for our study’s objectives.

Comparison with observations clearly indicates that the model underestimated the magnitude of the NLLJ using the default vertical grid with any horizontal spacing. This underestimation was confirmed by the negative $BIAS_N$ values presented in Tables 2.3 and 2.4 and Fig. 2.6. In both cases, the underestimation was particularly large within the core of the jet. The model produced a NLLJ that is too diffuse in the vertical direction compared to the observed jet. Tests showed that the increase in computational costs associated with the 1-km spacing apparently offers no direct benefit over the 4-km configurations. While specific details of model solutions differed among configurations with differing PBL schemes, the results were overall similar (see Tables 2.3 and 2.4 and Fig. 2.6). This finding is consistent with results from previous studies, especially those conducted over the terrain representative of the Great Plains. Gibbs et al. (2011) found that model runs employing 4-km horizontal grid spacing produced near-surface turbulent flow parameters that were as accurate, if not more so, than those conducted using a grid with 1-km spacing. Kain et al. (2008), Schwartz et al. (2009), and Clark et al. (2012) all found that the finer details in convection forecasts produced by a WRF model run with 2-km horizontal grid spacing did not add enough value over the forecasts provided by the 4-km configuration to justify

the increased computational burden. Similar results were found in evaluations using object based evaluation methods (Johnson et al. 2013).

2.4.2 Vertical grid spacing

Given the strong vertical gradients shown in LABLE observations and their absence in simulations shown in Fig. 2.8, it is reasonable to hypothesize that adding additional vertical levels might improve the modeled NLLJ. This hypothesis was tested by comparing results obtained with the WRF model default vertical grid to those obtained using quasi-constant vertical spacing of 40-m. The 40-m constantly spaced vertical grid was constructed using the hypsometric equation. Initially, the 40-m grid in our case had 101 vertical levels with the first model level at 20 m and the model top near 4 km. Employing such a grid constrained the vertical extent of the model domain, but the NLLJ exists within this portion of the atmosphere, and these cases did not include persistent strong vertical motions, so the initial and boundary conditions were relied upon to represent the larger scale conditions. These simulations will be called low model top simulations. For all grids, a Rayleigh damping layer was applied in the top 600 m of the domain. The construction of the quasi-constant vertical grid and the damping option are similar to the approach described in Mirocha et al. (2014). Levels for both vertical grids in the lowest 2 km of the model domain are illustrated in Fig. 2.5. We initially focus on the runs with the YSU PBL parameterization scheme (Fig. 2.9).

As mentioned in Sect. 2.4.1, a consistent underestimation of NLLJ magnitude was observed when applying the default vertically stretched grid for both considered nights. This underestimation was most prevalent in the core of the jet. Simulations with the default WRF grid can therefore miss important features of the temporal evolution and structure of the NLLJ. For both cases, the noted underestimation in **YSU4kmDef** was still present in the **YSU4km40m** simulations with a low model top (Fig. 2.9c,g), but the structure and temporal evolution of the jet were both improved. However, the **YSU4km40m** runs with

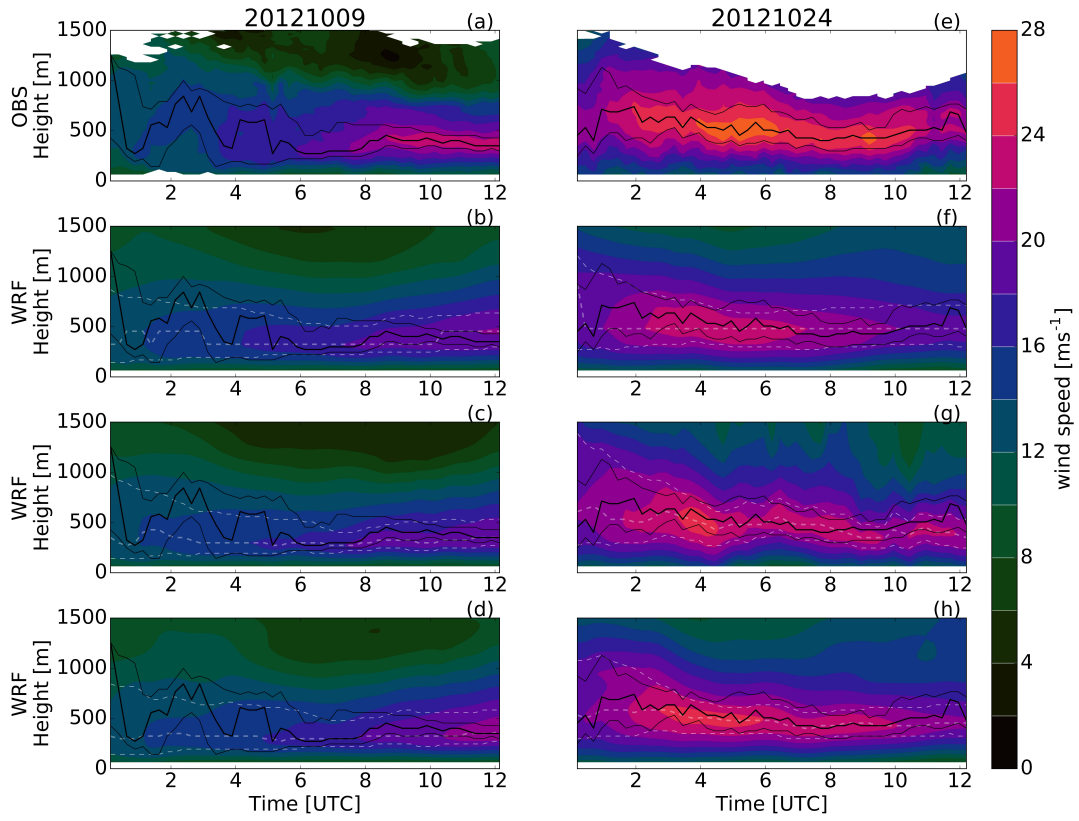


Figure 2.9: As in fig. 2.8 except WRF simulations are shown with the default stretched vertical grid (panels b and f), 40-m vertical spacing with a low model top (panels c and g), and 40-m vertical spacing with a high model top (panels d-h). All simulations shown use 4-km horizontal spacing and the YSU PBL scheme.

a low model top over-predicted wind speed below the height of the observed NLLJ maximum, which is likely caused by spatial errors in the predicted and observed NLLJ height and depth. The appearance of the wind field was notably improved by better representation of the jet core and changes to its structure in time. For 09 October 2012, the WRF model predicted lower values for the height of the NLLJ maximum early on and after 0700 UTC. Additionally, the model struggled to reproduce the narrow jet core, but simulations with finer vertical spacing and a low model top still showed some improvement in this regard. For 24 October 2012, the depth of the NLLJ was well predicted, but the NLLJ maximum was again positioned too high early on and after 0900 UTC, when the runs with finer vertical spacing and a low model top failed to reproduce the lifting of the jet. In both cases, the finer vertical grid spacing allowed for the temporal evolution of the height and magnitude of the NLLJ to be more representative of the observed evolution. Indeed, the overall performance for the strongly turbulent NLLJ on 24 October 2012 was generally improved with $BIAS_N$ and MAE_N values decreasing for the **YSU4km40m** runs with a low model top as compared with the **YSU4kmDef** run (see Table 2.4 and Fig. 2.6). $CRMSE_N$ increased slightly. The same cannot be said for the weakly turbulent case on 09 October 2012, with metrics either increasing or not changing for the **YSU4km40m** runs with a low model top as compared with the **YSU4kmDef** run. However, MM values including both cases for the **YSU4km40m** runs with a low model top were similar to those of the **YSU4kmDef** runs. The 40-m spaced vertical grid offered some improvement of jet prediction over the default stretched grid based on both the visual comparison of the simulated and observed NLLJ wind fields and the more objective performance metric evaluation.

Mesoscale simulations of the NLLJ with a typical default vertical grid configuration showed weak sensitivity to the choice of PBL scheme. Since it has been shown that a 4-km horizontally spaced grid with finer constant vertical spacing offers improvement to the simulated NLLJ, sensitivity to the three PBL parametrization schemes discussed in Sect. 2.3 was revisited with this grid configuration (i.e., 4-km horizontal spacing and 40-m

vertical spacing with a low model top). Simulated wind speeds are shown in Fig. 2.10, and simulated potential temperature data are shown in Fig. 2.11.

For both dates, it is immediately clear that the **MYNN4km40m** runs with a low model top (Fig. 2.10c,g) did not develop a valid NLLJ, with the modeled jet being diffused vertically through the entire boundary layer. Corresponding potential temperature fields from the **MYNN4km40m** simulations with a low model top (Fig. 2.11c,d) were similarly mixed throughout the boundary layer. We ran the MYNN scheme within three previous versions of the WRF model to confirm this behavior for grid configurations with a low model top. In each version and for both cases, the MYNN scheme produced results similar to those shown in Figs. 2.10c,g and 2.11c,g for the 40-m vertically spaced grid with a low model top (see Tables 2.3 and 2.4 and Fig. 2.6). Similar behavior of the MYNN scheme was noted in Olsen and Brown (2011) and Jahn et al. (2014). In the latter paper, the authors suggested that the LES-derived closure constants in the scheme may be unsuitable for some conditions. We hypothesize that the MYNN scheme may be especially sensitive to the grid configuration when determining the mixing lengths prescribed in the scheme.

The unrealistic behavior of the **MYNN4km40m** simulations with a low model top motivated us to test the importance of the model top height to the resulting wind field. A new vertical grid was constructed by blending the 40-m grid with 101 vertical levels with the default grid above 4-km. The resulting grid consisted of 126 vertical levels and brought the model top to about 16-km to match the height of the default grid. These simulations will be called high model top simulations. The wind fields for the **YSU4km40m** configuration with a high model top are shown in Fig. 2.9d,h. Compared to the **YSU4km40m** configuration with a low model top (Fig. 2.9c,g), the increased model top height had a weak impact on the wind field. Figs. 2.12 and 2.13 show the wind speed and potential temperature fields from simulations using the higher model top and all three PBL schemes. Impacts on simulations using the MYNN scheme were large. The performance metrics shown in Fig. 2.6 confirm that the impact of the higher model top is small for runs using YSU or QNSE but

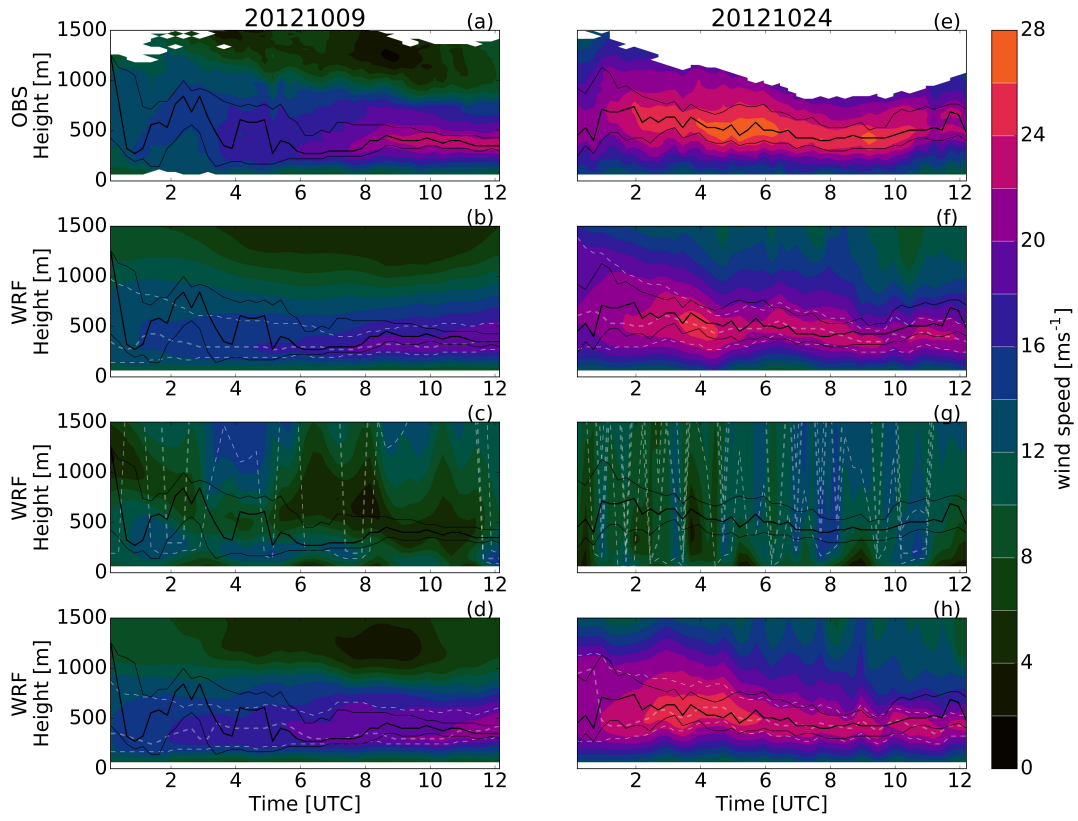


Figure 2.10: As in fig. 2.8 except WRF simulations are shown with the YSU PBL scheme (panels b and f), the MYNN PBL scheme (panels c and g), and the QNSE PBL scheme (panels d-h). All simulations shown use 4-km horizontal spacing and 40-m vertical spacing with a low model top.

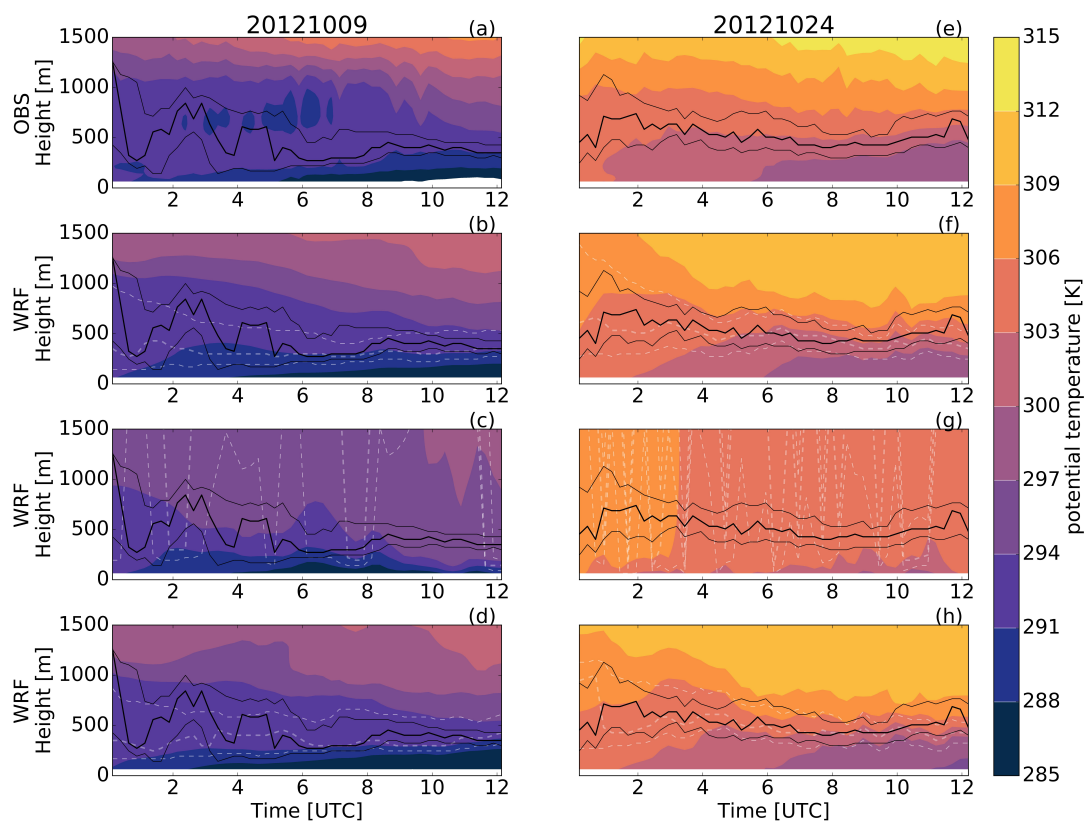


Figure 2.11: As in fig. 2.10, but showing observed and simulated potential temperature.

large for simulations using the MYNN scheme. The improvement of simulations using the MYNN scheme when increasing the model top suggests a sensitivity in the scheme that is not present in the other evaluated schemes. The sensitivity of the MYNN scheme to model top height cannot be readily explained in physical terms at this point.

The previous analysis showed that the **YSU4km40m** configurations with either model top (Figs. 2.10b,f and 2.12b,f) yielded a NLLJ with realistic temporal evolution and vertical structure for both cases, despite an apparent underestimation of the NLLJ magnitude. The **MYNN4km40m** simulations produced non-physical results with a low model top (Fig. 2.10c,g), but performed comparably to simulations using other schemes when used with a high model top (Fig. 2.12c,g). The **QNSE4km40m** simulations (Figs. 2.10d,h and 2.12d,h) performed comparably to **YSU4km40m** simulations with either model top, but offered improvements in the appearance and behavior of the jet, especially in the 09 October 2012 case. Specifically, the **QNSE4km40m** configurations more closely predicted the magnitude and structure of the NLLJ. Areas where the wind speed was under- or overestimated were limited to the periods of jet development and decay, leaving a more accurate representation of the jet core as compared to other configurations. The temporal evolution of the jet was generally consistent with observations, as was its vertical structure. This was true even for the period before the NLLJ fully developed prior to 0600 UTC on 09 October 2012. The metrics summarized in Fig. 2.6 are consistent with this interpretation, where **QNSE4km40m** runs performed slightly better than **YSU4km40m** runs and the **MYNN4km40m** run using a high model top. Additionally, the **QNSE4km40m** configurations offered subtle improvements to the predicted evolution of the potential temperature fields (Figs. 2.11d,e and 2.13d,e).

Similar conclusions were drawn by Vanderwende et al. (2015), in which the QNSE scheme performed the best among the considered PBL schemes, especially in moderate-to-strong NLLJ cases. Mirocha et al. (2016) also noted the superior performance of the QNSE scheme in predicting boundary layer wind at night as compared with MYNN and YSU.

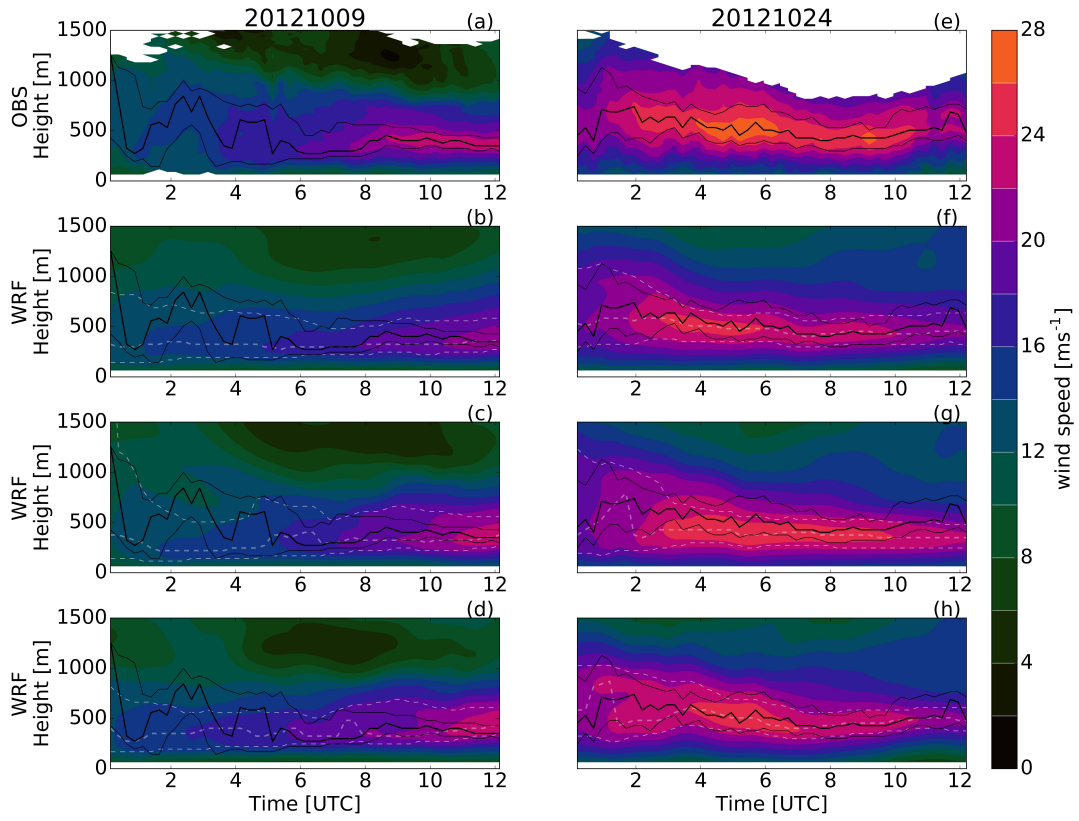


Figure 2.12: As in fig. 2.8 except WRF simulations are shown with the YSU PBL scheme (panels b and f), the MYNN PBL scheme (panels c and g), and the QNSE PBL scheme (panels d-h). All simulations shown use 4-km horizontal spacing and 40-m vertical spacing with a high model top.

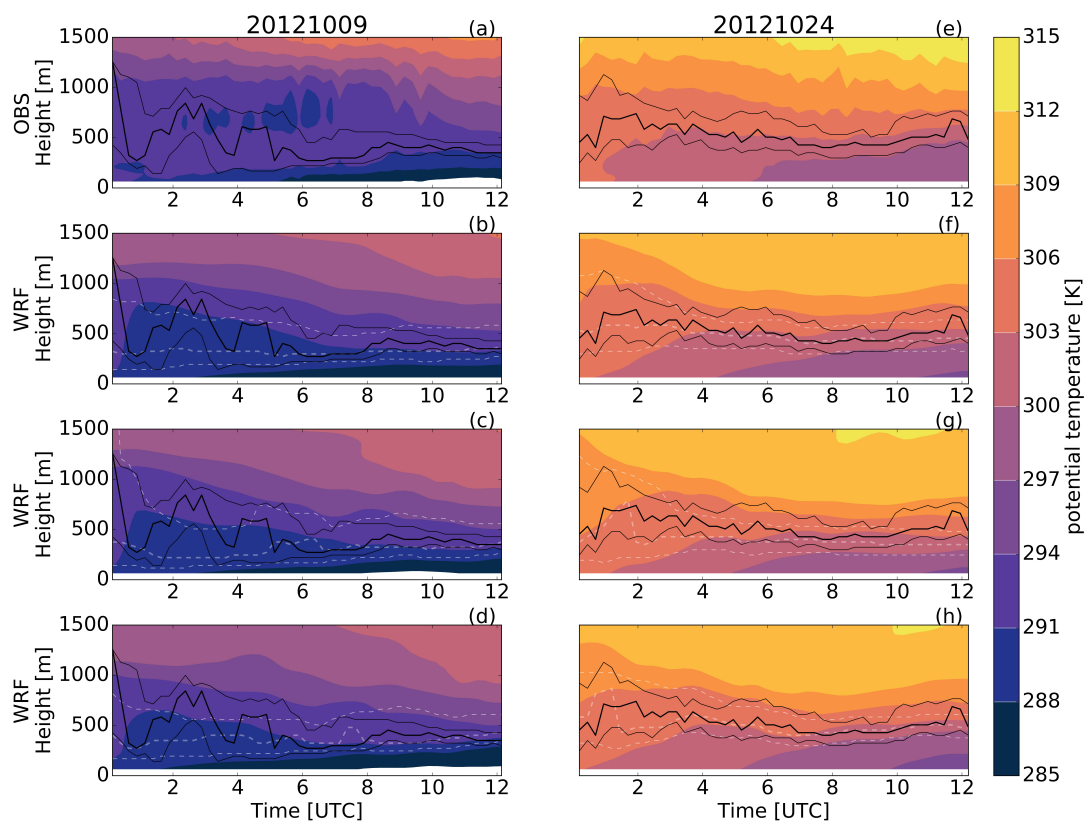


Figure 2.13: As in fig. 2.12, but showing observed and simulated potential temperature.

The authors of *op. cit.* specifically noted how the QNSE performance demonstrates the benefits of improving model physics for particular environments for which more traditional approaches may be inadequate. The SBL is a prime example of such an environment. The present study confirms these results using different grid configurations and for a different set of NLLJ cases than previously considered.

2.4.3 Expanded case data set

The same normalized metrics discussed in Sect. 2.3 were computed for the ten LABEL cases listed in Table 2.1. The metrics are visualized in Fig. 2.14. The conducted analysis included tests of all three PBL schemes using the 4-km 40-m (high model top) and 4-km default grid configurations. Time series of NLLJ maximum wind speed are shown in Fig. 2.7. The MYNN PBL scheme often struggled with strongly turbulent cases when applied with the default vertically stretched grid. This result was not apparent in either of the cases discussed in detail above. As mentioned in Sect. 2.4.2, we hypothesize that the decline in performance may result from sensitivities related to the mixing length specification in the MYNN scheme. Further investigation is needed to understand the origins of this issue in the scheme, but is beyond the scope of the presented work. Otherwise, the varying PBL schemes and grid configurations produced different outcomes for the ten cases. There was no consistent trend for improved performance metrics for finer grid spacing or PBL scheme. The $BIAS_N$, MAE_N , and $CRMSE_N$ averages over all ten cases are shown as the last set of bars in each respective panel of Fig. 2.14. MYNN runs using the default grid produced the highest $BIAS_N$ values. MYNN runs with the 40-m vertical grid and YSU and QNSE runs on both vertical grids fared much better than the MYNN runs with the default grid, and the 40-m vertical grid offered minor improvement to the $BIAS_N$ for YSU and QNSE runs. A similar result is seen in the MAE_N values averaged over all ten cases. MYNN runs with the default grid produced the highest MAE_N , but other configurations all perform similarly

with a slight favor toward the 40-m grid. $CRMSE_N$ shows all configurations performed similarly, but again there was a slight favor toward the 40-m vertical grid.

The final panel of Fig. 2.14 shows the MM for all cases and for strongly and weakly turbulent cases separately. For all cases, MYNN runs with the default vertical grid performed the worst in terms of MM . MYNN runs with the 40-m grid, YSU runs, and QNSE runs performed similarly with QNSE showing a slight advantage with lowest MM values. For YSU and QNSE, there was very little difference in the runs using the default and vertical grids. Runs using the MYNN scheme benefited substantially from the increased number of vertical levels when the model top was high enough. Strongly turbulent cases followed the same pattern as all cases with similar performance for all configurations except for the MYNN runs with the default vertical grid. Weakly turbulent cases were much better captured in the MYNN runs using the default vertical grid, but these cases were best represented by the QNSE runs using the 40-m grid. In a general sense, runs using the MYNN scheme on the default vertical grid struggled the most to adequately represent the NLLJ. Runs using the MYNN scheme on the 40-m grid and YSU and QNSE on both vertical grids were all quite similar with slight differences between the default and 40-m vertical grid. MM values are shown for both wind direction and potential temperature in Fig. 2.15. Similar to the data shown in Fig. 2.14, MM values for wind direction and potential temperature indicate that, except for runs using MYNN on the default vertical grid, all configurations were comparable.

The average MB , MAE , and $CRMSE$ were computed for wind speed across all 10 cases. Using these averages, the 95% confidence intervals for each performance metric were constructed using an empirical bootstrap technique with 10000 replacement iterations. The resulting averages and confidence intervals are shown in Fig. 2.16. Again, except for runs using MYNN on the default vertical grid, all configurations were fairly comparable. While differences are small the confidence intervals do show that, for all metrics except $CRMSE$, all configurations performed better on the 40-m vertical grid than the default vertical grid.

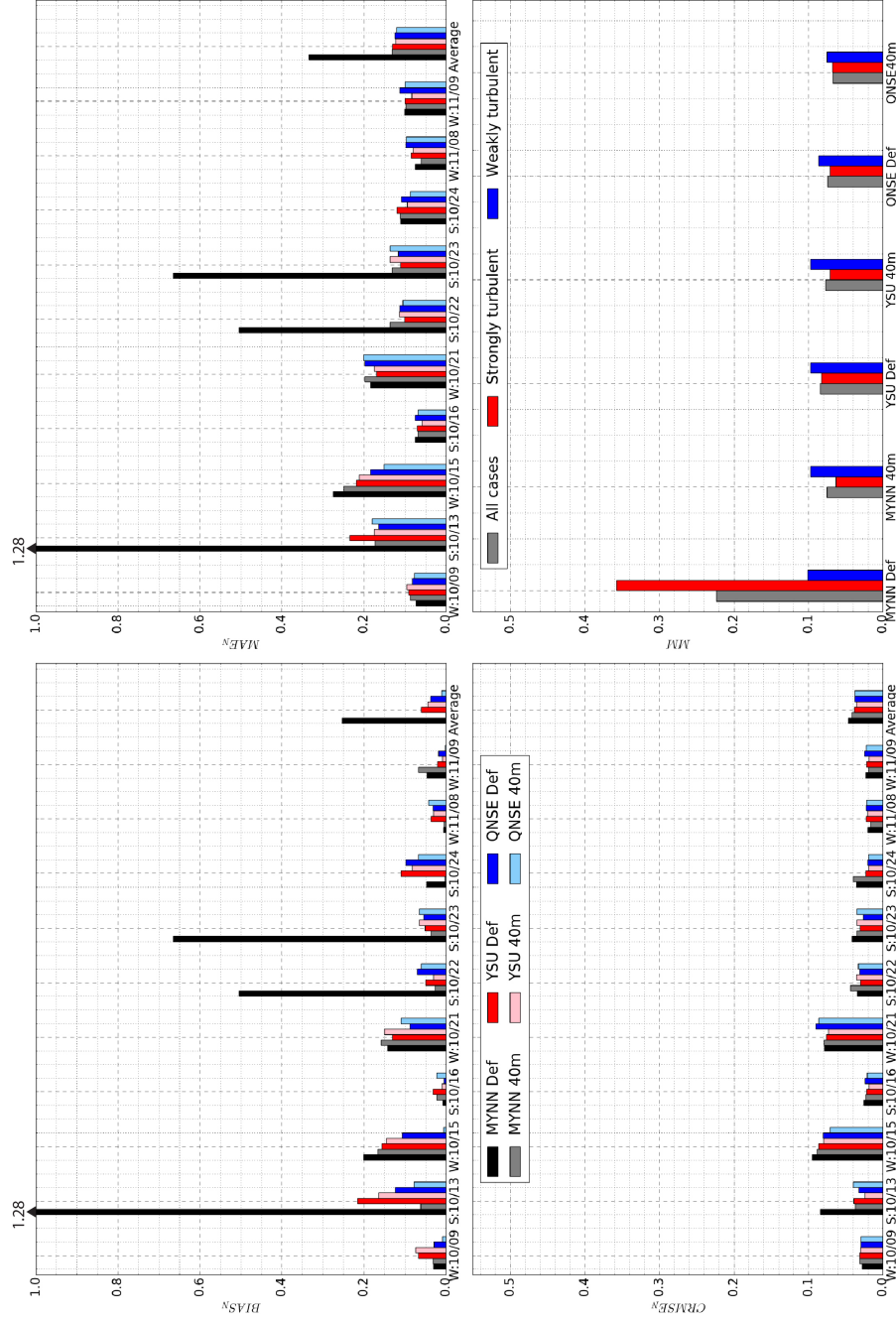


Figure 2.14: Bar plots show the values of $BIAS_N$ (upper left panel, displayed as an absolute value), MAE_N (upper right panel), and $CRMSE_N$ (lower left panel) for 10 LABLE cases. The case dates and classifications (W for weak, S for strong) are labeled on the x-axis. The lower right panel shows MM for all cases and for each classification.

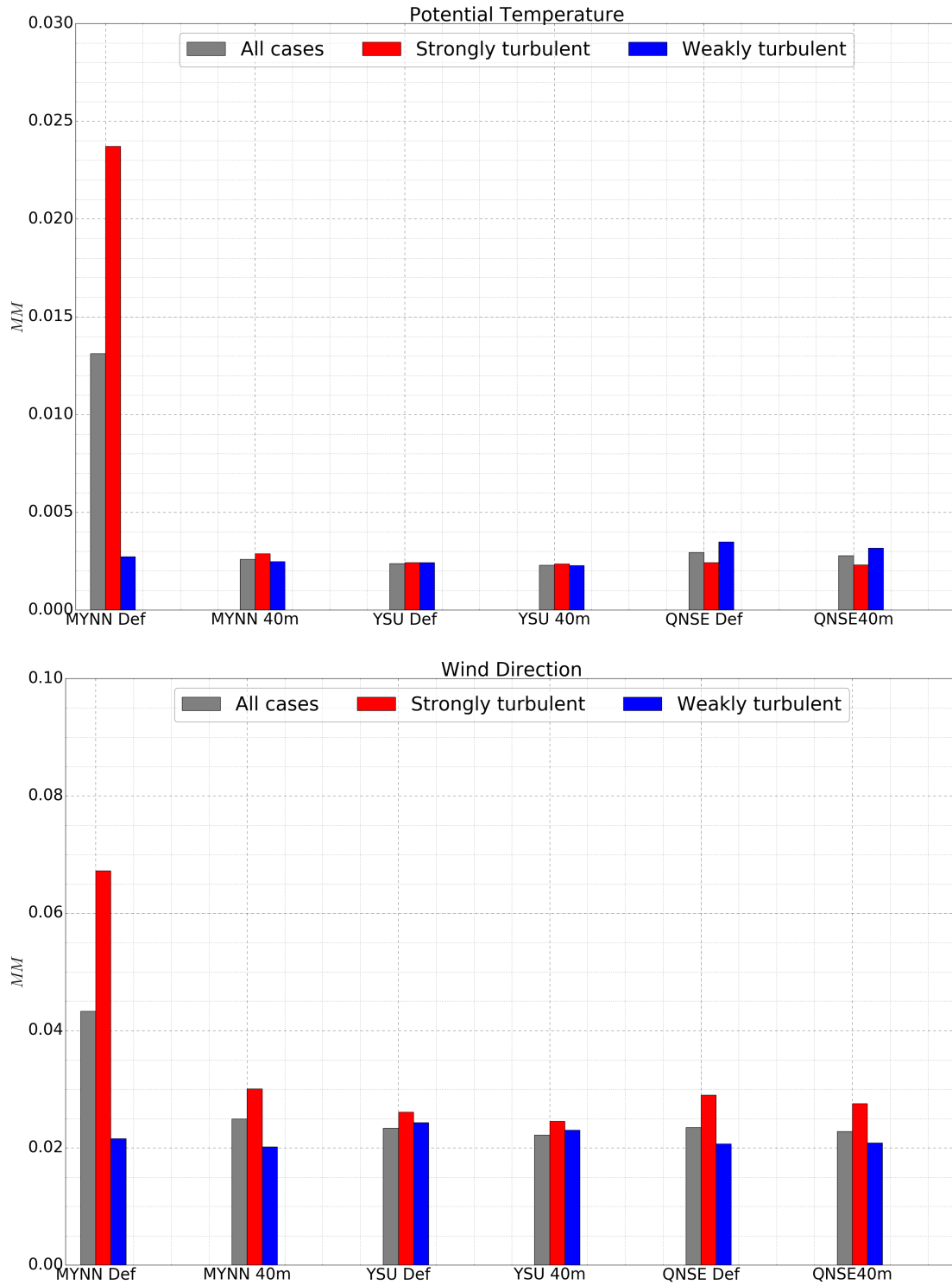


Figure 2.15: *MM* for all cases and for each classification for potential temperature (upper) and wind direction (lower).

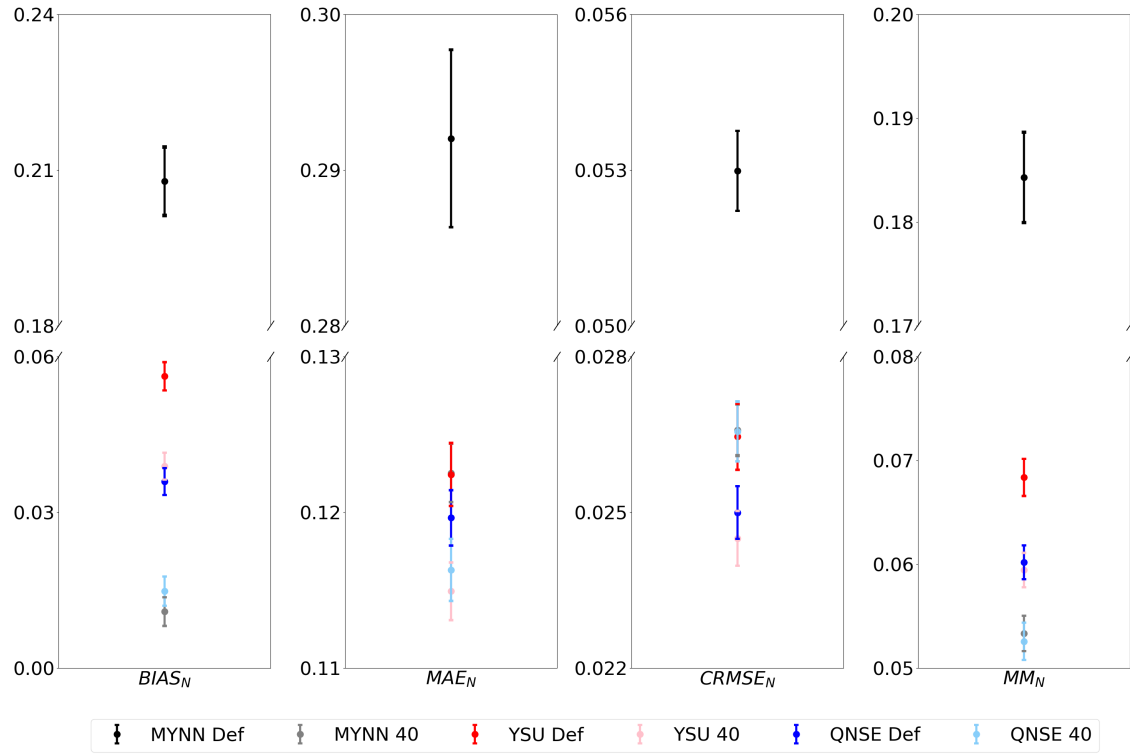


Figure 2.16: Averages for each configuration over all 10 cases are shown with 95% confidence intervals for each considered performance metric. Note that the y-axes vary across panels and contain breaks.

It is important to note that performance metrics can possibly degrade if simulations manage to predict a stronger NLLJ but fail to correctly predict the height and depth of the NLLJ core. Similar verification issues have been discussed previously in the literature highlighting the utility of object or feature based verification methods (e.g. Johnson et al. 2013, Mittermaier 2008). Bearing this in mind and reflecting on the visual analysis of the wind fields shown such as those in Fig. 2.9, NLLJ development and persistence was improved with finer vertical spacing. Evaluation of the potential temperature fields shown in Figs. 2.4 and 2.13 further supported the use of finer vertical grid spacing. While simulations using the MYNN (with 40-m spacing on a grid with a high model top), QNSE, and YSU schemes performed similarly, the QNSE scheme was ultimately chosen for our future studies because of slightly better performance in these cases and its focus on SBL physics. QNSE uses scale elimination to approximate exchange by interacting turbulent eddies, which can perhaps better capture the processes associated with the sharp vertical gradients of meteorological fields within NLLJs. These test results point to the configuration with a 4-km horizontally spaced and 40-m vertically spaced grid and the QNSE scheme as the most optimal considered configuration of the WRF model for research simulations of the NLLJ over the Great Plains.

2.5 Conclusions

Numerical experiments were run for ten NLLJs observed during LABLE field campaign. Two of these cases were chosen for detailed evaluation: a weakly turbulent NLLJ on 09 October 2012 and a strongly turbulent NLLJ on 24 October 2012. Overall results concerning grid spacing and PBL parameterization were consistent between the two cases even though the NLLJ developed quite differently in each case (see e.g., Fig. 2.2). The NLLJs simulated with the WRF model were found to have varying degrees of sensitivity to horizontal grid spacing, vertical grid spacing, and choice of PBL parameterization scheme.

Counter to the seemingly natural assumption that reducing grid spacing should improve predictions of atmospheric flow variables, findings of our study suggested that using 4-km horizontal spacing is no worse than using finer horizontal spacing (i.e., 1- or 2-km) for representing the NLLJ. In fact, our results showed that finer horizontal spacing could result in degraded wind field simulations. Accordingly, there is little justification for the increased computational burden associated with the use of a 1-km grid. These results are consistent with those reported in the literature and indicate that 4-km horizontal grid spacing is the optimal choice for WRF simulation of the considered NLLJs and associated nocturnal SBLs.

Vertical grid spacing is another key factor in simulating the NLLJ using the WRF model. While the default stretched vertical grid configuration of the WRF model performed generally satisfactorily, the use of a vertical grid with quasi-constant and finer spacing proved to be a worthwhile investment of computational resources. The simulations with a finer vertical grid provided improvements to the morphology of the NLLJ, especially to the representation of the temporal evolution and vertical structure of the jet. The MYNN PBL scheme severely underestimated the magnitude of the NLLJ and over-mixed the boundary layer flow when applied on a non-stretched vertical grid with a low model top. Similar trends were also observed with the default vertically stretched grid (in some strongly turbulent cases), confirming previously reported behavior (e.g., Olsen and Brown 2011, Jahn et al. 2014). This suggests that some grid configurations are not optimal with the MYNN scheme. When applied with a higher model top, the MYNN scheme produced acceptable results. Such strong sensitivity to model top height was not noted for the YSU or QNSE schemes. The YSU scheme produced a realistic jet in terms of its structure and evolution, but underestimated the jet magnitude. On the other hand, the QNSE scheme more accurately depicted the magnitude, temporal evolution, and structure of the NLLJ, with improvements also noted in the simulated potential temperature fields. The 40-m vertical

grid was found to be an optimal alternative to the default stretched grid when simulating the NLLJ in boundary layer studies.

Results presented for the full ten-case dataset in Fig. 2.14 showed that runs using any scheme with a high model top were fairly similar in terms of the performance metrics. The runs using the QNSE scheme showed a slight advantage over others. While some cases with default vertical spacing scored similarly well or even better than the finer vertical grids in various metrics, these diffuse jets have limited value for detailed NLLJ and SBL analyses. Combining the performance metric evaluation results with the visual comparison of the simulated and observed wind fields made clear the utility of the constantly spaced fine vertical grid over the vertically stretched grid. While all schemes performed similarly in the 4-km horizontally spaced and 40-m vertically spaced (with high model top) configuration, the relevant depiction of stable boundary layer physics in the QNSE makes it particularly attractive for NLLJ modeling.

Based on presented analyses, we found that the optimal grid configuration for simulation of the Great Plains NLLJ using the WRF model was a combination of 4-km horizontal spacing and constant 40-m vertical spacing. In conjunction with this grid, the QNSE scheme was identified as the optimal PBL parameterization. WRF model outputs using this configuration offer detailed information about the structure of the boundary layer and the NLLJ. These simulations also shed light on NLLJ temporal evolution, suggesting that the spatial evolution of the NLLJ is also well captured. The identified configuration will be used in future studies of PECAN cases in which the three-dimensional structure and evolution of the NLLJ over the Great Plains can be evaluated against high-resolution observations at several locations.

Chapter 3

Comparison of PECAN Observations and WRF Simulations

3.1 Introduction

Observations and simulations each have their own inherent limitations. Observations are limited to the spatial and temporal coverage and resolution of the deployed measurement platforms. The PECAN observations provide vertical profiles of kinematic and thermodynamic variables at several point locations with prescribed frequency (usually on the order of 2-5 min). While the PECAN dataset offers high-quality, extensive spatial and temporal observations of the NLLJ, these observations still cannot provide information beyond these set points. Numerical simulations are not as limited in space and time as observations. Depending on the available computational resources, simulations can provide data on fine temporal and spatial scales. However, simulations are limited by the ability of the model to represent key atmospheric properties and phenomena on a required range of scales. Additionally, simulation outcomes are dependent on the quality of initialization data. Even the best models will not produce reliable predictions if the initial or forcing data do not accurately represent the events of interest.

Without observations, there is no way to evaluate a model's performance or tune its parameters to produce output that is representative of the atmospheric phenomena of interest. Without simulations, the observations can only shed light on atmospheric phenomena of a local scope. Using observations and simulations in tandem provides opportunities for more robust analyses than possible when using just one or the other. In this chapter, the PECAN observations are employed to independently evaluate the optimal WRF model configuration identified in Chapter 2. The data and methods used are described in the following section. Then a summary of the cases of interest is presented followed by an evaluation of the model's performance.

3.2 Data and Methods

The PECAN field campaign was an international project funded by the National Science Foundation, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the Department of Energy (Geerts et al. 2016). Measurements were collected from 1 June to 15 July 2015 over a nine-state region during 31 intensive operational periods (IOPs) and 12 unofficial field operations. The primary goal of PECAN was to better understand nocturnal convection. Several important components related to nocturnal convection were identified for detailed study: mesoscale convective systems, bores, convection initiation, and NLLJs. Primary data sources for NLLJ cases were the boundary layer profiles measured by mobile and fixed PECAN Integrated Sounding Arrays (PISAs). These datasets included profiles of dynamic and thermodynamic parameters obtained at high temporal and vertical resolution using Doppler lidars, AERIs, radar wind profilers, radiosondes, and microwave radiometers (MWRs), providing observations to describe the SBL and NLLJ evolution. There were four mobile PISAs (MPs) roaming the domain on a mission by mission basis, and six fixed PISA (FP) sites dispersed across the PECAN domain in Kansas, Oklahoma, and Nebraska collecting data nearly continuously. For NLLJ IOPs, these PISA sites provided information about the spatial variability and evolution of the SBL and NLLJ. The PECAN observational domain and the locations of FPs and MPs (for a typical NLLJ deployment) are shown in Fig. 3.1.

The University of Oklahoma (OU) and the National Severe Storms Laboratory (NSSL) maintain an instrumentation platform called the Collaborative Lower Atmospheric Mobile Profiling System (OU/NSSL-CLAMPS), which was operated during PECAN as MP1 by a team of researchers including the author. Greensburg, Kansas hosted the FP2 site, and Ellis, Kansas hosted FP3. These three sites comprise a north-south oriented transect on which NLLJ observations were evaluated. This transect was chosen because all sites include Doppler lidars and AERIs and data quality was good. At MP1, FP2, and FP3, a scanning Doppler lidar conducted profile observations of the wind field (Turner 2016c,d; Delgado

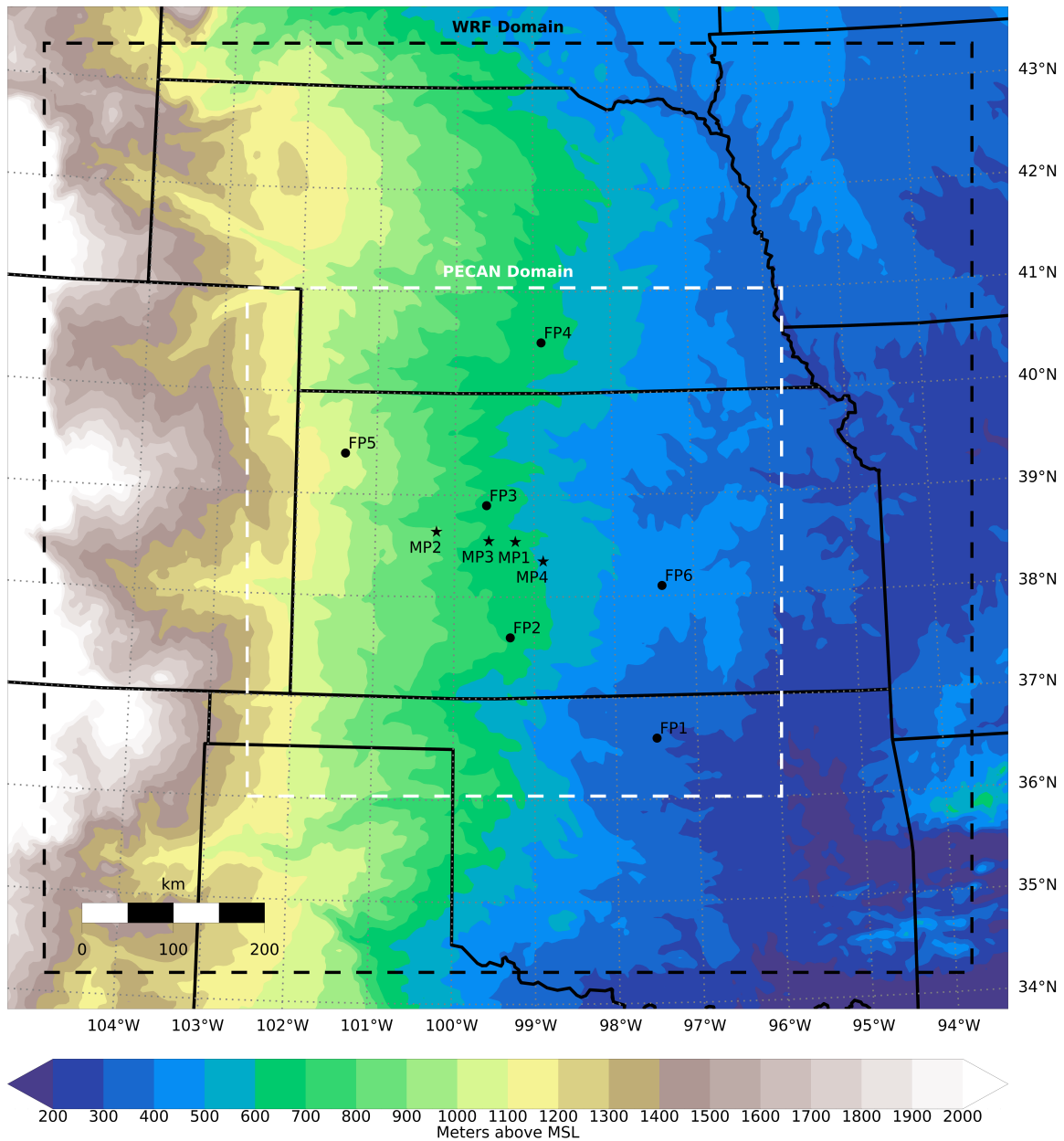


Figure 3.1: Geographical depiction of the observational domain, simulation domain, and the fixed PISA (FP; circles) and mobile PISA (MP; stars) observing platforms overlaid on the region's terrain height.

et al. 2015; Hanesiak and Turner 2016). The Doppler lidar data were passed through a signal-to-noise ratio (*SNR*) check for validity. The threshold used here was $SNR < 0.01 = -20$ dBz. Then, the data were only used in the analysis if the error in retrieval from the the velocity azimuth display (VAD) technique performed on plan position indicator (PPI) scans was low. These procedures typically removed data where the lidar return signal was weak. If they were not already removed, the lowest two range gates of the lidar data were also removed for quality purposes. At MP1, the Doppler lidar did a PPI scan at 70-deg elevation every 2 min with vertical stares in between (Turner 2016c). The Doppler lidar at FP2 ran in a 25-min cycle including PPI scans at 5-, 7.5-, 10-, 20- and 45-deg elevations. The rest of the cycle included four range height indicator scans and a 10-min vertical stare (Delgado et al. 2015). The five PPI scans were used together in a wind profile retrieval. At FP3, the Doppler lidar conducted a 4-point Doppler beam swing at 75-deg elevation every 15 s, from which the wind profile was retrieved (Hanesiak and Turner 2016). Each site also had an AERI, which observed the radiance spectra used to retrieve thermodynamic profiles (Turner 2016b,a, 2015) with 5-min temporal resolution. Information about the retrieval method is available in Turner and Löhnert (2014).

Using observational data similar to those collected during PECAN, Chapter 2 identified an optimal WRF model configuration for reproducing the Great Plains NLLJ. The considered tests included analyses of the effects of horizontal grid spacing, vertical grid spacing, and planetary boundary layer (PBL) scheme. The optimal grid configuration was identified as a non-nested numerical mesh with 4-km horizontal grid spacing and non-stretched 40-m vertical grid spacing. While performance evaluation parameters in Chapter 2 were similar for simulations with three different PBL schemes, the QNSE PBL scheme (Sukoriansky et al. 2005) added value for reproducing important features of NLLJ evolution and thermal structure of the NBL. Accordingly, simulations in the present study used the same configuration with the QNSE scheme. The simulation domain was centered on Hays, Kansas and

Table 3.1: Summarized settings for the WRF model used in this study.

WRF Version	ARW–3.8.1
Initial and boundary condition model	NAM 12km, 6 hourly updates
Spin-up time	24-hours prior to 00Z on date of interest
Domain	$256 \times 256 \times 256$ centered on Hays, Kansas
Horizontal grid	Non-nested 4-km spacing
Vertical grid	Non-stretched 40-m spacing (1st level:20m, top level:10220m)
Microphysics	Ferrier scheme
Longwave radiation	RRTM scheme
Shortwave radiation	Dudhia scheme
Surface layer	Unified Noah land-surface model
Boundary layer	Quasi-Normal Scale Elimination scheme (with QNSE surface layer scheme)
Cumulus	No cumulus option

was configured such that it fully encompassed the entire PECAN observation domain as shown in Fig. 3.1. Details about the WRF model configuration are listed in Table 3.1.

To compare the PECAN observations with the WRF model output, model predictions from the four nearest grid cells to the observation location were spatially averaged to generate a representative modeled vertical profile. Using the average over four cells accounts for small effects in each cell as well as small translation errors. Time-height cross-sections of the simulated data were compared with time-height cross-sections of the observed data. Simple visual comparison provided information about the ability of the WRF model to reproduce NLLJs with similar characteristics as those observed during PECAN. These

comparisons included wind characteristics and thermodynamic variables. Model performance was also assessed by examining the height of the NLLJ maximum and the position of the core region, where the wind speed is 90% of the maximum wind speed. To assess the spatial evolution and horizontal heterogeneity of the NLLJ, time-height cross-sections were compared for different locations across the PECAN domain. Additionally, plan view analyses and vertical cross-sections were evaluated to better understand the temporal and spatial characteristics of the NLLJ.

3.3 PECAN NLLJ IOPs

PECAN IOP02, IOP12, and IOP13 are considered in this study. All three IOPs were NLLJ specific missions. It is worth noting that IOP07 was also a NLLJ specific mission, but CLAMPS/MP1 was not fully operational during that night, so IOP07 data are not included here. For all three cases, CLAMPS/MP1 was deployed just east of La Crosse, Kansas (see Fig.3.1). Each case can be classified as a weakly turbulent NLLJ and follows the expected synoptic patterns (no strong trough to the west with generally weak synoptic forcing and slowly increasing pressure gradients overnight) for weakly turbulent NLLJs described in Bonin et al. (2018).

IOP02 took place from 00 UTC to 06 UTC on 3 June 2015. On this night, a low-pressure system was located over the central-eastern contiguous United States (CONUS) with a high-amplitude trough-ridge extending to the Midwest. On the upstream side of the associated ridge, the PECAN domain was under mostly zonal flow at the upper and mid-levels with a weak northerly component. Closer to the surface, flow was southerly turning southwesterly by 12 UTC. Conditions overnight were stationary on the synoptic scale. A more detailed discussion of the synoptic conditions for this case can be found in Parish (2016). A NLLJ was observed beginning around 01 UTC at a height between 400 m and 500 m AGL. The maximum strength of the NLLJ was nearly 25 m s^{-1} (Figs. 3.2b,d, 3.3b,d, 3.4b,d).

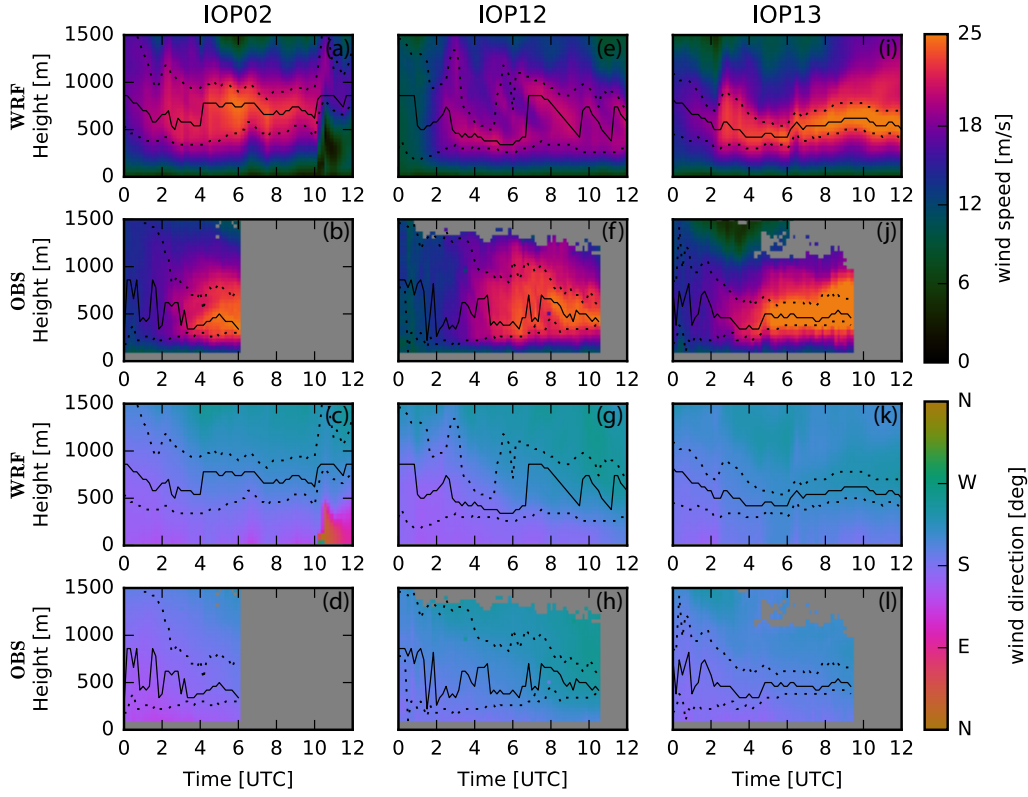


Figure 3.2: Observed and simulated wind speed and wind direction are shown at MP1 for IOP02, IOP12, and IOP13. Gray areas indicate observations are unavailable or omitted for quality purposes. Solid lines indicate the height of the NLLJ maximum, and the dotted lines encompass the core region, where the wind speed is at least 90% of the NLLJ maximum. MP1 observations are available in Turner (2016c).

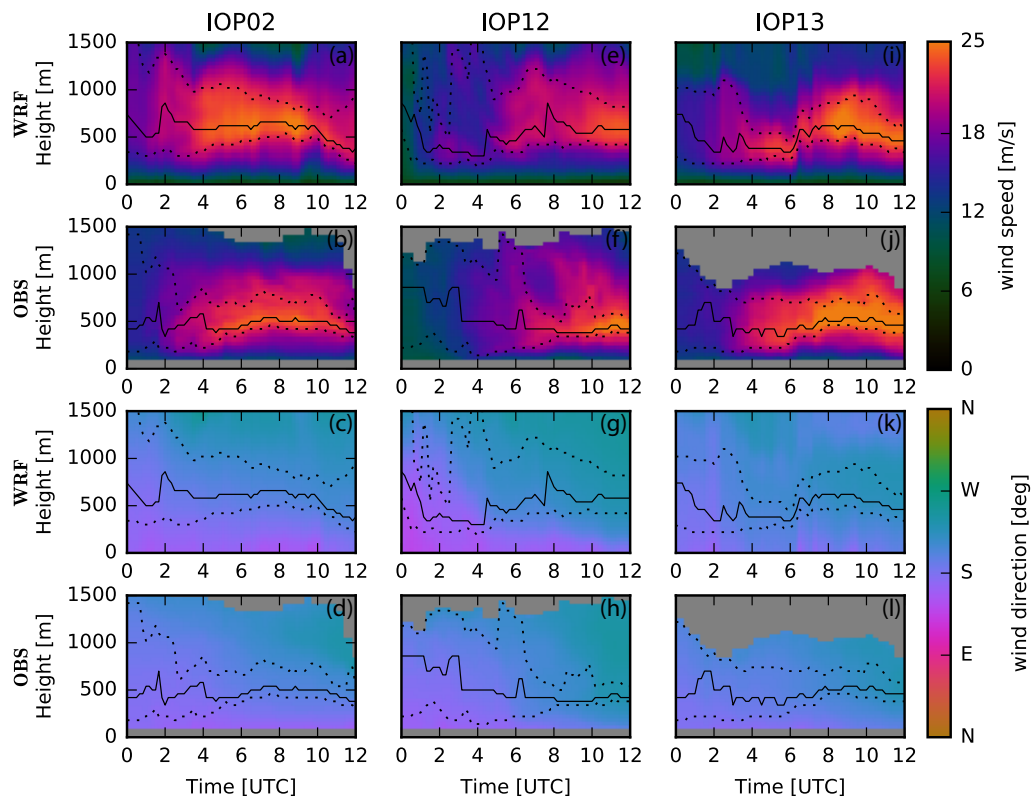


Figure 3.3: As in Fig. 3.2, but for site FP2. FP2 observations are available in Delgado et al. (2015).

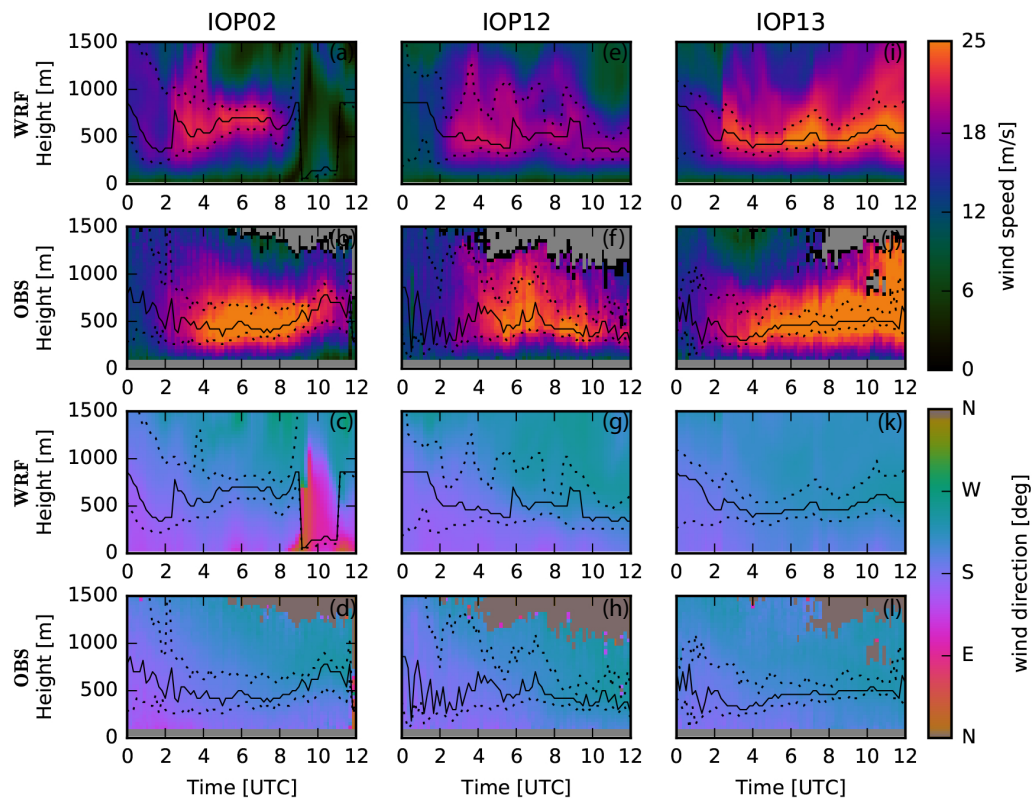


Figure 3.4: As in Fig. 3.2, but for site FP3. FP3 observations are available in Hanesiak and Turner (2016).

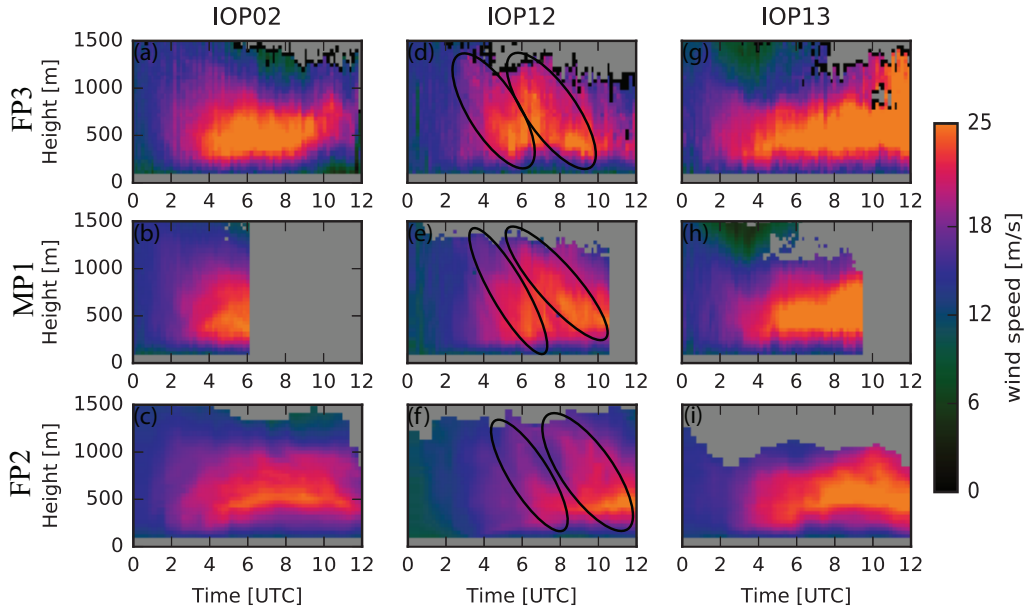


Figure 3.5: Wind speed observations from FP2 (a,d,g), MP1, (b,e,h), and FP3 (c,f,i) are reproduced with diagonal striations during IOP12 highlighted by black circles.

IOP12 took place from 00 UTC to 10 UTC on 20 June 2015. A low-pressure system was again located over the eastern United States, but a bit further west than during IOP02. On this night, a trough was present to the east, but not as high-amplitude as during IOP02. This trough gave way to weak zonal flow over the PECAN domain at upper levels. Mid-levels were more impacted by the proximity of the low pressure on this night, but flow was still mostly zonal. The near-surface flow had a stronger westerly component than during IOP02. Again, synoptic conditions, discussed in more detail in Parish and Clark (2017), were fairly stationary overnight. The NLLJ developed similarly to the NLLJ on IOP02 (Figs. 3.2f,h, 3.3f,h, 3.4f,h). This case was unique with peculiar diagonal striations in the time-height wind speed profile observed throughout the night (Fig. 3.5).

IOP13 took place from 00 UTC to 10 UTC on 22 June 2015. That night was characterized by zonal flow over most of the CONUS. Upper and mid-level flow over the area

of interest was zonal through the night, and near surface flow was southerly turning south-westerly in time. This NLLJ formed at a similar time and height as those during IOP02 and IOP12, but was stronger and deeper than in those two cases. This NLLJ was the strongest of the three cases considered in this study with a maximum magnitude near 30 m s^{-1} (Figs. 3.2j,l, 3.3j,l, 3.4j,l).

3.4 Model Evaluation

Figure 3.2 shows simulated (a,e,i) and observed (b,f,j) wind speed at MP1. Similar data are presented in Figs. 3.3 and 3.4 for FP2 and FP3, respectively. The NLLJs reproduced by the WRF model formed earlier than those observed by lidar. For example, the IOP02 simulation had already formed a wind maximum at MP1 in the low levels prior to 02 UTC (Fig. 3.2a). The height of the NLLJ maximum assessed from lidar data was uncertain during the early portion of IOP02 due to ongoing mixing within the boundary layer (Fig. 3.2b). This mixing was not present in the WRF model output, which points to premature NLLJ formation. The modeled NLLJs also formed too early at MP1 in the IOP12 and IOP13 cases. The vertical structure of the NLLJ was realistically reproduced by the WRF model, including the diagonal striations present during IOP12 (Fig. 3.2e,f). Similar to results for MP1, the NLLJ was observed to develop later than the WRF model prediction at FP2, however the difference in magnitude between observations and simulations was smaller at FP2 than at MP1. The diagonal striations noted at MP1 were also observed and simulated at FP2. The NLLJ height and core region were also well represented at FP2 as they were at MP1. Results at FP3 mirrored those for FP2 and MP1, except that the WRF model struggled more at this site to reproduce the observed NLLJ magnitude. Data at FP3 for IOP02 are affected by storms outside the area of interest producing outflow, which approached the location too early in the simulation. This behavior is clearly seen in Fig. 3.4a after 09 UTC. Consistent with results at the other sites, the simulated NLLJ formed prematurely, was too strong early in the simulation window, and too weak at the later stages.

The structure and evolution of the NLLJ were still well captured in the simulations. The IOP12 NLLJ was characterized by the previously discussed diagonal striation features.

Perhaps related to differences in timing of NLLJ formation, each NLLJ simulated by the WRF model was too strong early in the night and too weak once fully developed. This behavior is well documented in the literature, with many studies showing underestimation of NLLJ magnitude and depth (e.g., Storm et al. 2009; Steeneveld et al. 2008; Vanderwende et al. 2015; Mirocha et al. 2016; Klein et al. 2016). However, underestimation of NLLJ magnitude and depth in the simulations used in this study was relatively small (usually less than 5 m s^{-1} .) Simulations misrepresent the NLLJ magnitude at FP3 (Fig. 3.4) more so than at FP2 and MP1 (Figs. 3.3 and 3.2). Reasons for this are unclear, but could be related to site characteristics not represented by the model or unknown observation biases.

The depth of the NLLJ was well reproduced in the simulations, as can be seen by comparing the core region enclosed by dashed lines in all panels of Figs. 3.2, 3.3, 3.4. At any given time, the height of the NLLJ or the depth of the core region may have matched imperfectly, but the general evolution of the simulated NLLJ was similar to that observed by lidar. In addition to representing the NLLJ magnitude and height well, the WRF model also captured the sudden variations in observed boundary layer winds. For example, while the simulated wind speed was weaker than observed at each site during IOP12, the simulation depicted the characteristic diagonal striations in the time-height wind profiles similar to those found in the observations. Figs. 3.2, 3.3, and 3.4 also show simulated (c,g,k) and observed (d,h,l) wind direction. Generally speaking, the wind direction was well represented in the simulations as compared with observations at all sites, except for the case of the mistimed outflow at FP3 late in IOP02.

Figures 3.6, 3.7, and 3.8 show simulated (a,e,i) and observed (b,f,j) vertical velocity. Due to differences in scan strategies at each site, the temporal resolution and length of vertical stare data from Doppler lidars varied. To allow for better comparison between sites, the various vertical stares were all averaged into 15-min bins for this analysis. Sudden

instances of vertical motion were observed during several PECAN NLLJ cases at numerous sites. While the magnitudes of the vertical velocity in these updrafts were small, they were nevertheless measurable bursts of vertical motion. Such updrafts were also present in the WRF model output. Although the timing was imperfect, the basic updraft features were similar between the observations and the simulations. The observed and simulated updrafts were not as strong or frequent at FP2 as compared with the updrafts at MP1. At FP3, vertical velocity observations and simulations revealed similar updrafts as those present at MP1. The nature of these updrafts will be discussed in greater detail below.

Figures 3.6, 3.7, and 3.8 also show simulated (c,g,k) and observed (d,h,l) potential temperature fields. Overall the general pattern of potential temperature evolution was well represented in the simulations. One particularly promising result is evident when focusing on the later portions of the nights at MP1 (Fig. 3.6). After approximately 06 UTC, the near-surface air cools substantially. At the same time, the layer above the jet maximum warms. This simultaneous near-surface cooling and warming aloft, present in both the observations and simulations, results in isotherms packing in the NLLJ core region. At MP1, this feature is more readily seen in IOP12 and IOP13 observations because data collection at the mobile PISAs stopped earlier during IOP02. The AERI was not yet fully operational at FP2 during IOP02 (thus, the thermodynamic observations are lacking). Otherwise, simulated potential temperature fields appeared similar to those observed at this site. The cooling of the surface layer and the warming aloft were again well represented by the model. Potential temperature data from simulations and observations matched well at FP3 if, again, considerations are made for the mistimed outflow during IOP02. The cause of observed warming above the NLLJ will be explored in the next section.

3.5 Conclusions

The PECAN field campaign provided high-resolution observational datasets including data on several NLLJ cases. Using these data in conjunction with optimally configured WRF

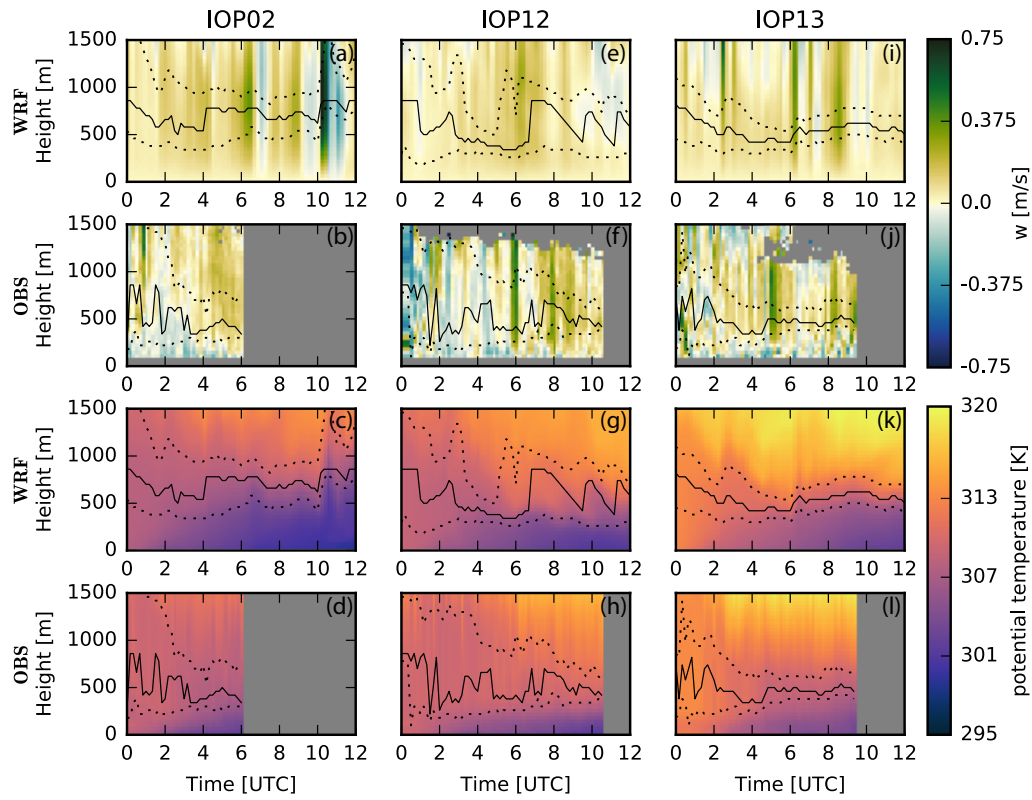


Figure 3.6: Observed and simulated vertical velocity and potential temperature are shown at MP1 for IOP02, IOP12, and IOP13. Gray areas indicate observations are unavailable or omitted for quality purposes. Solid lines indicate the height of the NLLJ maximum, and the dotted lines encompass the core region, where the wind speed is at least 90% of the NLLJ maximum. MP1 observations are available in Turner (2016d,b).

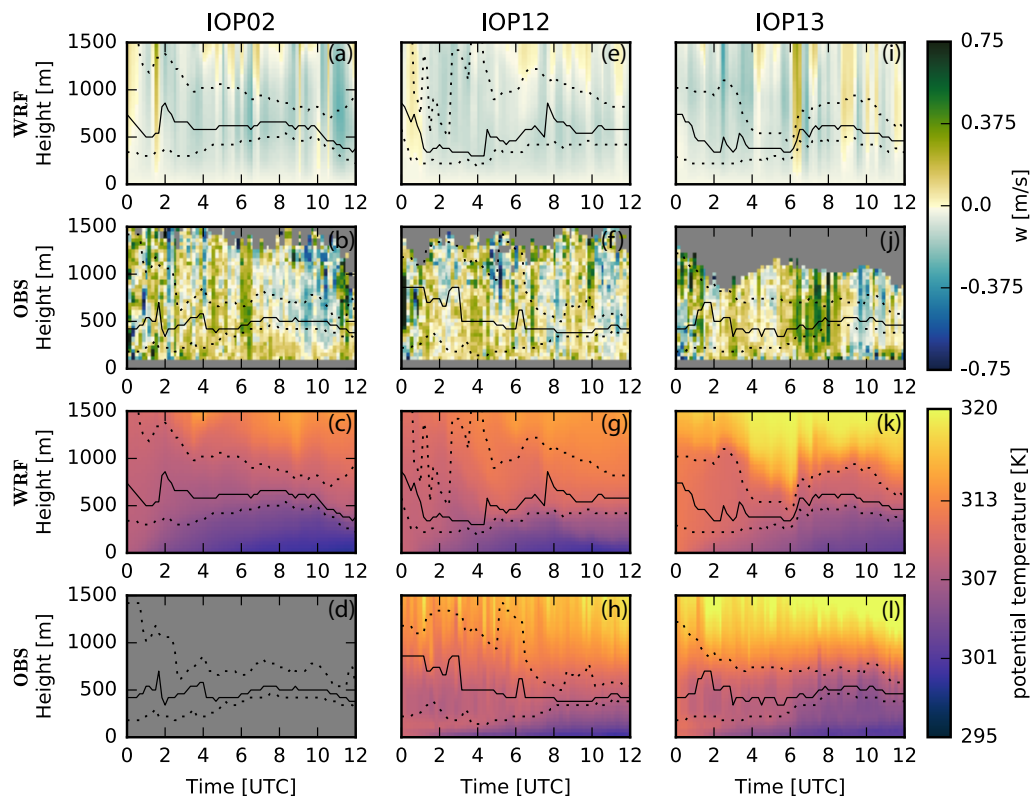


Figure 3.7: As in Fig. 3.6, but for site FP2. FP2 observations are available in Turner (2016a).

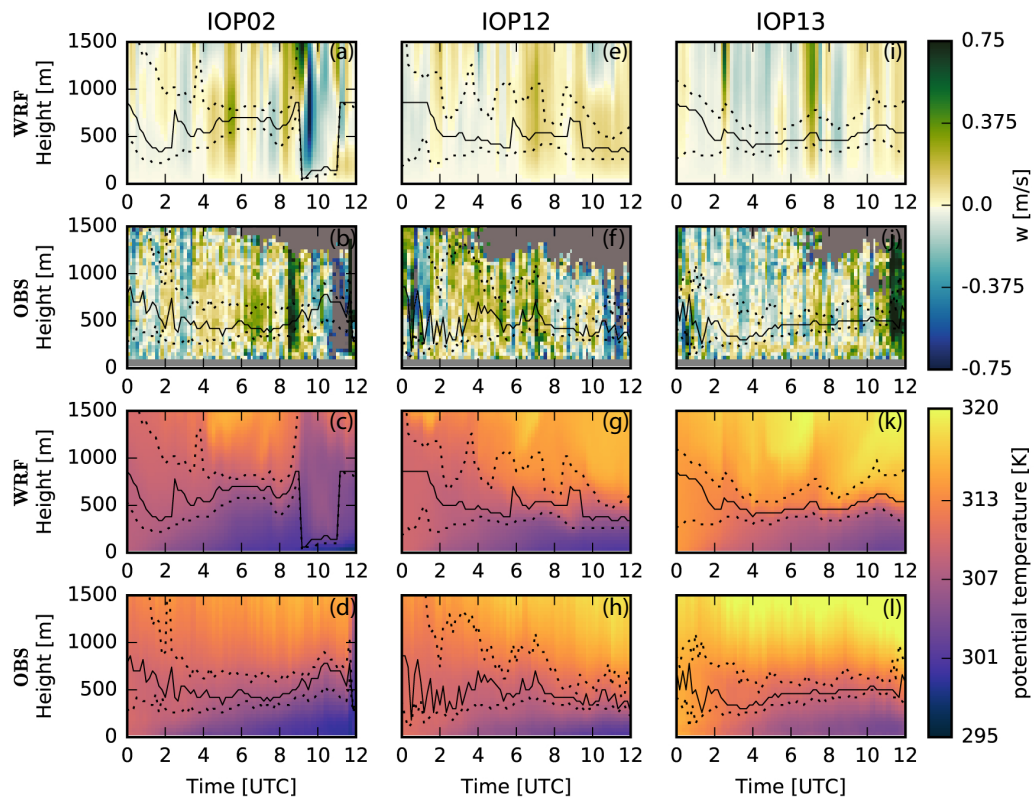


Figure 3.8: As in Fig. 3.6, but for site FP3. FP3 observations are available in Turner (2015).

model simulations offered a robust dataset for analyses of the NLLJ and the atmospheric boundary layer in which it forms. Profile observations from PECAN sites along a north-south transect, MP1, FP2, and FP3, were used to further evaluate the WRF model configuration introduced in Chapter 2. Analyses concluded that the simulated NLLJs formed earlier than the observed NLLJs. These simulated NLLJs were too strong early in the night and too weak later in the night as compared with observations. Nevertheless, the WRF model successfully represented the general structure and evolution of the observed NLLJs and was able to reproduce sudden variations in boundary layer winds such as the diagonal striations observed during IOP12. The height of the NLLJ maximum and the core region of the jet were also well represented by the WRF model. Simulated potential temperature fields matched closely observations closely, as they successfully captured the simultaneous surface layer cooling and warming above the NLLJ maximum. Finally, the WRF model produced bursts of vertical motion resembling the updrafts that were observed at several sites during PECAN. Overall, the carefully configured WRF model simulations were found to represent NLLJ features well.

Chapter 4

Observed and Simulated Characteristics of PECAN NLLJs

4.1 Introduction

Given the slope of the Great Plains, NLLJs in this part of the world can be complicated by radiative heating and cooling of the sloping terrain (e.g., Holton 1967), buoyancy effects (e.g., Shapiro and Fedorovich 2009), or a combination of various factors (e.g., Shapiro et al. 2016). Recent studies by Parish (2017) and Fedorovich et al. (2017) link the prevalence of the NLLJ in the Great Plains to slope effects. While Parish (2017) identified the thermal wind forcing and related horizontal pressure gradient over the sloping terrain of the Great Plains as key mechanisms for NLLJ formation, Fedorovich et al. (2017) highlighted the role of along-slope temperature advection in modulating the NLLJ structure.

Gaps in our understanding of the NLLJ may be connected to gaps in our understanding of the nocturnal boundary layers (NBLs) in which they form. Many studies attempted to connect NLLJ characteristics to features observed at or near the surface. Using CASES-99 data, Banta et al. (2002) and Banta et al. (2003) related NLLJ characteristics including wind speed, height of wind maximum, wind direction, a measure of sub-NLLJ shear, and a NLLJ Richardson number to mixing and turbulence across the NBL. Later work expanded such relations to analysis of stability effects (Banta et al. 2006). Banta (2008) connected strong NLLJs to continuous turbulence and weak NLLJs to intermittent turbulence with an intermediate range between the two extremes. Changing stability in the NBL has been linked to advection of thermodynamic properties by the NLLJ (Bonin et al. 2015), and intermittent turbulence bursting events have been linked to changing stability (Ohya et al. 2008). More direct connections between wind speed in the nocturnal boundary layer and turbulence regimes were found in Sun et al. (2012), where a threshold wind speed was identified to maintain turbulence. Klein et al. (2016) found correlations between NLLJs and

daytime stability and turbulence, but weak to no relationship between NLLJs and nighttime stability and turbulence.

Several of the aforementioned studies found that near-surface flow parameters alone often were not representative of the changes observed in the NLLJ and the NBL. Classification of NLLJs based on the turbulence state of the environment in which they formed showed that NLLJ evolution is different for strongly turbulent and weakly turbulent NLLJ cases (Bonin et al. 2018). Banta et al. (2003) found the relationships between turbulence and NLLJs did not hold well in very stable boundary layers. Later work indicated that the top-down generation of turbulence, or upside down boundary layer, limited the validity of traditional boundary layer scaling approaches (i.e., scaling based on the friction velocity, u_* , was not as useful as scaling based on the the NLLJ wind speed) suggesting that local surface features may not be as important for understanding NLLJ characteristics and evolution (Banta et al. 2006). Furthermore, Banta (2008) speculated that in stable cases some turbulent bursting events may be more connected to what he called imported disturbances. The lack of correlation between NLLJ features and nighttime stability and turbulence in Klein et al. (2016) also suggests that NLLJ evolution throughout the night may not be well represented by local NBL characteristics.

Traditional approaches used in the literature to understand NLLJs are often limited by the available observations which are typically confined to towers erected on the Earth's surface or single point observations. This limitation can be addressed in two ways: 1) three-dimensional numerical simulations and 2) more extensive observations covering a broader domain. In this chapter, PECAN observations and the WRF simulations described in Chapters 2 and 3 are jointly analyzed to advance understanding of NLLJ physical processes.

4.2 NLLJ Physics

To better understand the evolution of the NLLJ, the nocturnal jet from IOP12 is chosen for further analysis. This choice was made for several reasons. IOP12 and IOP02 NLLJs formed similarly under similar synoptic conditions. IOP02 was not selected since mobile observations ended early. The NLLJ during IOP13 was stronger than other cases and formed under somewhat different synoptic conditions. Thus, IOP12 remains as a case with good data availability, which showed features of heterogeneous NLLJ morphology including observed and simulated diagonal striations and sudden bursts of vertical motion. PECAN observations from IOP12 along the north-south transect at MP1 (Figs. 3.2, 3.6), FP2 (Figs. 3.3, 3.7), and FP3 (Figs. 3.4, 3.8) showed the NLLJ forming during the evening transition at about 750 m AGL. After sunset (at approximately 02 UTC), the SBL was formed while the NLLJ lowered to 500 m AGL and strengthened to about 25 m s^{-1} . The observed flow was generally southerly but veered to south-southwesterly in time and in height. Potential temperature observations show the SBL deepening overnight while warming occurred above the NLLJ. As discussed in Sect. 3.4, sudden vertical motions were observed at MP1 and FP3, but not at FP2. The observed instances of vertical motion coincided with diagonal striation features in the wind speed time-height profiles.

As discussed in Section 4.1, observed sudden mixing events have often been related to possible shear-generated turbulence as the jet strengthens (e.g., Banta et al. 2002, 2003; Banta 2008; Sun et al. 2012). However, the PECAN observations from IOP12 showed mean (rather than turbulent) motions over a rather thick layer that seemingly coincided with changes in NLLJ structure above its nose resulting in diagonal striations in the time-height wind profiles. These diagonal striations were observed at several locations at different times. Under a loosely applied assumption of frozen turbulence, diagonal striation features in time-height wind profiles point to spatial evolution of the NLLJ structure. We

hypothesize that spatial evolution of the NLLJ rather than local changes in shear play an important role. However, with PECAN observations limited to only a few locations in space, the spatial features cannot be explored with observations alone.

Three-dimensional flow fields from the WRF model can offer more information about NLLJ evolution in time and space. Since the optimally configured WRF model produced NLLJs that were generally representative of the observed features of the NLLJ at MP1, FP2, and FP3 in all three cases discussed above, we feel confident that the three-dimensional simulated data are appropriate to use for further analysis designed to complement interpretations of the observations. Plan-view wind speed and water vapor mixing ratio fields at 500 m AGL (near the height of the NLLJ maximum) are shown in Figs. 4.1 and 4.2. At 00 UTC (Figs. 4.1a, 4.2a), the NLLJ had not yet formed and the 500 m winds were out of the south-southeast. A tongue of moisture was situated over most of Kansas with the highest moisture content located on the Kansas-Oklahoma border southwest of FP2. By 03 UTC (Figs. 4.1b, 4.2b), wind speed increased – especially in the western parts of Kansas and Oklahoma, and winds were more southerly. Moisture was still in place, with an area of increased moisture content stretched further north from west of FP2 to northwest of FP3, implying southerly advection had occurred. At 06 UTC (Figs. 4.1c, 4.2c), wind speed had continued to increase especially in western Kansas and Oklahoma. Wind vectors began to turn indicating the 500-m wind was veering at Hays and locations west. The eastern parts of Kansas and Oklahoma were still characterized by weaker winds from the south. The veering winds began to push the moisture tongue toward the east, advecting drier air into place from the west. Finally, at 09 UTC (Figs. 4.1d, 4.2d) the wind vectors had a westerly component across the entirety of Kansas and Oklahoma. Winds were still weaker in the eastern portion of the domain. The moisture tongue was now located over the eastern portion of Kansas as drier air was moving into west Kansas, where winds were more westerly indicating westerly advection had become significant overnight. This evolution suggests that the NLLJ was moving across the Great Plains and advection was prominent along the

slope during the night. The presented analysis, however, does not offer any information about how the vertical structure of the NLLJ evolved through the night.

To track the evolution of the structure of the NLLJ, vertical cross-sections were taken across the slope of the Great Plains at about 39.55° N near the Kansas-Nebraska border (Fig. 4.3). At 00 UTC (Fig. 4.3a), isentropes were nearly vertical indicating a well-mixed boundary layer. The moisture field was bounded within this well-mixed boundary layer. At the initial time, the moisture distribution and isentropes indicated that the boundary layer was deeper over the western portion of the slope as compared with the eastern portion. Except for regions near the surface and outside the boundary layer, winds were already mostly southerly, with some locally stronger winds over the western most portion of the slope. By 03 UTC (Fig. 4.3b) the SBL formed near the surface. Wind speeds increased within the NLLJ, with the area of strongest winds located west of 99° W. In the western most portion of the cross-section, the wind direction had already begun to veer near the top of the NLLJ as it acquired an increased westerly component. This westerly component began to transport the moisture field from west to east down the slope. As suggested by the plan-view analysis (see Figs. 4.1 and 4.2), by 06 UTC (Fig. 4.3c) stability and the NLLJ strengthened, and the region with stronger winds reached further east. Moisture advected east, which deepened the moist layer over the eastern region and reduced moisture in the west. Winds were weaker and mostly southerly over the eastern-most portion of the domain. Winds had veered vertically throughout the NLLJ west of 99° W. Just east of 99° W, the veering of NLLJ winds with height was apparent near the top of the NLLJ, but not yet in the core or near the surface. Finally, at 09 UTC (Fig. 4.3d) stability in the boundary layer generally continued to increase. By this time, the moisture field was drastically different than how it looked early in the night with a deep layer of moisture in the east and a very shallow moisture layer in the west. The region of strongest NLLJ winds was also further east at this point, and the increasing westerly component made the winds become south-southwesterly across the entire slope.

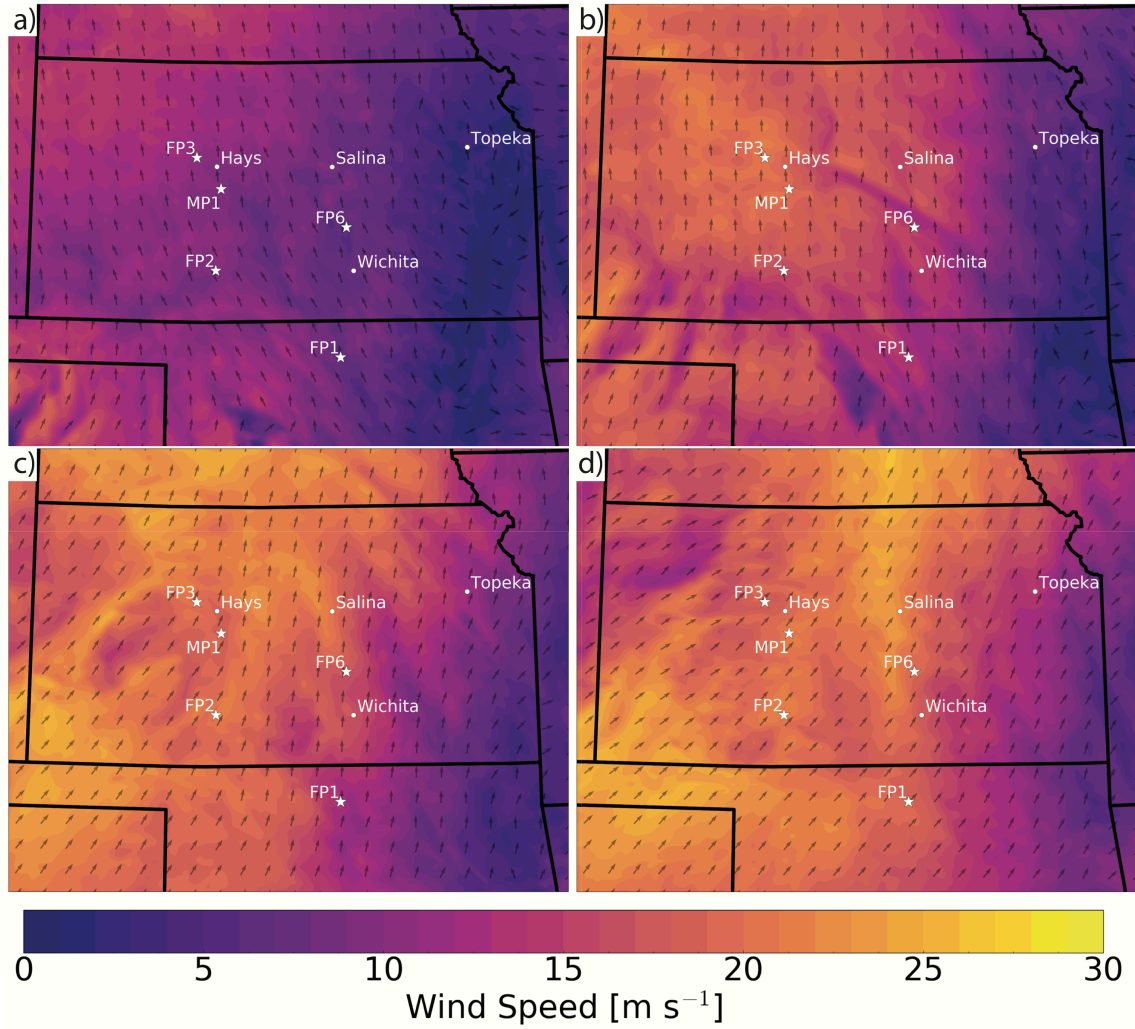


Figure 4.1: Plan views of the NLLJ at 500 m AGL are shown for IOP12 WRF simulation at at 00 UTC (a), 03 UTC (b), 06 UTC (c) and 09 UTC (d). Arrows denote wind direction while the colorfill shows the wind speed.

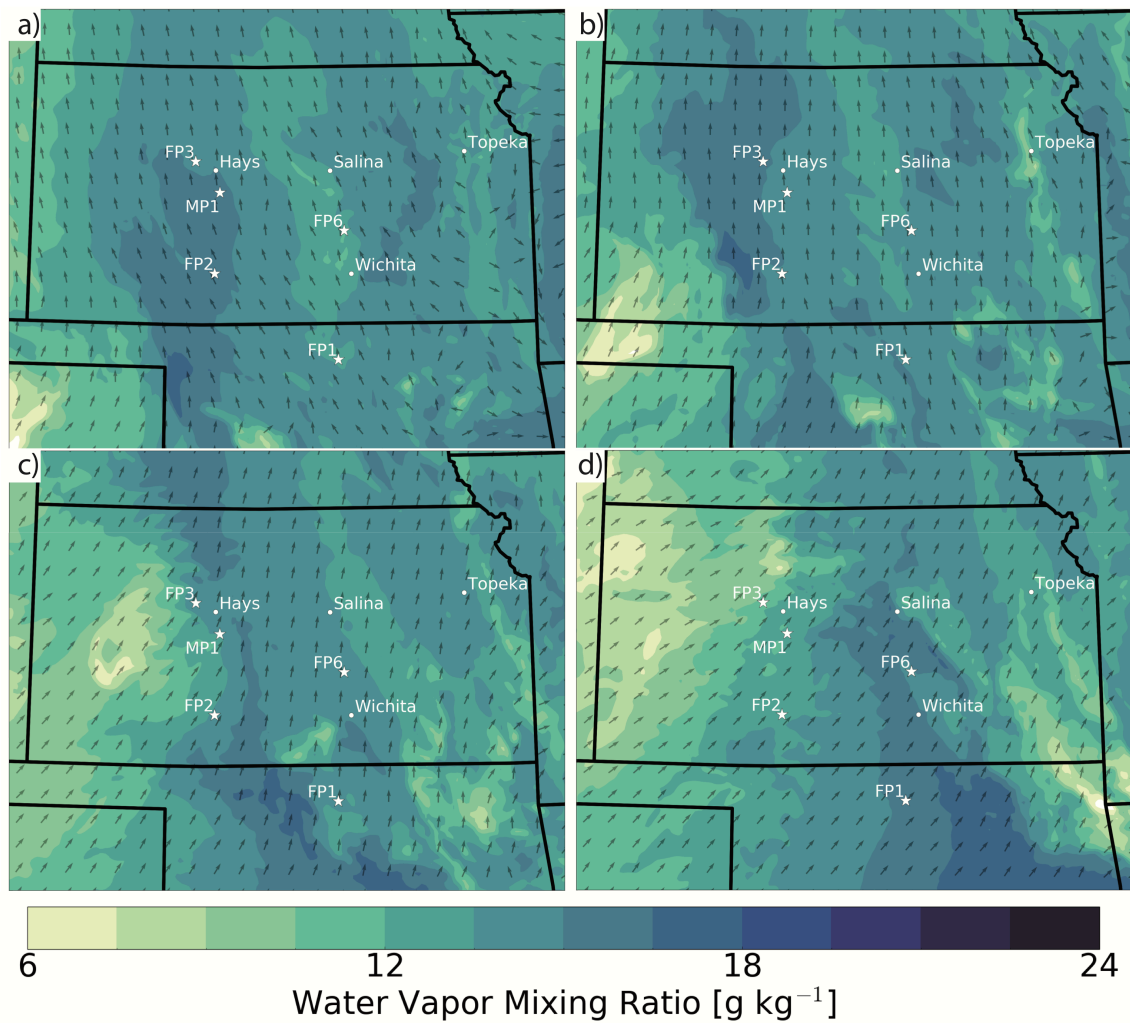


Figure 4.2: As in Fig. 4.1, but the colorfill shows water vapor mixing ratio.

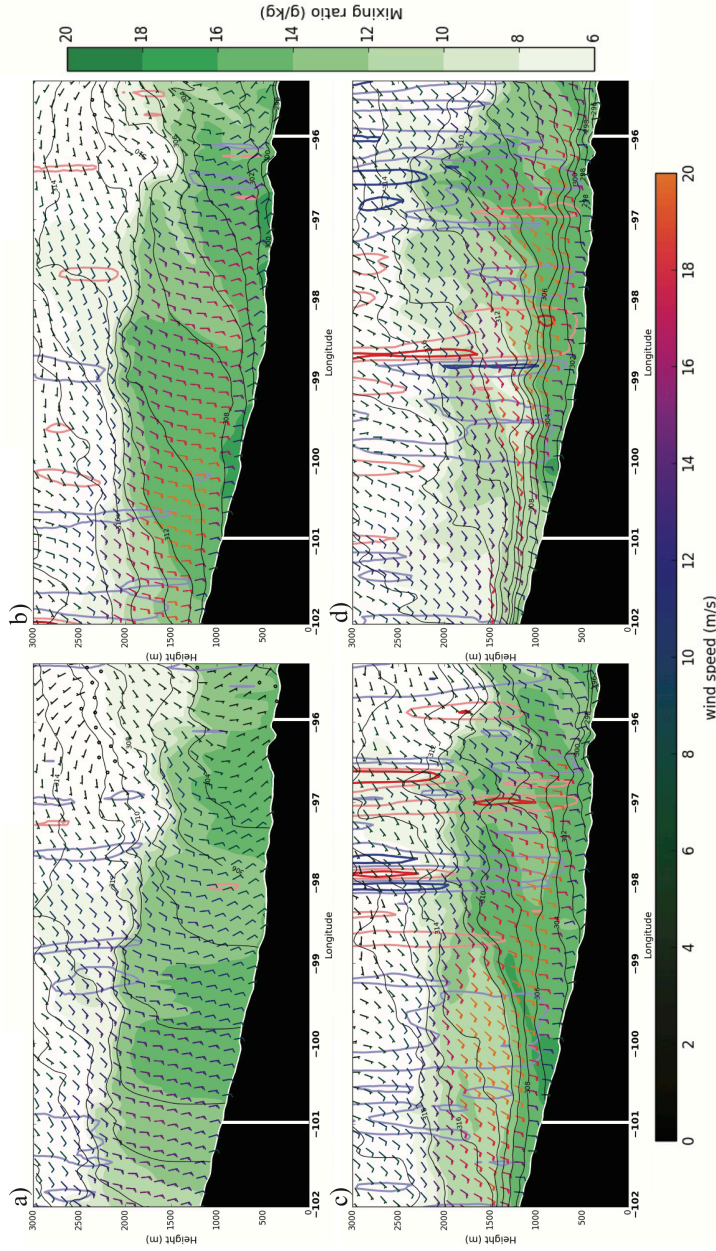


Figure 4.3: Vertical cross-sections were taken along latitude 39.55 near the Kansas-Nebraska border from the IOP12 WRF simulation. The panels show potential temperature (K, black contours), wind speed (m s^{-1} , colored barbs), vertical velocity (m s^{-1} , colored contours where blue/red denotes downward/upward motion), and water vapor mixing ratio ($>6\text{gkg}^{-1}$, green shading) at 00 UTC (a), 03 UTC (b), 06 UTC (c) and 09 UTC (d). The sloping terrain of the Great Plains is represented by the black region along the bottom of each panel. White lines over the terrain mark locations of profiles shown in Fig. 4.5.

As the region of westerly flow expanded, zones conducive to local convergence developed and could have been the source of the observed vertical motions (Figs. 3.6, 3.8). Previously, vertical motions like these have usually been explained by convergence at the eastern edge or at the terminus of the NLLJ. The NLLJ has been known to veer with time due to the inertial oscillation (Blackadar 1957). The associated change of wind direction causes convergent regions within the NLLJ to evolve in time (Bonner 1966). More recently, Walters and Winkler (2001) showed that half of NLLJs observed over the Great Plains do veer with height. Veering in time and height means that the cross-jet component (the u -component in the Great Plains) becomes important, and the non-linear advection terms in the equations of motion can result in eastward down-slope advection of the NLLJ by the NLLJ itself (Fedorovich et al. 2017; Gebauer et al. 2018). Paegle and Rasch (1973) suggested that the non-linear terms can create vertical motions within the horizontally heterogeneous NLLJ.

The NLLJ from IOP12 is a clear example of NLLJ evolution along the sloping terrain of the Great Plains as shown in Fig. 4.3. Comparing the 00 UTC panel with the 09 UTC panel makes the down-slope propagation of the core region of the NLLJ clear. It is proposed that veering wind direction with height causes differential down-slope advection of the NLLJ. In other words, the NLLJ moves from west to east down the slope. The increased westerly wind component (the u -component) at the top of the NLLJ combined with NLLJ heterogeneity (e.g., non-uniform NLLJ height and wind speed from west to east) results in a local convergence region at the top eastern edge of the NLLJ which is favorable for the development of local updrafts. A conceptual diagram of this process is shown in Fig. 4.4a-c. Profiles of u -component velocity in Fig. 4.5 show that the u maximum is first located at or above 1000 m and descends through the night, but the maximum descends much earlier in the western profiles. In Fig. 4.3 a local region of convergence and associated vertical motion can be seen at 06 UTC just east of 99° W. Note that an updraft feature was simulated and observed at MP1 and FP3 at about this time. This mechanism is proposed as a possible

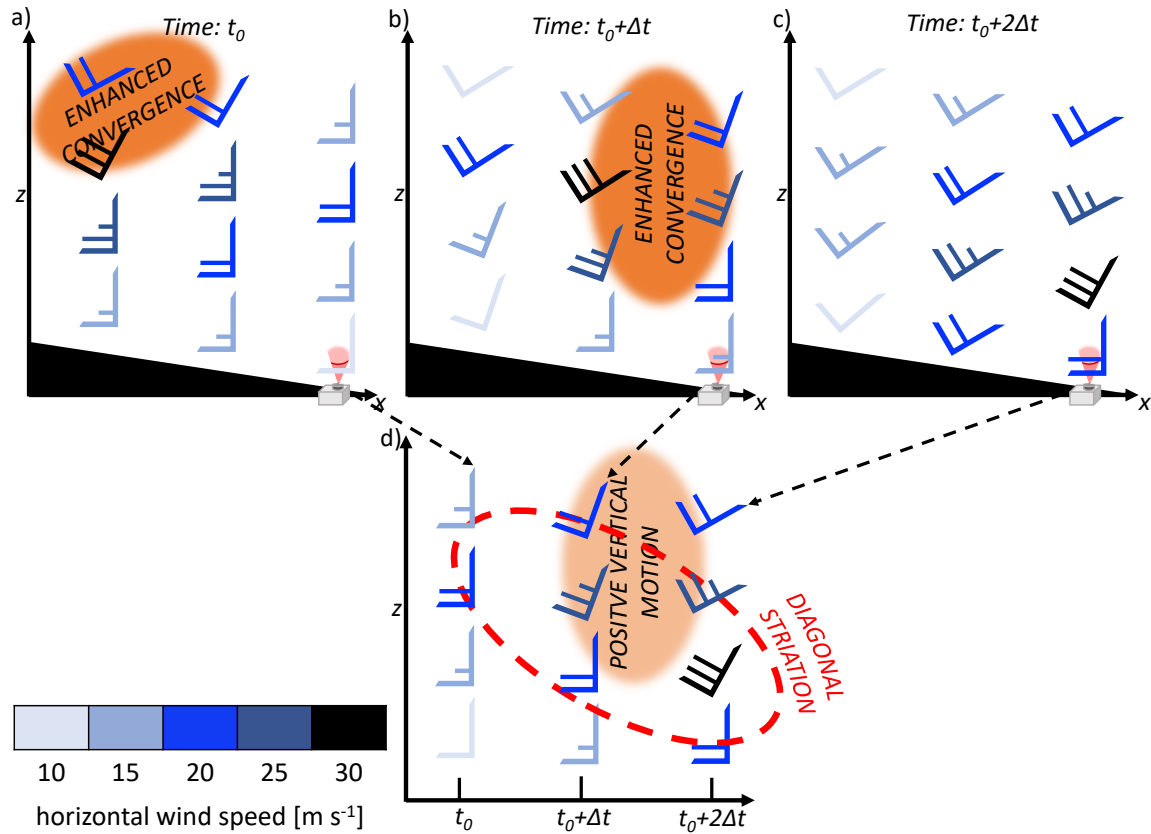


Figure 4.4: Conceptual diagram of the evolution of the heterogeneous NLLJ across the slope (a-c) and the resulting profile observation (d).

source of the vertical motions observed and simulated with the WRF model for PECAN cases. It is also a possible driver of nocturnal convection initiation over the Great Plains (Gebauer et al. 2018).

Diagonal striations are an observed signature that can reveal NLLJ spatial evolution from a single point observation. The veering of NLLJ winds in height and in time as well as its downslope advection explains the diagonal striations seen in time-height cross-sections of wind speed. As shown in Fig. 4.4, NLLJ wind speed increases and wind direction veers first at the top of the NLLJ, then deepens from the top down. At a point (Fig. 4.4d), the differential advection of the stronger winds to the west manifests as a diagonal striation. In the PECAN observations, diagonal striations in the wind speed fields coincided with an increased westerly component of the wind. This same process causes the warming in the

region above the NLLJ. As the westerly wind component increases, warm and dry air is advected from the west. This advection is evident in the profiles shown in Fig. 4.5, where the trends in the moisture and potential temperature profiles were connected to maxima in the u profile.

The identified spatial-temporal evolution of the NLLJ results in local temporal NLLJ evolution appearing differently at different locations on the slope. Time-height cross-sections similar to those shown in the previous section are presented in Fig. 4.6 at FP3, FP2, FP6, and FP1 (see Fig. 3.1 for locations) to compare the evolution of local NLLJ features across the PECAN domain. At the western sites (FP3, FP2), the NLLJ depth and magnitude were greater compared to the eastern sites (FP6, FP1). As mentioned in the previous section, a sudden instance of upward vertical motion was simulated at FP3 at about 07 UTC, while no such updraft occurred to the south at FP2. To the east at FP6, a similar but shorter duration vertical motion was simulated shortly after 08 UTC; however, the southern site, FP1, did not show one. At all four sites, some diagonal striation features appeared in the wind speed field. The northern sites, FP3 and FP6, showed more drastic examples of these diagonal striations. The first diagonal striation at FP3 began at about 06 UTC near 1000 m AGL and reached 500 m AGL by 07 UTC. This feature coincided with the updraft simulated at FP3. The diagonal striation at FP6 began later, at about 08 UTC, near 1000 m AGL and reached 500 m AGL by 10 UTC. Again, this feature was coincident with the updraft simulated at FP6. At all sites, the NLLJ veered with height and time, but differences exist in the timing based on sited longitude. The wind direction pattern shows that the diagonal striations in the wind speed at each site coincided with increased westerly component of the wind and rising motions. Related to sunset time, the SBL formed at similar times at all considered locations. However, the warming in the region above the NLLJ happened later and was less pronounced at eastern sites (FP6 and FP1).

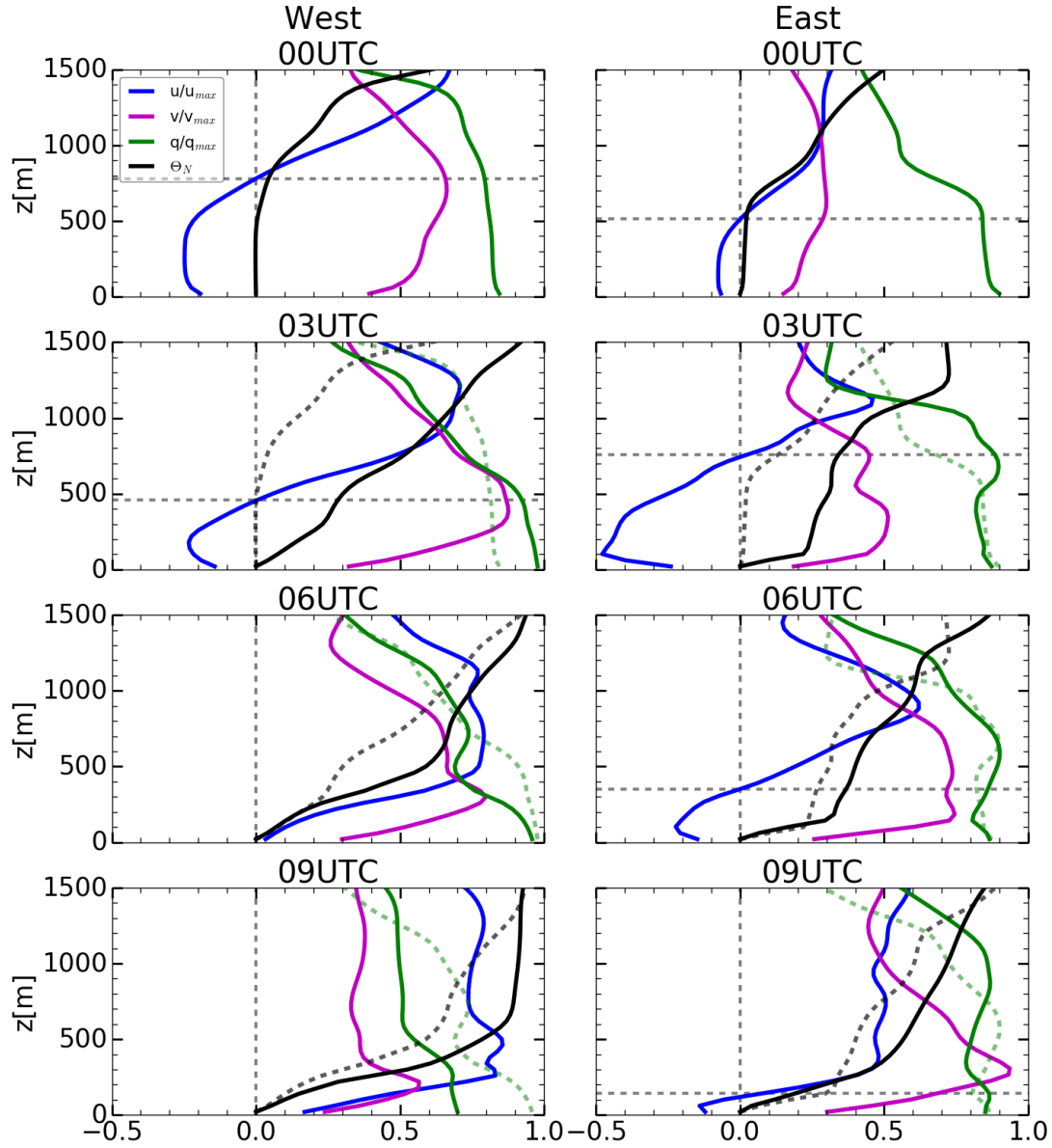


Figure 4.5: Profiles on the west (101° W) and east (96° W) portion of the slope at 39.55° W are shown for u , v , q (all normalized by their respective overnight maxima), and θ_N (the deviation of θ from its surface value normalized by the overnight maximum deviation). For 03-09 UTC the previous time's θ and θ_N profile is shown by the dashed green and black lines, respectively. Dashed grey lines show the zero profile and the height at which u becomes zero where applicable. The locations where the profiles are taken are shown by white lines in Fig. 4.3.

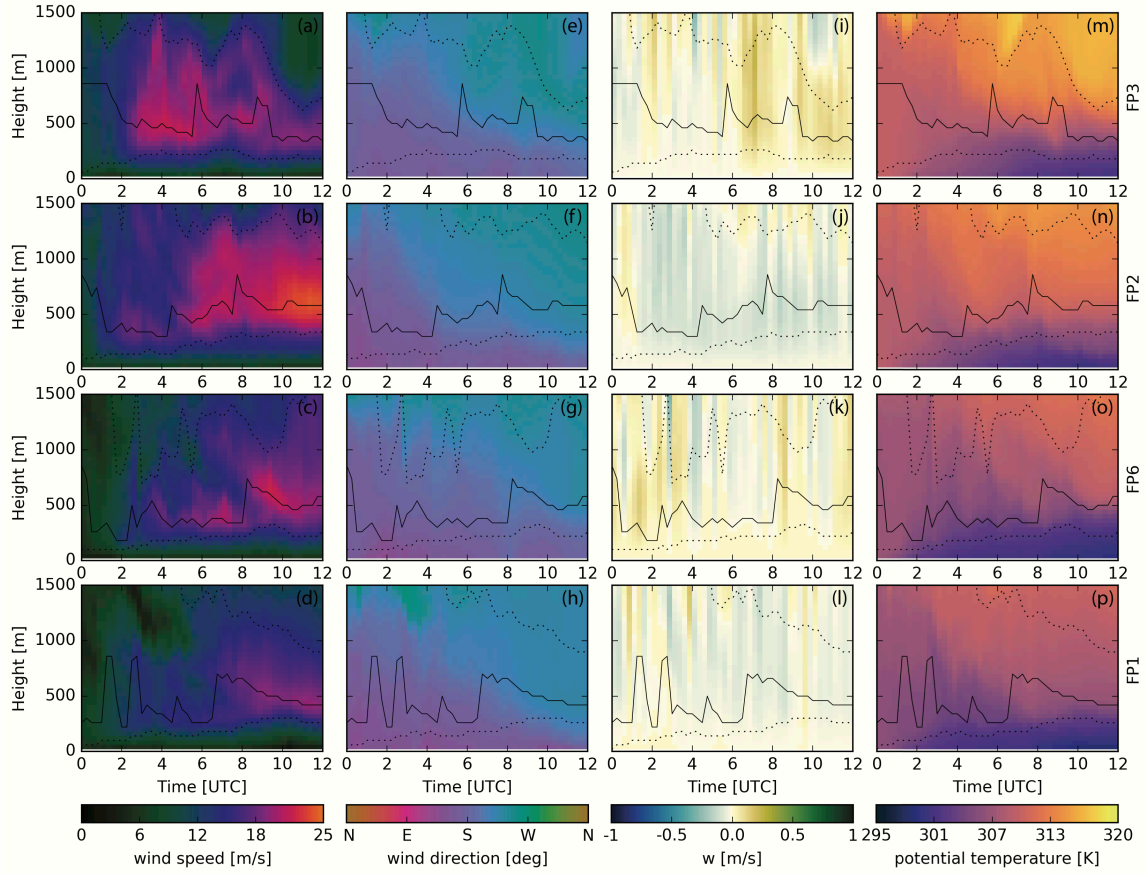


Figure 4.6: Time-height cross-sections of WRF simulated wind speed (a-d), wind direction (e-h), vertical velocity (i-l), and potential temperature (m-p) are shown during IOP12 at four sites: FP3 (a,e,i,m), FP2 (b,f,j,n), FP6 (c,g,k,o), and FP1 (d,h,l,p). Solid lines indicate the height of the NLLJ maximum, and the dotted lines encompass the core region, where the wind speed is at least 90% of the NLLJ maximum.

4.3 Additional PECAN cases

The previous section focused on IOP12 as an example of NLLJ heterogeneity and dynamic evolution. Three additional PECAN NLLJ missions were undertaken during the field campaign: IOP02 on 03 June 2015, IOP07 on 10 June 2015, and IOP13 on 22 June 2015. During IOP07 MP1 was not fully operational, which negatively impacts data quality along the considered north-south transect. As such, IOP07 is not included in this section. IOP02 and IOP13 will now be explored and compared to the example of IOP12.

4.3.1 IOP02

The details of IOP02's synoptic setup and data collection are discussed in Sect. 3.2. Observations from this case are shown in Figs. 3.2 – 3.8. These data indicate that the NLLJ formed during the evening transition near 500 m AGL. After sunset, the SBL formed and NLLJ height remained at or near 500 m AGL through the night. Flow was observed as generally southerly with a weak easterly component near the surface early in the night, but, as in IOP12, veered toward the south-southwest with time and height. Observations of potential temperature were curtailed at MP1 and not yet available at FP2. At FP3 these observations showed a SBL that was deeper and cooler than IOP12 with less warming aloft during the night. After the mobile operations ended (thus, after MP1 observations ended) sudden instances of vertical motion were observed at FP2 and FP3 similar to those observed during IOP12. At FP2, the sudden instance of vertical motion did not coincide with drastic changes in the structure of the wind field, but wind direction became more westerly after the vertical motion. At FP3, the core of the NLLJ narrowed after the observed vertical motion.

Although clear diagonal striations are not apparent in observations of the IOP02 NLLJ, observations still suggest mean motions coinciding with changes in the NLLJ structure. Simulated wind speed and water vapor mixing ratio at 500 m AGL are shown in Figs. 4.7 and 4.8, respectively. At 00 UTC (Figs. 4.7a, 4.8a) 500 m AGL winds in the convective

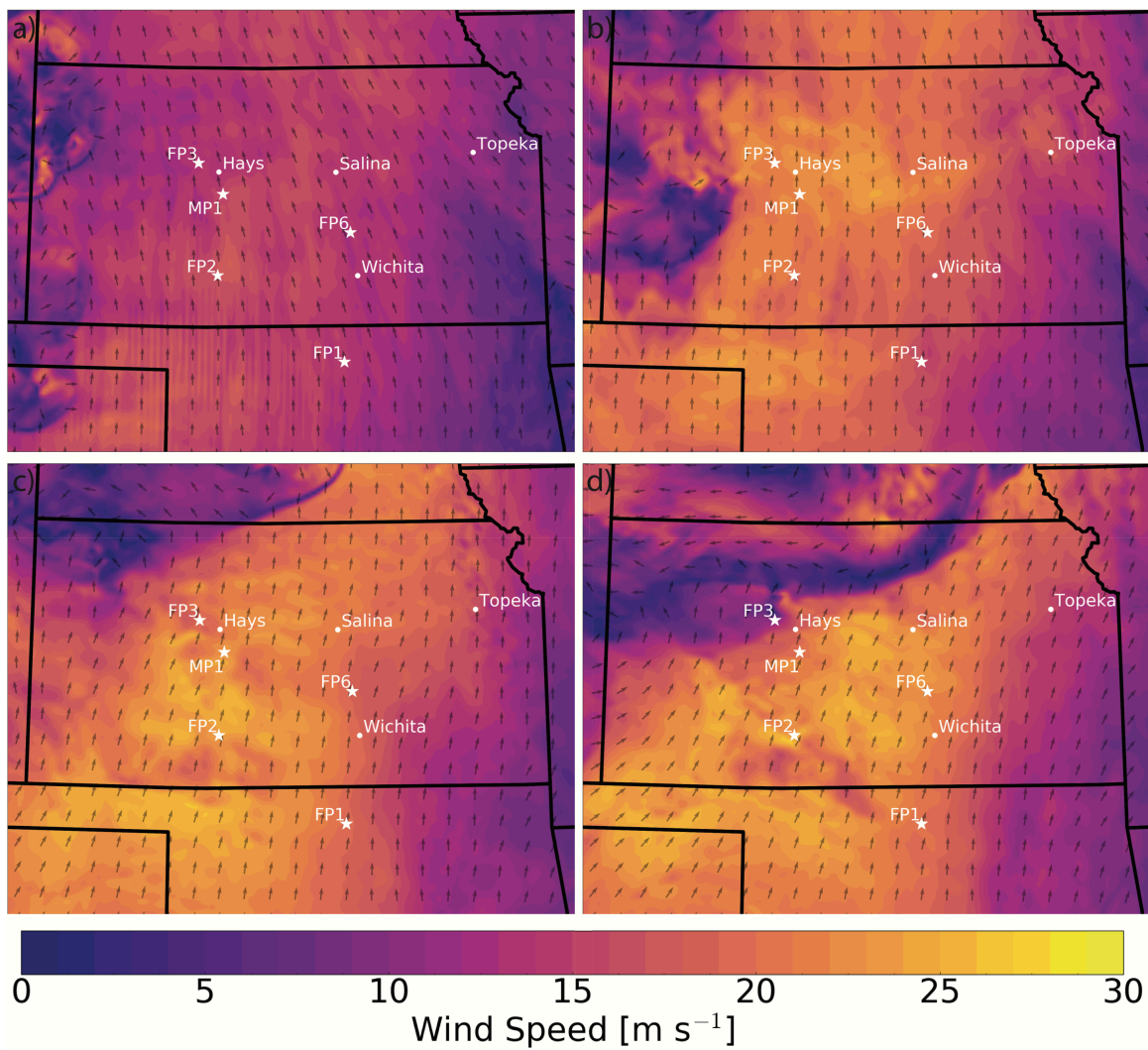


Figure 4.7: As in Fig. 4.1, but for IOP02.

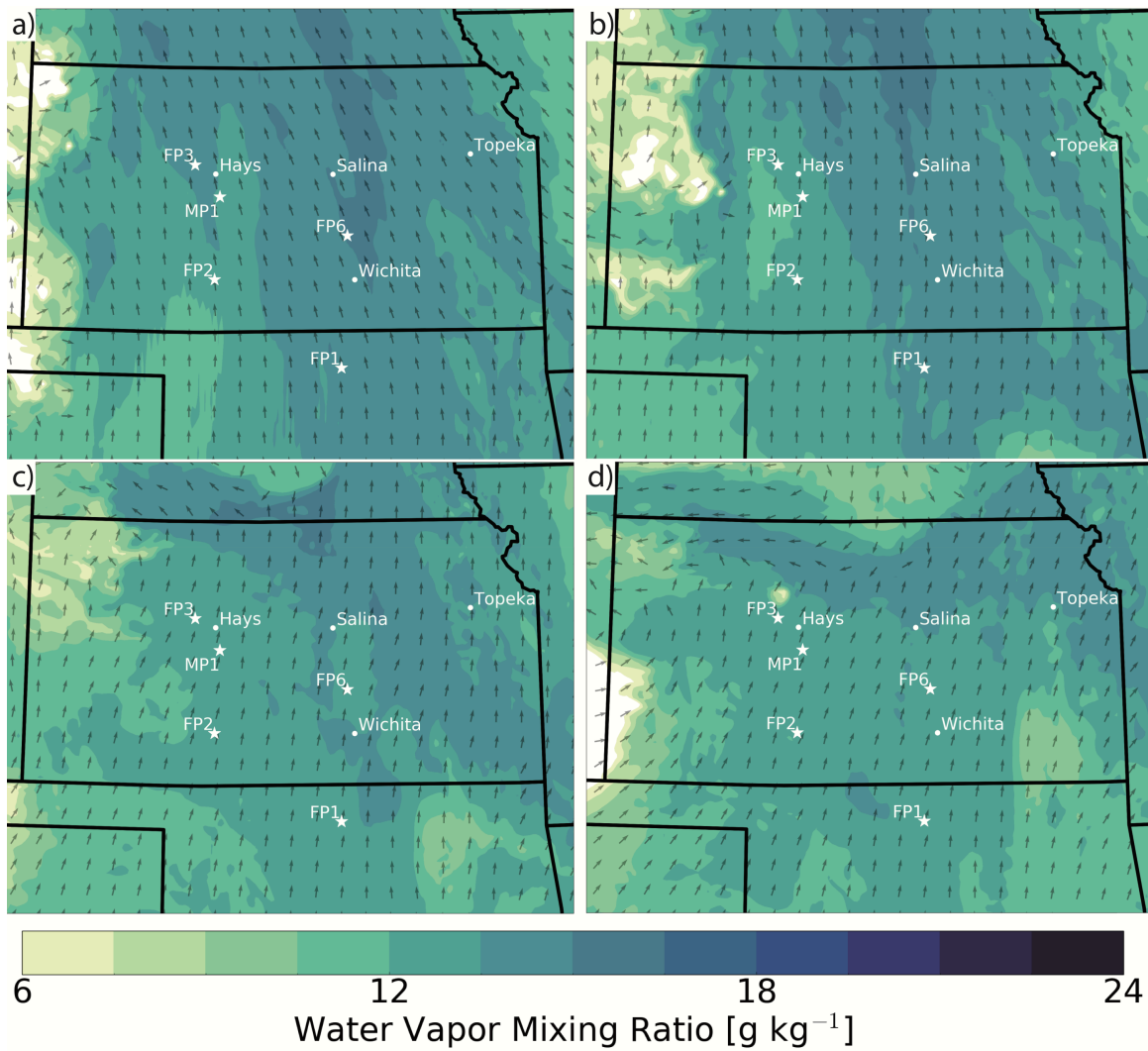


Figure 4.8: As in Fig. 4.2, but for IOP02.

boundary layer were stronger and moisture content was lower over the western portion of OK and west-central KS compared to lower wind speeds and increased moisture over regions further east. At 03UTC (Figs. 4.7b, 4.8b), the strongest part of the NLLJ was apparent in the zone between FP3 and FP1, and the moisture field suggests some advection from west to east. By 06 UTC (Figs. 4.7c, 4.8c) NLLJ winds began to develop a westerly component in the western most portion of the NLLJ core zone. Movement of the NLLJ from west to east had only barely begun at this point, but the moisture field suggested west to east advection more strongly at this time than at 03 UTC. Finally at 09 UTC (Figs. 4.7d, 4.8d), the NLLJ developed a strong westerly component over the western half of the domain. The eastern edge of the core NLLJ zone moved from east to west. Dry air from the west moved further east. This case was impacted by convective storms north and west of the domain and associated outflow that propagated into the domain to quickly in the simulations. However, in the regions not impacted by the outflow (apparent in NW corner of Fig. 4.7c, d), the NLLJ evolved similarly to IOP12.

The evolution of IOP02's NLLJ along the slope of the Great Plains is shown in Fig. 4.9. Compared to IOP12 (Fig. 4.3), the vertical motion field during IOP02 is chaotic. The wind barbs and moisture field confirm the evolution described via Figs. 4.7 and 4.8. The NLLJ first formed over the western part of the slope (Fig. 4.9b.). With time, the NLLJ and the moisture field moved from west to east down the slope while a westerly component developed. In Fig. 4.9c, an localized region of convergence and associated updraft is located just east of 99° W which is concurrent with the observed and simulated vertical motion at FP3 (see Fig. 3.8a,b). A similar instance of vertical motion was observed at FP2, but it was not well simulated (see Fig. 3.7a,b).

Profiles of normalized u , v , water vapor mixing ratio, and potential temperature during IOP02 at 101° W and 96° W are shown in Fig. 4.10. Comparing the western profiles to the eastern profiles, the u -component developed a low-level maximum earlier in the west. This u -component maximum was stronger and lower during earlier times at the western site

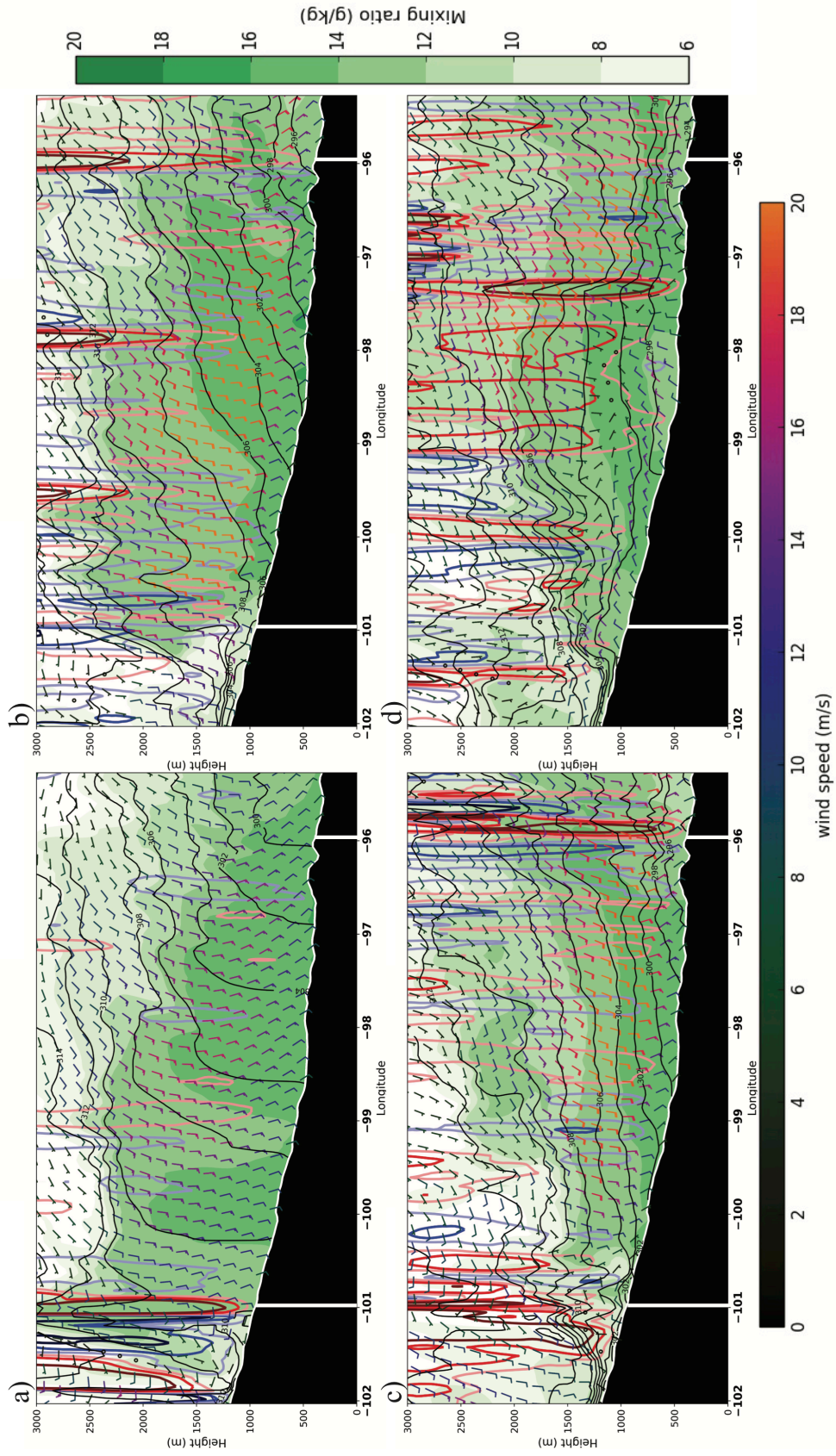


Figure 4.9: As in Fig. 4.3, but for IOP02. White lines over the terrain mark locations of profiles shown in Fig. 4.10.

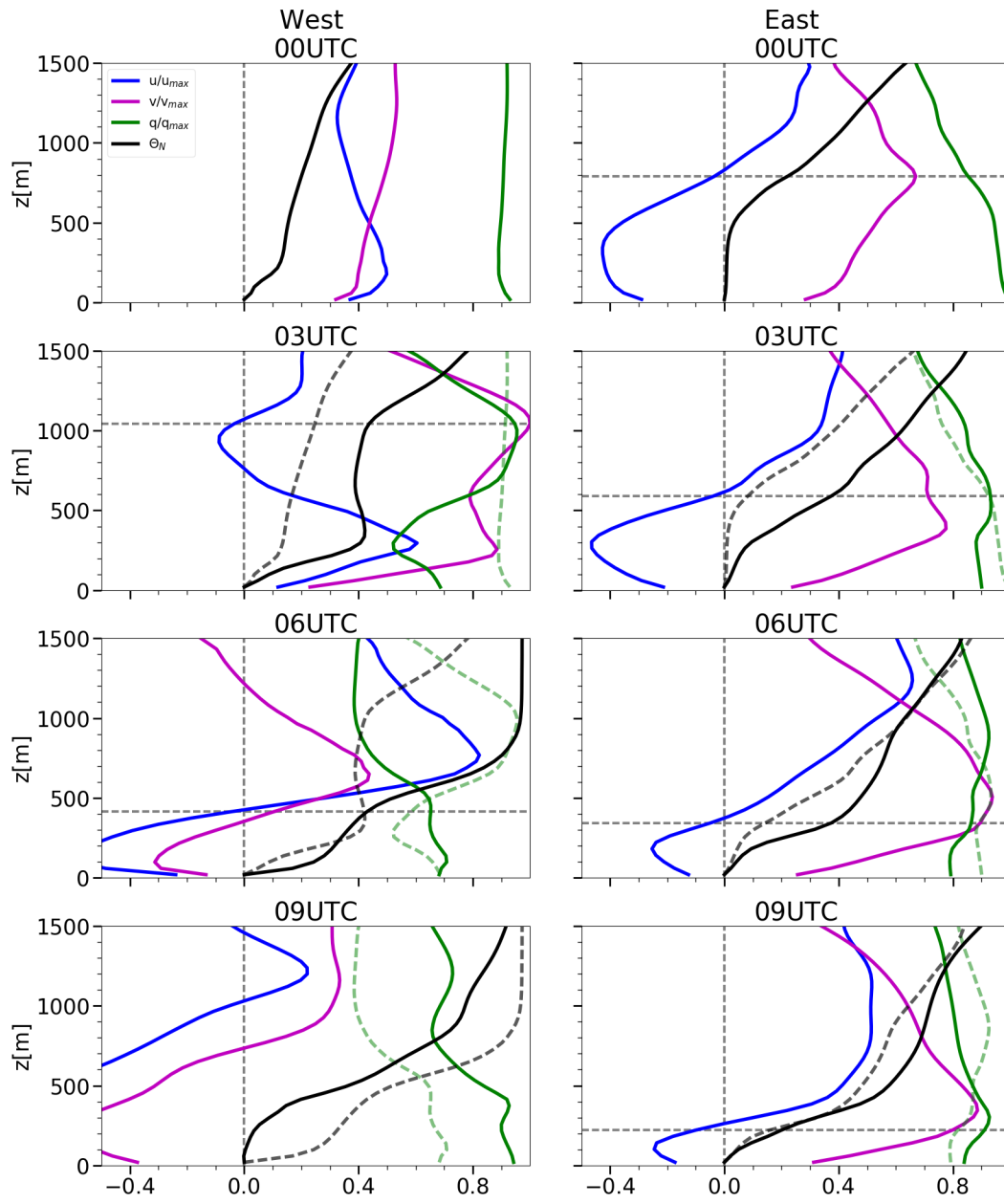


Figure 4.10: As in Fig. 4.5, but for IOP02. The locations where the profiles are taken are shown by white lines in Fig. 4.9.

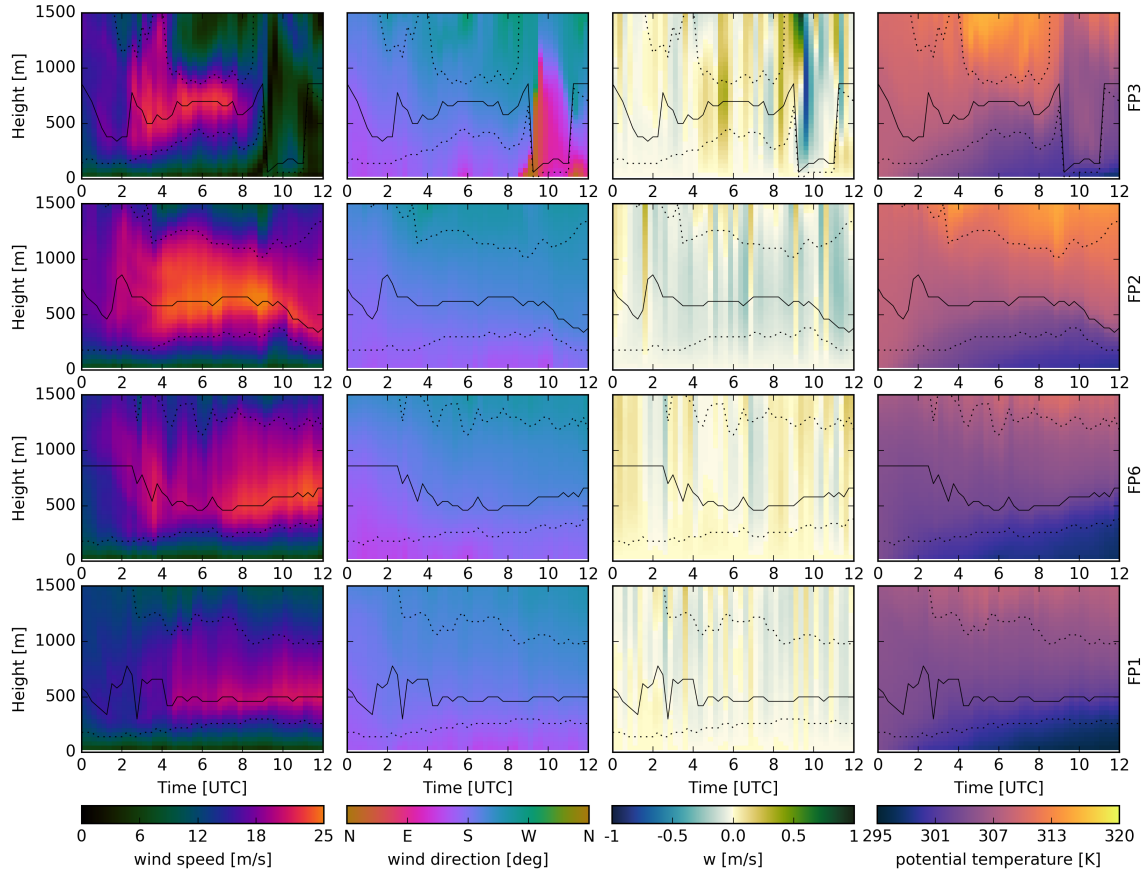


Figure 4.11: As in Fig. 4.6, but for IOP02.

compared to the eastern site until 09 UTC, at which point the NLLJ core region had moved east and away from the western site. Profiles in Fig. 4.10 also suggest that the u -component was responsible for advection of temperature and moisture as trends in these profiles were strongest where the u -component was strongest.

As mentioned in Sect. 4.2, the spatial evolution of the NLLJ results in different local temporal evolution at different locations in the Great Plains. Time-height cross-sections of WRF simulated data from IOP02 are shown at FP3, FP2, FP6, and FP1 in Fig. 4.11 (see Fig. 3.1 for locations). The NLLJ formed earlier at western sites (FP3, FP2) than at eastern sites (FP6, FP1). Potential temperature time-height profiles show that the SBL formed at approximately 02 UTC at all four sites, however the SBL was cooler and deeper at the eastern sites (FP6, FP1). Differing SBL structure makes some sense as the NLLJ had not

formed over the eastern sites (FP6, FP1) allowing the SBL to form without the large mechanical shear influence of the NLLJ. Except at FP3, the simulations do not show the sudden instances of vertical motion as seen in IOP12. Nonetheless, western sites (FP3, FP2) show evidence that westerly advection occurred with warm air advection and increased westerly components above the level of the NLLJ.

4.3.2 IOP13

As for IOP02, the details of IOP13's synoptic setup and data collection are discussed in Sect. 3.2, and observations from this case are shown in Figs. 3.2 – 3.8. The observations from FP3, MP1, and FP2 show that the NLLJ formed slightly above 500 m AGL during the evening transition, then became strong and maintained a height of about 500 m AGL throughout the night. This NLLJ was the strongest jet of the three PECAN cases. Flow in this case was southerly developing a south-westerly to westerly component with time and height. Potential temperature observations show that the SBL formed at sunset time near 02 UTC and the preceding convective boundary layer was warmer than that in IOPs 02 and 12. Warming aloft was also strongest above the NLLJ in this case. At FP2, a broad period of positive vertical motion as observed between 06 and 08 UTC. This period of vertical motion coincided with a slight increase in NLLJ height, narrowing of the NLLJ core, and an increase in westerly wind direction. At MP1, two instances of vertical motion were observed at approximately 05 UTC and between 08 at 09 UTC, respectively. The first vertical motion coincided with a slight increase in NLLJ height and increase in NLLJ magnitude. The second instance coincided with another slight increase in NLLJ height and SBL depth. There is not an observed shift of wind direction at this site. At FP3, a less pronounced instance of positive vertical motion was observed between 07 and 08 UTC. This vertical motion coincided with a very slight and short-lived change in NLLJ height and was followed with an increased westerly wind direction.

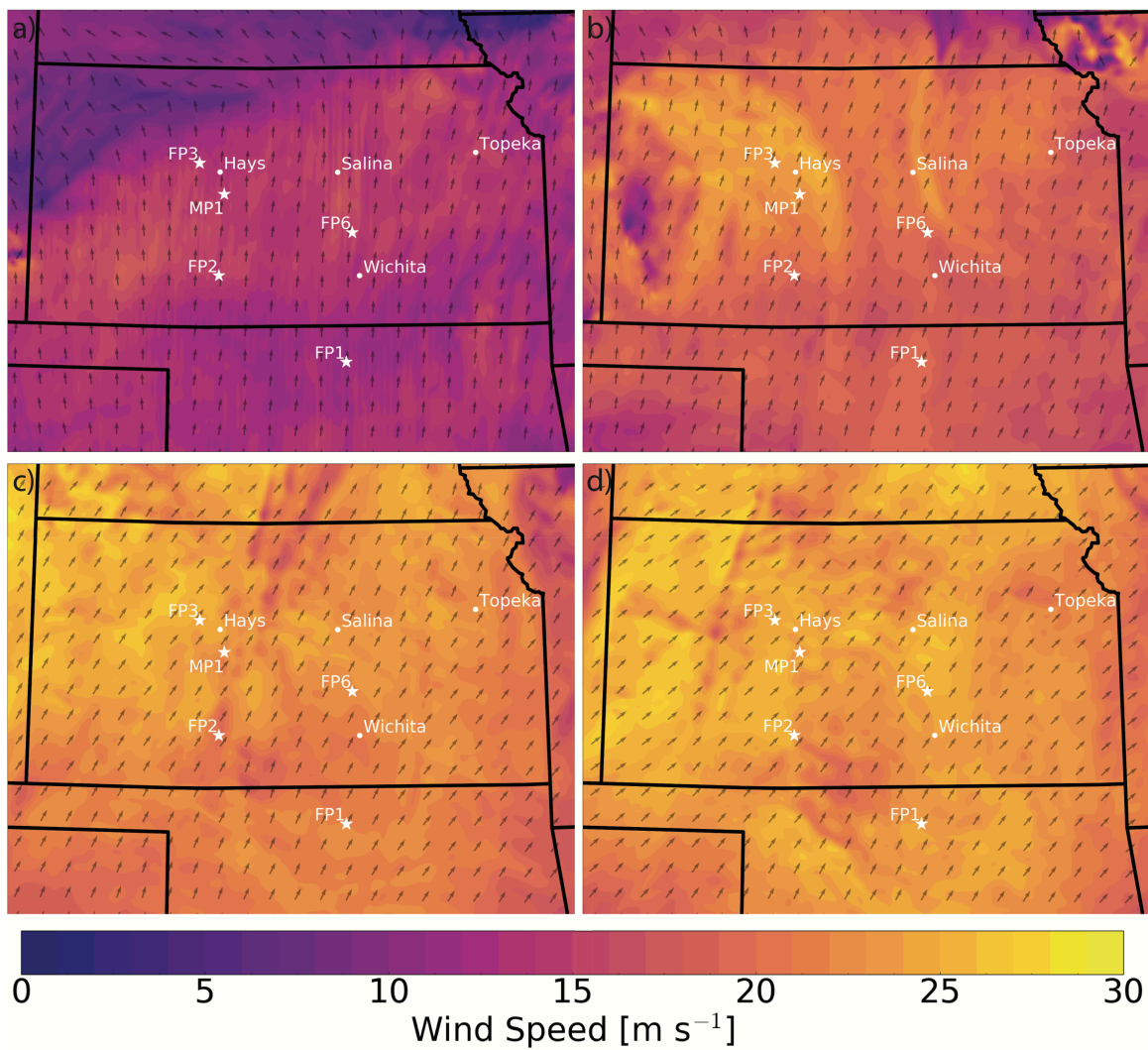


Figure 4.12: As in Fig. 4.1, but for IOP13.

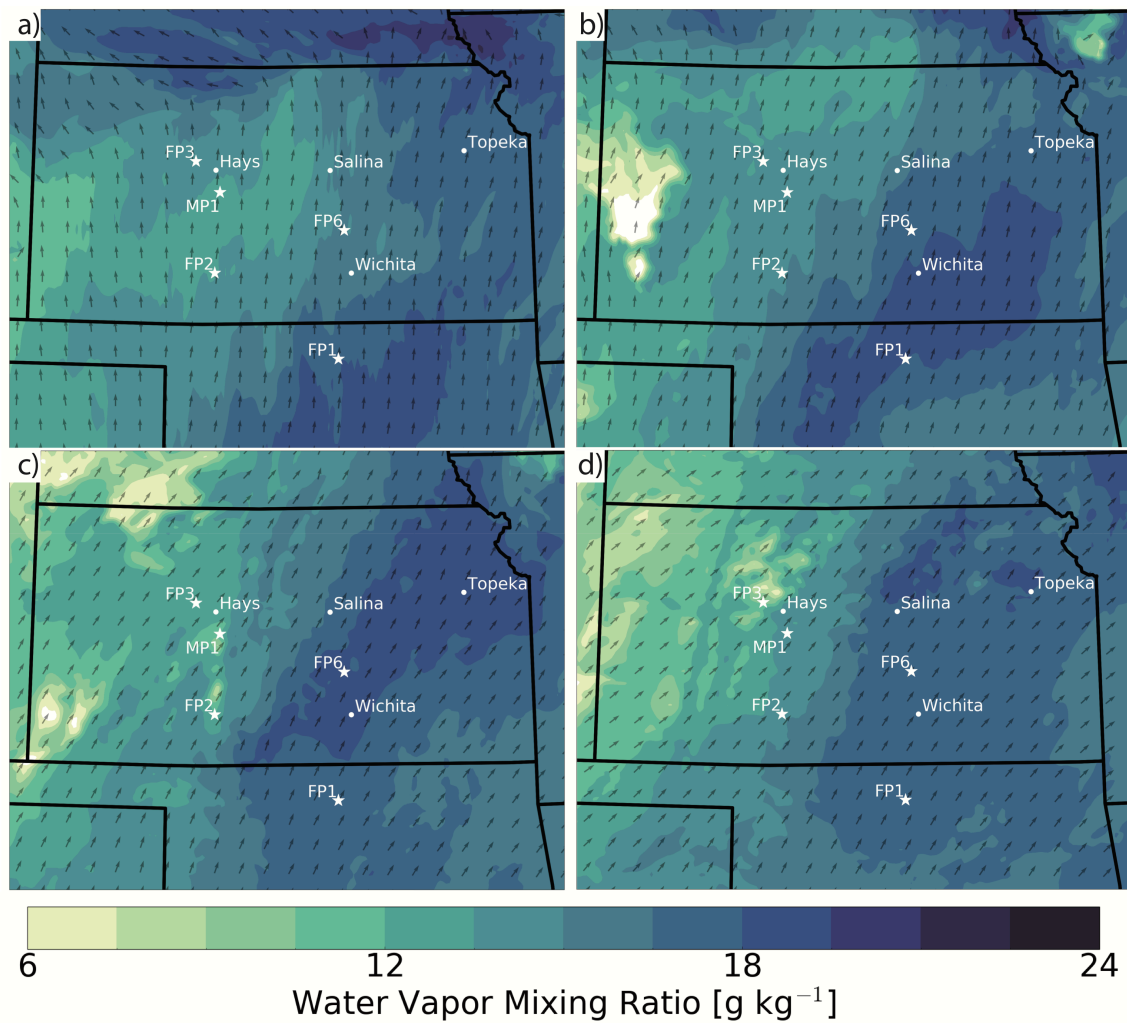


Figure 4.13: As in Fig. 4.2, but for IOP13.

Again, clear diagonal striations are not apparent in observations of the IOP13 NLLJ. IOP13 looks more similar to IOP02 than IOP12. Observations still suggest mean motions coinciding with changes in the NLLJ structure. Simulated wind speed and water vapor mixing ratio at 500 m AGL are shown in Figs. 4.12 and 4.13, respectively. At 00 UTC ((Figs. 4.12a, 4.13a) the winds were southerly and mostly uniform across the domain. Moisture was highest over central OK and eastern KS. By 03 UTC (Figs. 4.12b, 4.13b) the NLLJ had begun to form with the strongest winds over the area near FP3 and Hays, KS. Increased moisture over the eastern half of KS suggests southerly advection was dominant at this time. At 06 UTC (Figs. 4.12c, 4.13c) the NLLJ was strong over the entire domain unlike in the IOP02 and IOP12 cases. Wind vectors show that the wind direction gained a westerly component by this hour across the entire domain. Drier air began to move in from the west indicating that westerly advection was happening at this time. By 09 UTC (Figs. 4.12d, 4.13d) the NLLJ has strengthened a bit more and the westerly components had become more prominent. Dry air advection from the west had moved into the region near and west of Hays, KS. This NLLJ evolved somewhat differently than IOP02 and IOP12 with the entire domain seeing strong and nearly uniform winds. However, the wind did develop a westerly component with time, and the moisture field still suggested westerly advection consistent with the other two PECAN cases.

Along-slope cross-sections are shown for IOP13 in Fig. 4.14. Compared to IOP12 (Fig. 4.3), the vertical motion field during IOP13 is chaotic like that in IOP02 (Fig. 4.9). This case shows the deepest CBL and thus deepest moisture compared to IOP02 and IOP12. The evolution shown Fig. 4.14 agrees with the evolution described via Figs. 4.12 and 4.13. The NLLJ formed by 03 UTC (Fig. 4.14b) with the strongest winds over the western portion of the domain. By 06 UTC (Fig. 4.14c), strong NLLJ winds covered the entire domain and westerly components had increased. By this time, moisture had become much shallower in the more stable environment and transported to the east. At 09 UTC (Fig. 4.14d) most moisture was confined to the eastern portion of the domain. Through this evolution, several

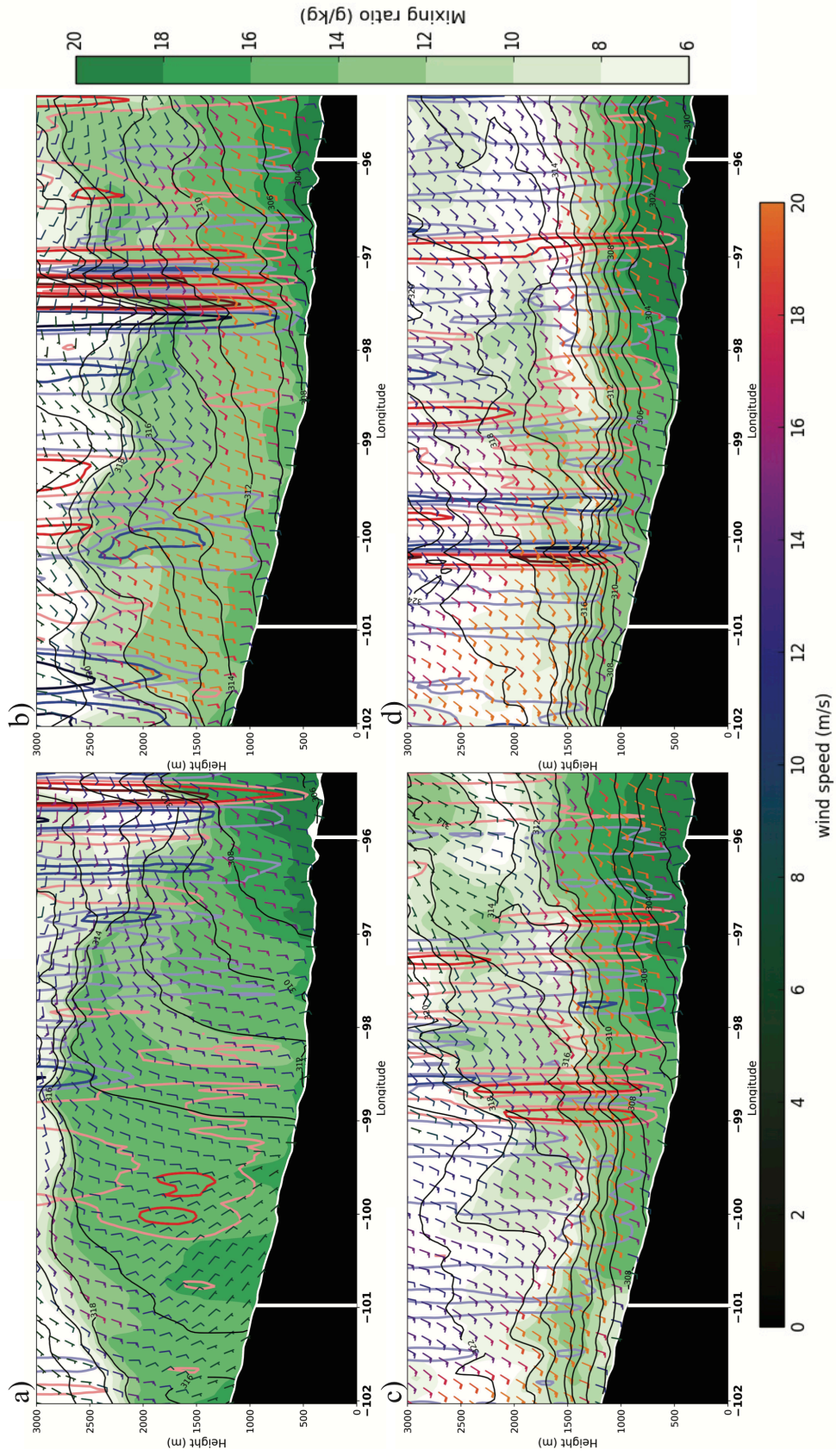


Figure 4.14: As in Fig. 4.3, but for IOP13. White lines over the terrain mark locations of profiles shown in Fig. 4.15.

instances of vertical motion appear in the vertical velocity field shown in Fig. 4.14, but not all of them are obviously connected to a local heterogeneity suggesting other forcings may have been at play. However, at 06 UTC (Fig. 4.14c) a region of positive vertical motion seems to be connected to local wind speed convergence near and just east of 99° W. This is coincident with the observed and simulated instance of vertical motion along the north-south transect of FP3 (Fig. 3.8), MP1 (Fig. 3.6), and FP2 (Fig. 3.7).

As for IOP02 and IOP12, profiles of normalized u , v , water vapor mixing ratio, and potential temperature during IOP13 at 101° W and 96° W are shown in Fig. 4.15. By 06 UTC, it is clear that the western u -profile developed a maximum lower and earlier than the eastern profile. As in the other cases, it is also apparent that the trends of the water vapor mixing ratio and potential temperature profiles were strongest at the same levels as the strongest u -component velocity, suggesting significant westerly advection.

To analyze the spatial evolution of the NLLJ and different local temporal evolution at different locations in the Great Plains, time-height cross-sections of WRF simulated data from IOP13 are shown at FP3, FP2, FP6, and FP1 in Fig. 4.16 (see Fig. 3.1 for locations). As in IOP02, the NLLJ formed earlier at western sites (FP3, FP2) than at eastern sites (FP6, FP1). Potential temperature time-height profiles show that the SBL formed at approximately 02 UTC at all four sites. Again, the SBL was cooler and deeper at the eastern sites (FP6, FP1). Sudden instances of vertical motion were simulated at all sites except FP1. Interestingly, the eastern most site (FP6) had a sudden vertical motion before the two western sites (FP3, FP2). It is not clear why this is the case but could be related to a local heterogeneity in the NLLJ not shown in this analysis or some other type of forcing. The similarly timed instances of vertical motion at FP2 and FP3 are likely related to the local convergence zone previously mentioned and shown in Fig. 4.14c. The vertical motions are coincident with additional features in the local temporal evolution of the NLLJ at FP2 and FP3. At FP3, the sudden instance of upward motion occurred around 07 UTC. At this time, the wind speed field showed a slight decrease in NLLJ maximum height, which could

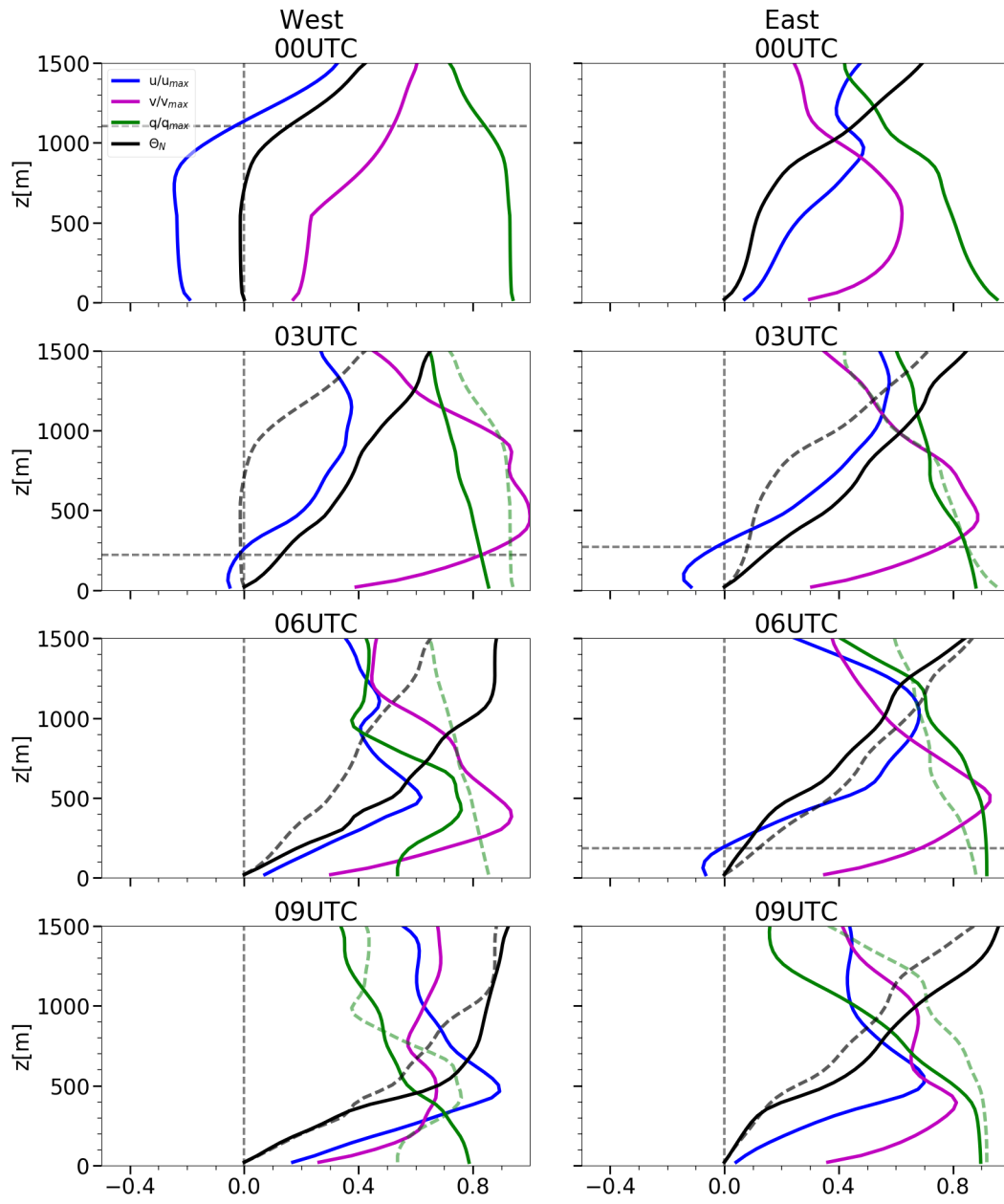


Figure 4.15: As in Fig. 4.5, but for IOP13. The locations where the profiles are taken are shown by white lines in Fig. 4.14.

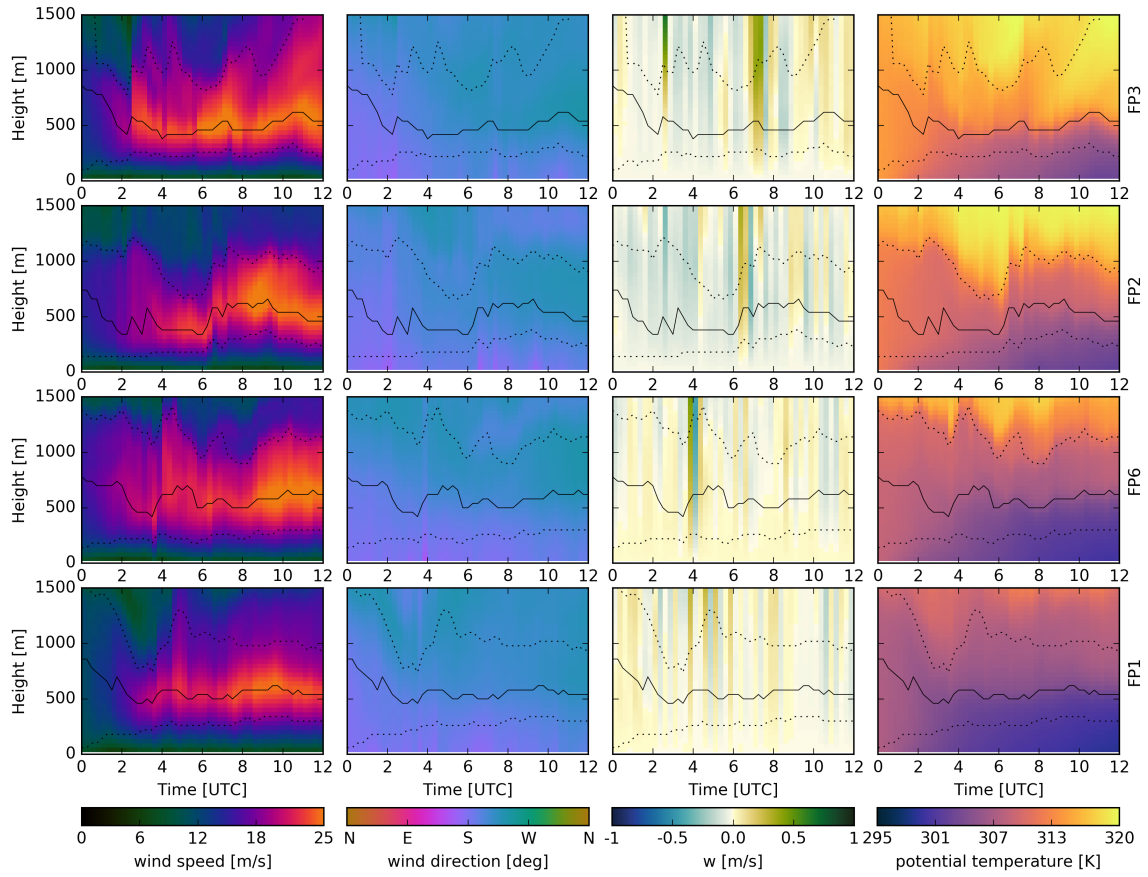


Figure 4.16: As in Fig. 4.6, but for IOP13.

perhaps be considered a small and brief diagonal striation. In the wind direction field, the westerly component increased and reached down to the level of NLLJ maximum at about 07 UTC. In the regions where wind direction included this westerly component, warm air was shown in the potential temperature field suggesting warm air advection from the west. The evolution at FP2 is similar with the sudden instance of vertical motion simulated at about 06 UTC at the end of a diagonal striation-like feature in the wind speed field (from 03-06UTC). Again, wind direction became more westerly and appears to have brought in warm air at the time of the sudden instance of vertical motion and during the hours after. The evolution of the NLLJ around the time of the simulated positive vertical motion at FP6 is not the same as that at FP2 and FP3, further suggesting this instance may be related to a different mechanism.

4.4 Conclusions

Three-dimensional simulation data were used alongside PECAN observations to explore characteristics of the NLLJ over the Great Plains. A summary of PECAN observations suggested that the spatial evolution of the NLLJ was responsible for sudden changes in the NLLJ structure manifest via diagonal striations in the time-height wind profiles with coincident rising motion and warm advection above the NLLJ nose. Plan-view analyses of WRF modeled wind speed and water vapor mixing ratio showed that the NLLJ moved from west to east down the slope during the night. This momentum advection by the NLLJ was associated with the increased westerly component as the NLLJ veered in time. Strong westerly components were shown to advect warm and dry air from the west to the east. Vertical cross-sections across the slope of the Great Plains showed that NLLJ winds veered not only in time but also in height. The westerly component first increased at the top of the NLLJ and gradually descended. This veering in height and time together appeared as a diagonal striation in time-height cross-sections of wind observed and simulated at each site. Heterogeneous NLLJ depth, wind speed, and wind direction was identified as a potential

source of localized convergence and associated vertical motions. With sufficient saturation, this mechanism could be important for nocturnal convection initiation as in Gebauer et al. (2018).

Indeed, the spatial evolution of the NLLJ lead to sudden changes in NLLJ structure and mixing in the NBL. In idealized simulations, Fedorovich et al. (2017) showed similar effects. Comparison of time-height cross-sections of dynamic and thermodynamic variables at FP3, FP2, FP6, and FP1 showed that evolution of the NLLJ was quite different at the western sites (FP3, FP2) compared to the eastern sites (FP6, FP1). Additionally, the heterogeneity was more prominent at the northern sites (FP3, FP6). While this study mostly focused on NLLJ heterogeneity during IOP12, it is important to note that similar structure has been noted in additional cases (e.g., Gebauer et al. 2018). PECAN cases IOP02 and IOP13 were briefly explored to evaluate their similarity to IOP12. While such clear examples of diagonal striation were not prominent in these cases, similar spatial and temporal NLLJ evolution was described. All cases showed the NLLJ moving from west to east across the slope of the Great Plains with veering wind direction in time and height. Local heterogeneity was also connected to observed and simulated sudden instances of vertical motion in all cases.

The presented analyses are an example of the advantage of using optimally configured WRF model simulations in tandem with high-resolution observational data. By using observations alone, it would have been far more challenging to understand how the spatial and temporal characteristics of the NLLJ are connected and to propose sources of the sudden vertical motions. Verifying simulated data using observations allows one to make inferences about NLLJ physics beyond features that are explicitly observed. Initial results suggest that components of the described spatial-temporal NLLJ evolution may be common, but more cases are needed to understand how frequently the evolution occurs. Initial results also suggest that the degree of NLLJ heterogeneity varies; IOP12 was the most heterogeneous PECAN NLLJ while IOP13 was the least heterogeneous case with IOP02

falling in the middle. This study was able to connect local mixing events to NLLJ spatial evolution, which, to the author's knowledge, has not been previously documented in the literature. However, the physics behind spatially heterogeneous NLLJs and their motion across the Great Plains has not yet been described.

The unified NLLJ theory described in Shapiro et al. (2016), highlights that the evolution of the NLLJ depends on two main processes: (i) the inertial oscillation caused by the sudden drop of turbulent mixing around sunset (the Blackadar mechanism, Blackadar 1957) and (ii) effects of surface buoyancy (Holton mechanism, add Holton 1967) caused by the diurnal heating and cooling of a sloped surface. Results from their analytical model showed that interactions between the two mechanisms play an important role and simulations with strong daytime heating resulting in stronger jets than simulations that only accounted for the Blackadar mechanism. Previous observational studies of the NLLJ have often followed the Blackadar mechanism approach and focused on connecting locally defined boundary layer features to NLLJ characteristics and evolution (e.g., Banta et al. (2002, 2003, 2006); Ohya et al. (2008); Banta (2008); Sun et al. (2012); Bonin et al. (2015); Klein et al. (2016)) but have not really addressed the potential influence of buoyancy effects. This approach was natural since most boundary layer observations have been limited to single or few point observations at or near the surface only. The development and application of more sophisticated observing and simulation techniques have allowed for a new perspective on the relationship between the boundary layer and the NLLJ. This study for the first time documented the temporal-spatial evolution of the NLLJ over the Great Plains in detail. Utilizing the mesoscale model (i.e., the WRF model) was critical for the analysis of these spatiotemporal characteristics. On the other hand, the chosen approach of running simulations with 4-km spaced grids using PBL parameterization is not ideal for diagnosing turbulence and stability parameters (e.g., turbulent diffusivity, TKE, Richardson number, etc.) in the boundary layer. This means that the effect of spatial-temporal variations of turbulent mixing on NLLJ evolution could not be evaluated using the mesoscale model output. Based

on the results described in Shapiro et al. (2016), we hypothesize that variations in buoyancy may be an important mechanism contributing to the pronounced spatial-temporal evolution of the NLLJ, and these effects can be investigated using the mesoscale model output. This will be addressed in the next chapter.

In summary, the results presented in this chapter demonstrated that the Great Plains NLLJ is essentially heterogeneous in structure, wind speed, and wind direction. Additionally, the heterogeneous NLLJ was shown to be moving across the sloping terrain of the Great Plains through the night. As such, the spatial and temporal characteristics of the NLLJ are deeply connected and should be considered together. Open questions which we intend to address in further analysis are the following:

- How common is the described spatial-temporal NLLJ evolution?
- What is the source of spatial heterogeneity in the NLLJ?
- What are the impacts of local changes in buoyancy?
- How do buoyancy gradients impact NLLJ evolution?

The next chapter will use more cases to answer these questions and explore buoyancy as a potential driver of NLLJ heterogeneity and spatial-temporal evolution.

Chapter 5

Spatial and Temporal Characteristics of LABLE and PECAN NLLJs

5.1 Introduction

Using the PECAN observations alongside WRF simulations, Chapter 4 showed that the spatial and temporal characteristics of the NLLJ are connected and consideration of both is necessary to understand NLLJ evolution. However, PECAN NLLJ observations were limited to four cases, IOP02, IOP07, IOP12, and IOP13, and data quality for IOP07 precludes it from full consideration. While having distributed observations over a spatial domain makes the PECAN observations very useful, just three cases are not enough to understand typical NLLJ evolution and structural features. Several NLLJs were observed during the LABLE campaign, ten of which were not considered to be strongly forced by fronts or boundaries nearby the SGP/FP1 observation site (see Table 2.1). While the LABLE observations were collected just at a single point, the WRF simulations described in Chapters 2 and 3 are considered to be representative enough to supplement the observations and provide three-dimensional data for analysis. As discussed in Section 4.4, utilizing a mesoscale model allowed for documentation and description but limited boundary layer analysis of the NLLJ and its evolution. Diagnosing turbulence and stability parameters from 4-km spaced grids using PBL parameterization is not direct. This means the available mesoscale model output is not sufficient to follow traditional boundary layer approaches to understand spatial variations of turbulence. Following from NLLJ theory as described in Shapiro et al. (2016), we hypothesize that changes in buoyancy may explain some of the physical mechanisms, and we can use the mesoscale model output to evaluate buoyancy variations.

This chapter aims to address four open questions posed in Chapter 4:

- How common is the described spatial-temporal NLLJ evolution?
- What is the source of spatial heterogeneity in the NLLJ?

- What are the impacts of local changes in buoyancy?
- How do buoyancy gradients impact NLLJ evolution?

To do so, cases from PECAN and LABEL are evaluated together. This combined dataset can help show how common the identified spatial-temporal NLLJ evolution is and evaluate seasonal and location-based differences in the evolution. The ten LABEL cases will first be categorized based on their similarity to the identified spatial-temporal NLLJ evolution from the PECAN cases. Categories are as follows: clear cases, similar cases, and unclear cases. Clear cases will include cases that have strong similarity to the spatial-temporal NLLJ evolution identified in Chapter 4 including east-west NLLJ motion, local convergence zones, sudden vertical motions, and westerly advection. Similar cases will include cases that have some similarity to the spatial-temporal NLLJ evolution identified in Chapter 4, but may not show all features or may be impacted by synoptic patterns in the larger domain. Unclear cases will include cases that may have locally exhibited NLLJ like features, but otherwise do not appear to have NLLJ features on the larger spatial scale. The fourteen LABEL and PECAN cases and their evolution similarity categories are outlined in Table 5.1. Out of fourteen cases there are four clear cases, eight similar cases, and two unclear cases. LABEL NLLJ cases from each category are evaluated and compared to the previously identified spatial-temporal NLLJ evolution in detail in Appendix A.

5.2 Bulk NLLJ features

These analyses aim to explore bulk NLLJ features categorized by case type. Overnight maximum NLLJ magnitude, U_{LLJ} was compared to the CBL profile averaged wind in Fig 5.1. The CBL is represented by averaging a 2-hour window prior to sunset time; for PECAN cases this window is 00-02 UTC (sunset at 02 UTC), and for LABEL cases it is 22-00 UTC (sunset at 00 UTC). The CBL profile averaged wind is the average of profiles below 1000 m AGL during the CBL time period. The scatter plot shows a strong positive relationship between U_{LLJ} and the CBL profile averaged wind, with stronger CBL profile

Table 5.1: Fourteen NLLJ cases categorized based in their similarity to the spatial-temporal NLLJ evolution identified in Chapter. 4.

Date	Category	Date	Category
2012 Oct. 09	Clear Case	2012 Oct. 24	Clear Case
2012 Oct. 13	Similar Case	2012 Nov. 08	Clear Case
2012 Oct. 15	Unclear Case	2012 Nov. 09	Similar Case
2012 Oct. 16	Similar Case	2015 June 03 (IOP02)	Similar Case
2012 Oct. 21	Similar Case	2015 June 10 (IOP07)	Similar Case
2012 Oct. 22	Similar Case	2015 June 20 (IOP12)	Clear Case
2012 Oct. 23	Unclear Case	2015 June 22 (IOP13)	Similar Case

averaged wind speeds related to stronger U_{LLJ} . As such, we used the CBL profile averaged wind as a scaling velocity, denoted as U_s . Scaling the NLLJ magnitude as U_{LLJ}/U_s allowed for comparison between cases with varying magnitudes.

In this analysis we consider four sites that make a somewhat diagonally stretched rectangle: FP3 – a northwest site, FP2 – a southwest site, FP6 – a northeast site, and SGP/FP1 – a southeast site. First, the average pre-NLLJ and mature NLLJ normalized wind profiles are shown for each case category in Fig. 5.2. On average, clear cases had stronger normalized NLLJ maxima. These cases also tended to have stronger pre-NLLJ winds in the low levels, perhaps indicating a more deeply mixed CBL. Cases categorized as similar showed much more variability than cases categorized as clear, especially at night. At most locations, unclear cases showed less uniformly mixed pre-NLLJ profiles, suggesting those cases are complex before the sun sets. Between locations, there was not much difference in the profiles. At the northwest site, FP3, the clear cases showed narrow spread. This could be attributed to the NLLJ core zone moving west and south of that site in the clear spatial-temporal evolution, causing NLLJ winds to be less variable later in the period at that site.

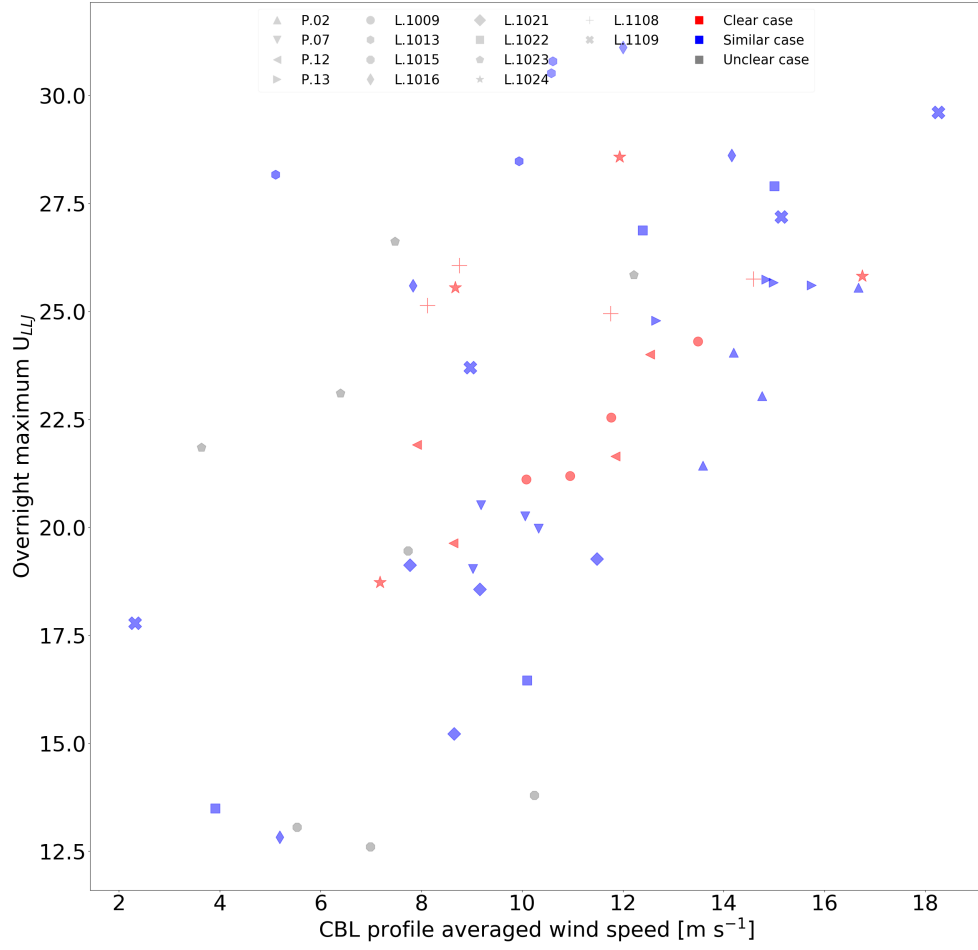


Figure 5.1: Scatter plot showing the relationship between overnight maximum U_{LLJ} and CBL profile averaged wind speed, U_s for all 14 PECAN (P) and LABEL (L) cases categorized as described in Sect. 5.1.

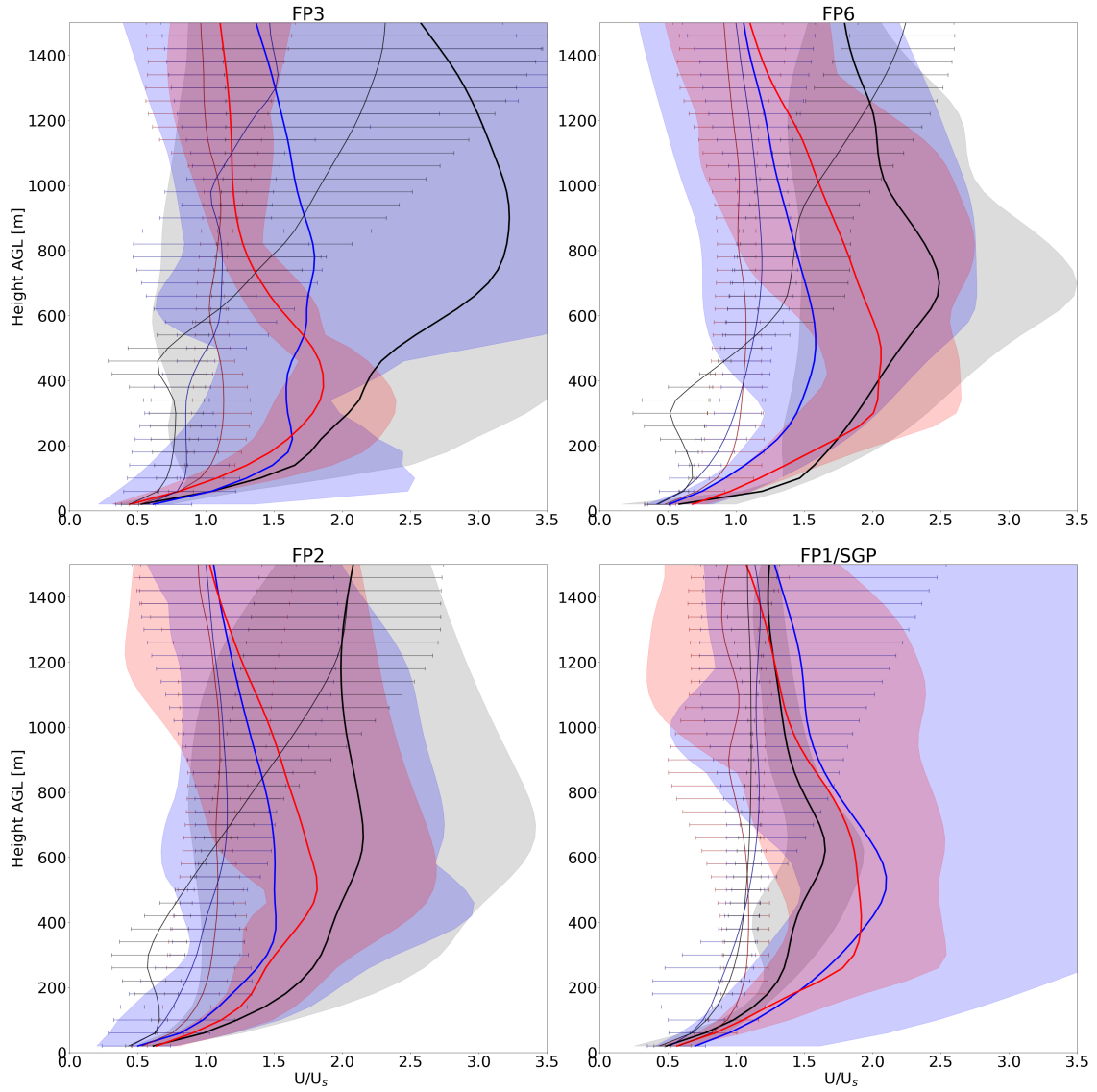


Figure 5.2: Clear (red), similar (blue) and unclear (black) cases are shown with the line denoting the average among each category and the fill or bars showing the spread among the cases for four locations in the domain: FP3(NW), FP2(SW), FP6(NE), and SGP/FP1(SE). Thin lines with bars show the normalized profile averaged from 2200 - 0030 UTC representing pre-NLLJ conditions while thick lines and color fill show the normalized profile average from 0800 - 0830 UTC representing the mature NLLJ.

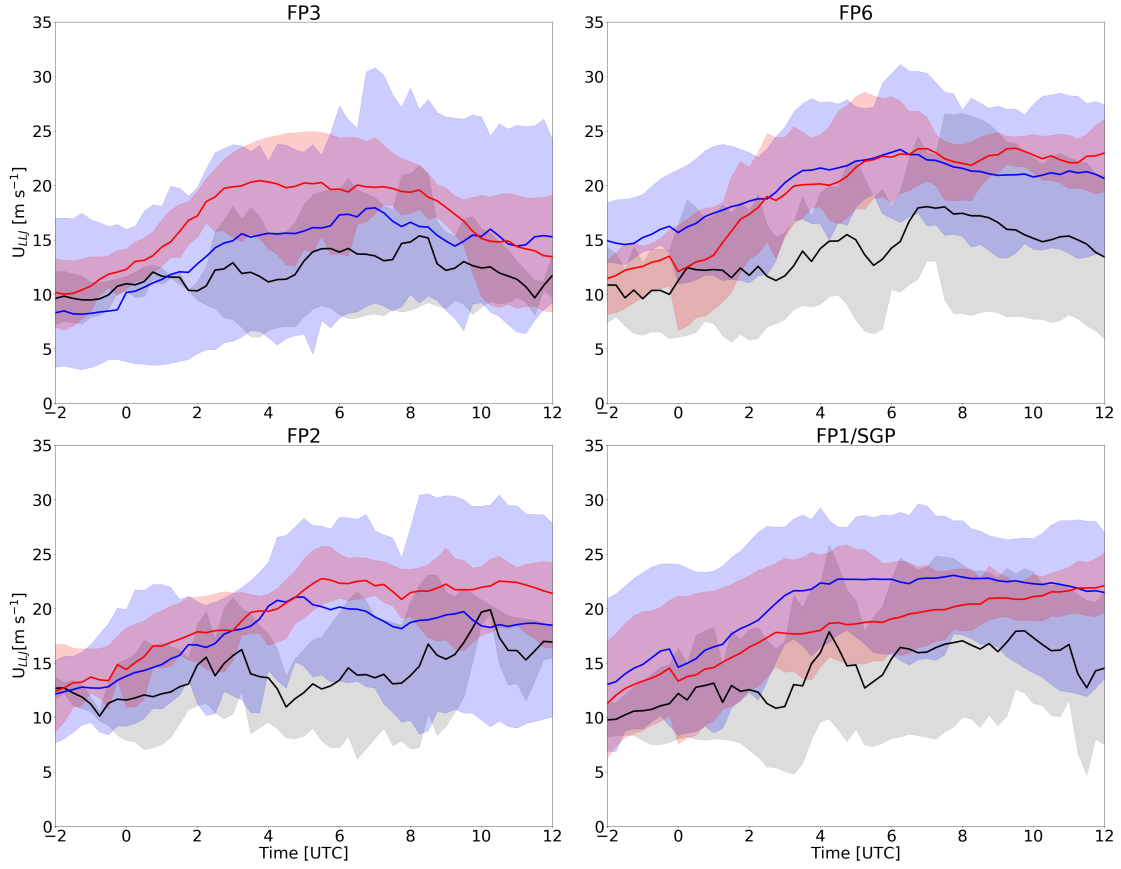


Figure 5.3: Time series of U_{LLJ} are shown for clear (red), similar (blue) and unclear (black) cases, with the line denoting the average among each category and the colorfill showing the spread among the cases for four locations in the domain: FP3(NW), FP2(SW), FP6(NE), and SGP/FP1(SE).

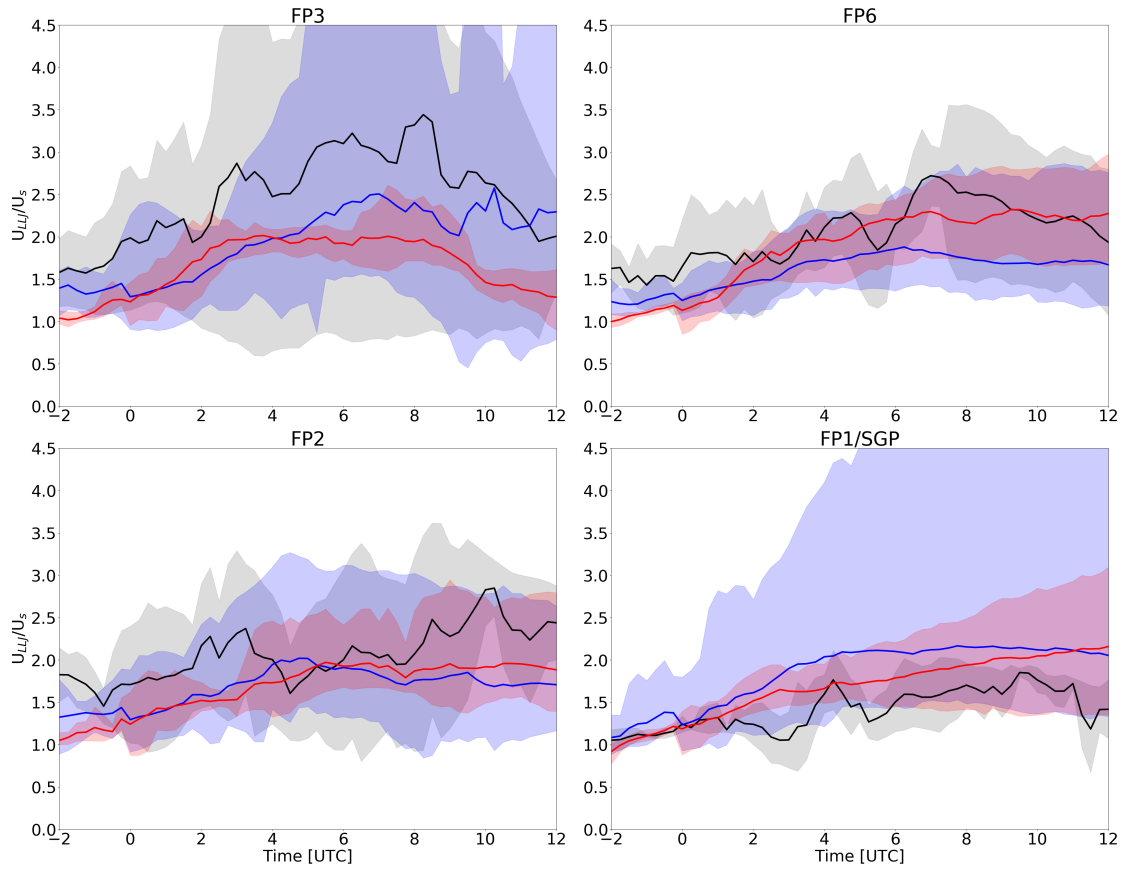


Figure 5.4: As in Fig. 5.3, but showing time series of U_{LL}/U_s .

Time series of non-normalized and normalized NLLJ wind speed are shown in Figs. 5.3 and 5.4, respectively. Showing both versions of the time series of NLLJ magnitude showed that non-normalized NLLJ magnitudes were often larger for the clear cases, but normalized magnitudes were rarely the strongest. Otherwise, the two time series show similar characteristics. At all sites, clear cases showed an increase in NLLJ magnitude during the first portion of the night. At the western sites (FP3 and FP2), the NLLJ magnitude increase stopped about halfway through the night and became more constant. At the northwest site (FP3), the NLLJ magnitude decreased during the later portion of the night. At the eastern sites, the clear cases showed steady NLLJ magnitude increase throughout the night, especially at the southeast site, SGP/FP1. The difference in time series of NLLJ magnitude between sites can be attributed directly to the spatial-temporal NLLJ evolution identified in Chapter 4. The NLLJ was shown to move from west to east, and this effect was most pronounced in the northern portion of the domain. This means that during this evolution, the core zone of the NLLJ would eventually move away from FP3 while moving toward and eventually over the SGP/FP1 site. During the early period of the night, the NLLJ is expected to form with the core region near the western sites, resulting in the gradual increase of NLLJ magnitude at these sites during the first half of the night. Over the eastern sites, the NLLJ forms with the core region to their west. Overnight, the core zone moves from west to east resulting in continual increase at the eastern sites and either steady or decreasing magnitude at the western site as they are no longer in the core zone. This evolution was most obviously documented during clear cases, but comparable evolution was also documented during similar cases. At all sites except FP1/SGP, similar and unclear cases begin the night with winds already stronger than the scaling magnitude, U_s resulting in $U_{LLJ}/U_s > 1$. Noisy wind speeds during the CBL averaging window (00-02 UTC for PECAN cases, 22-00 UTC for LABLE cases) lead to a smaller U_s magnitude than the peak winds observed during that time period. If we define U_s as the maximum instead of the average wind speed observed below 1000 m AGL during the CBL averaging window, all

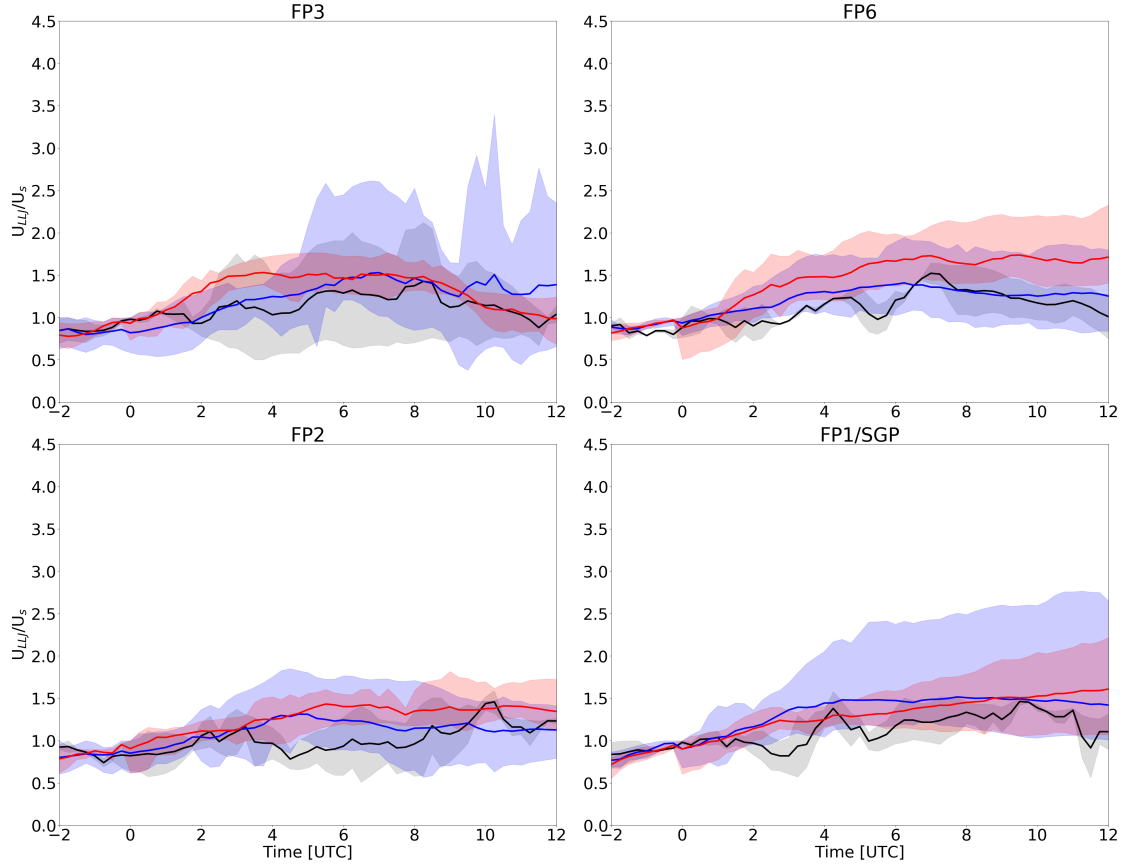


Figure 5.5: As in Fig. 5.4, but defining U_s as the maximum instead of the average wind speed observed below 100 m AGL during the CBL averaging window.

case types show U_{LLJ}/U_s near 1 early in the night as shown in Fig. 5.5. As noted during discussion of pre-NLLJ and mature NLLJ profiles (Fig. 5.2), clear cases likely have more well-mixed CBLs than similar and unclear cases, which allows scaling with U_s defined as the average wind speed observed below 100 m AGL during the CBL averaging window to accurately represent pre-NLLJ conditions. The temporal NLLJ evolution in Fig. 5.5 shows that clear cases tend to have the largest relative speed-up of winds with the scaling based on maximum CBL wind speed. This could be a possible indicator that buoyancy effects play a role in strengthening the NLLJ in addition to the inertial oscillation.

Time series of NLLJ height and depth are shown in Figs 5.6 and 5.7, respectively. NLLJ height is simply the height of the NLLJ maximum (maximum in the wind profile

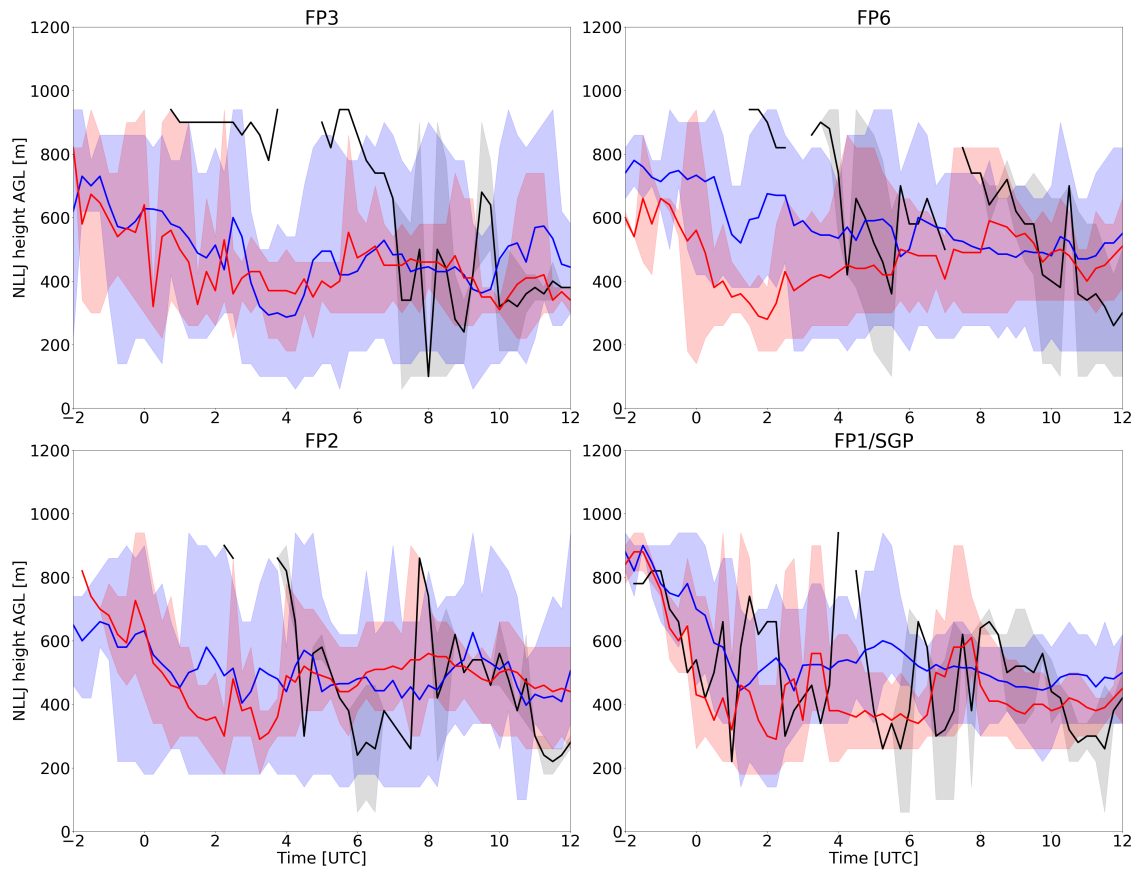


Figure 5.6: As in Fig. 5.3, but showing time series of NLLJ height.

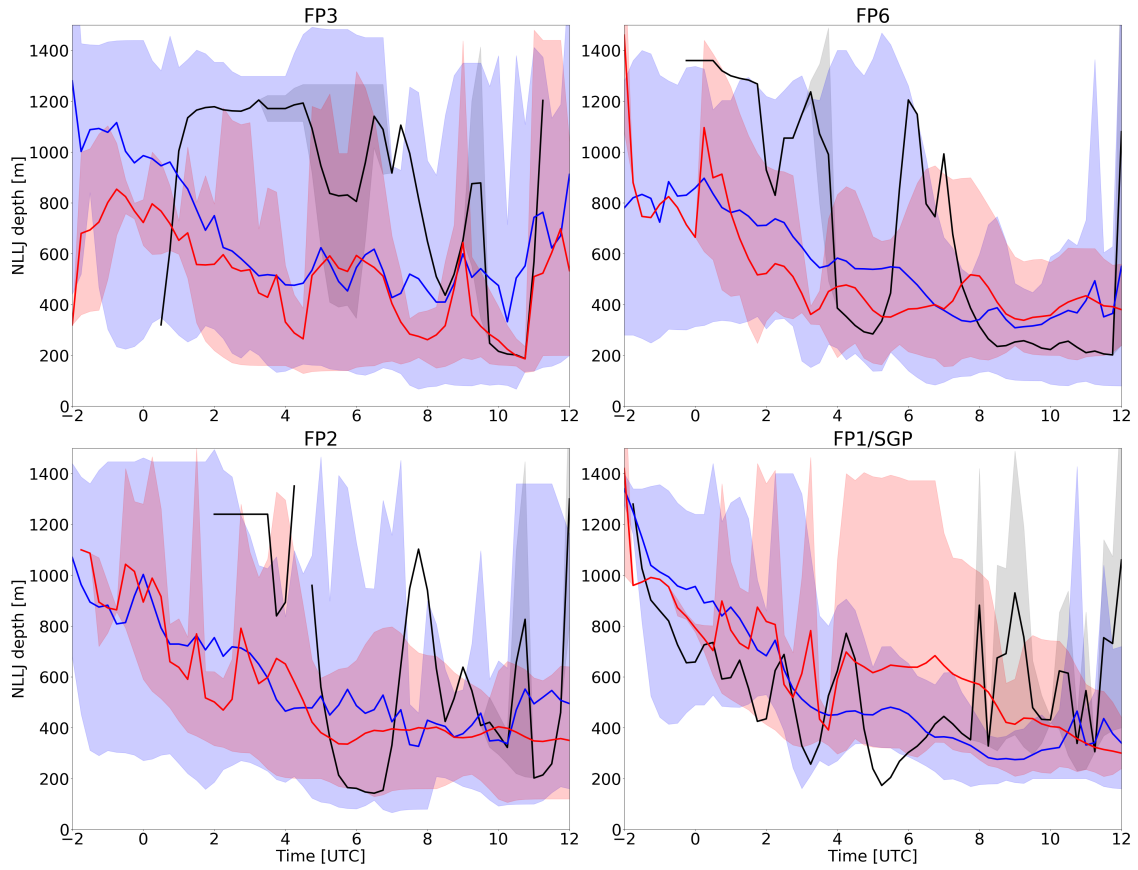


Figure 5.7: As in Fig. 5.3, but showing time series of NLLJ depth, defined as the depth of the region where wind speed is at least 90% of U_{LLJ} .

below 1000 m AGL). NLLJ depth is defined as the depth of the region where wind speed is at least 90% of U_{LLJ} , and represents the depth of the core of the NLLJ. As expected, the temporal evolution of NLLJ height and NLLJ depth is similar. NLLJ height was more variable over eastern sites. Clear cases showed a lower NLLJ height in a general sense compared to similar and unclear cases. In clear cases, NLLJ height decreased during the first half of the night before becoming fairly steady at the western sites. At the eastern sites, NLLJ height also decreased during the first half of the night but then became more variable than over western sites. NLLJ depth decreased throughout the night and variability decreased for western sites. At eastern sites, NLLJ depth also decreased throughout the night, but variability became larger later in the period. Based on the identified spatial-temporal evolution, this difference between western and eastern sites could be attributed to each site's location with respect to the moving NLLJ. In clear cases and some similar cases, the NLLJ forms early in the night at all sites, but the NLLJ core zone is located closer to the western sites. Thus, NLLJ height and depth decreases at all sites early in the period as the NLLJ forms. Later in the night, the core zone of NLLJ winds moves from west to east, away from the western sites and toward the eastern sites. NLLJ height and depth become mostly constant and variability decreases at the western sites as the core zone moves away. NLLJ height and depth show temporary increases and an increase in variability as the core zone moves toward them. This is most likely associated with heterogeneity in wind speed and direction changing the local structure of the NLLJ profile as the core zone moves over the eastern sites.

Finally, time series of static stability are shown in Fig. 5.8. Here static stability is defined as the vertical gradient of potential temperature within the NLLJ core region, where winds are at least 90% of the NLLJ magnitude. Studies by Bonin (2015) showed that some NLLJs intensified and became more shallow as static stability increased bringing isentropic surfaces closer together. Temporal evolution of static stability was different over western sites than over eastern sites. Clear and similar cases both showed static stability

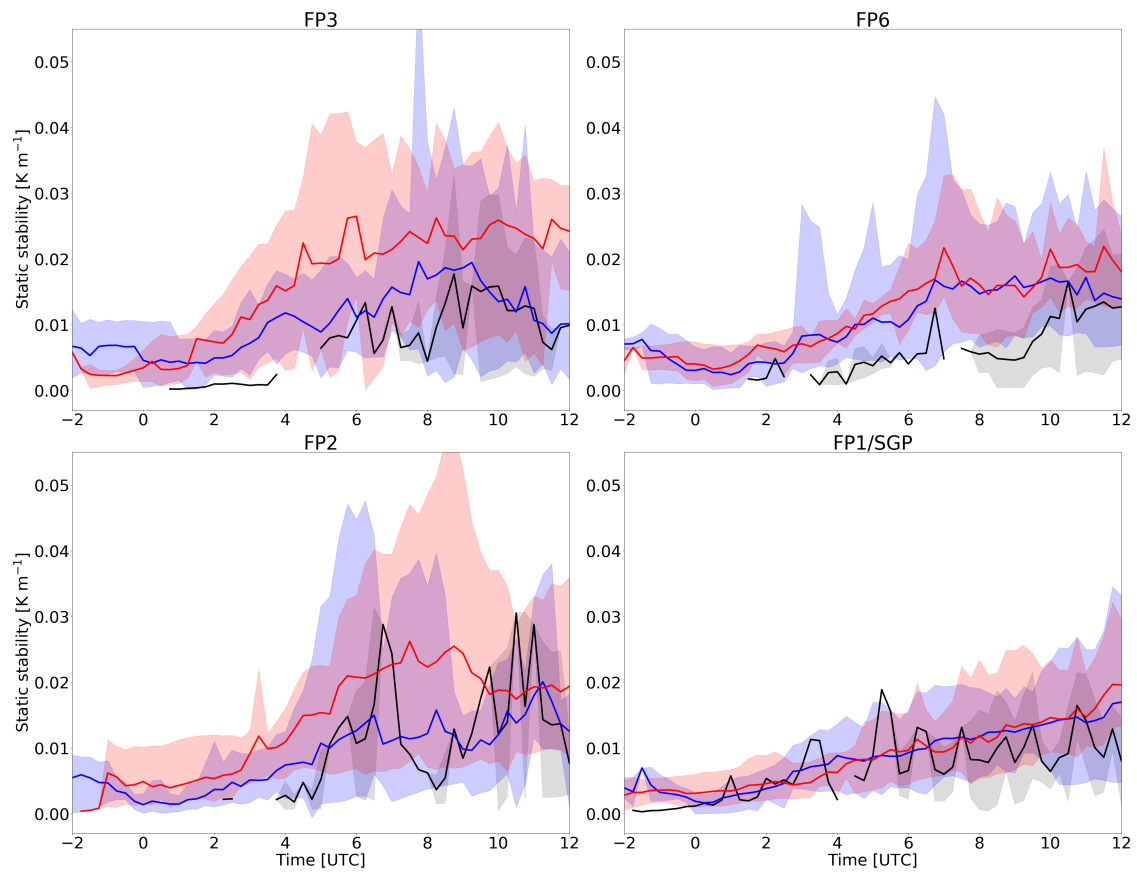


Figure 5.8: As in Fig. 5.3, but showing time series of static stability

increased during the first half of the night, then became steady or even decreased by the end of the night over western sites. At eastern sites, static stability gradually increased throughout the night. This differing evolution is consistent with findings from Chapter 4 concerning advection. As the NLLJ evolves in space and time, the westerly component becomes significant and contributes to advection. The stronger westerly components are expected to form first in the west and act to advect warmer potential temperatures from west to east, thus warming upper levels. This warming above the NLLJ was apparent in several observed and simulated potential temperature fields shown in previous sections. Eventually the core zone of the NLLJ moves east and advection is weaker at the western sites, which explains the more steady static stability later in the period. However at the eastern sites, the core zone of the NLLJ continues to move toward the east and westerly components develop further east. The contribution of westerly advection is thus seen later and lasts longer into the night. Additionally, the absence of the strongest NLLJ winds over the eastern sites allow a more defined SBL to form which further contributes to increased static stability throughout the night.

These analyses showed that the spatial-temporal NLLJ evolution identified in Chapter 4 is fairly common in the 14-case Great Plains NLLJ dataset considered here. All but two cases were categorized and clear or similar NLLJ cases. Using these categories, additional characteristics of the NLLJ spatial-temporal evolution were identified and related to local NLLJ evolution. Spread in the cases marked similar suggest that individual cases may present varying degrees of similarity to the identified spatial-temporal NLLJ evolution. These cases may be more or less heterogeneous, and were often modulated by synoptic scale boundaries in the region. In this section, it has been established that the previously described NLLJ spatial-temporal evolution is not rare. We still have not identified the source of spatial heterogeneity in the NLLJ or the effects of buoyancy.

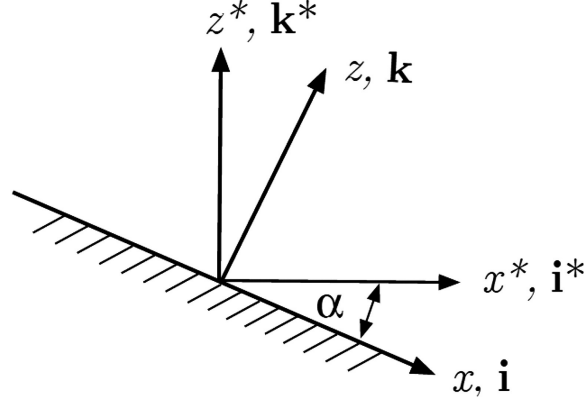


Figure 5.9: The slope following coordinate system used in the one-dimensional model of NLLJ dynamics proposed by Shapiro et al. (2016) (adapted from their Fig. 1).

5.3 Buoyancy and NLLJ evolution

In the previous section and previous chapters, it has been shown that the NLLJ is a dynamic feature moving across the Great Plains overnight. Up to this point, little to no physical reasoning for why this occurs has been offered. Previous studies, mostly analytical approaches, have pointed to buoyancy as a driving feature in NLLJ dynamics (Shapiro et al. 2016; Fedorovich et al. 2017; Gebauer et al. 2017, 2018). This section will present a brief and general discussion about buoyancy's potential role in forcing dynamic behavior of the NLLJ over the Great Plains.

A one-dimensional model for NLLJ dynamics was initially proposed in Shapiro et al. (2016) (and later summarized in Gebauer et al. 2017) based on the Boussinesq equations of motion and thermal energy in slope-following coordinates (see Fig. 5.9):

$$\frac{\partial u}{\partial t} = f(v - v_g) - b \sin \alpha + K \frac{\partial^2 u}{\partial z^2}, \quad (5.1)$$

$$\frac{\partial v}{\partial t} = -fu + K \frac{\partial^2 v}{\partial z^2}, \quad (5.2)$$

$$0 = -\frac{\partial \Pi}{\partial z} + b \cos \alpha, \quad (5.3)$$

and

$$\frac{\partial b}{\partial t} = uN^2 \sin \alpha - \delta b + K \frac{\partial^2 b}{\partial z^2}, \quad (5.4)$$

where x and z indicate the along-slope and normal directions, respectively. Figure 5.9 shows these coordinates compared to their true horizontal and vertical counterparts, marked as x^* and z^* . The slope angle is denoted by α and is treated as 0.1° to approximate the slope of the Great Plains. The x - and y -components of the wind are represented by u and v , respectively. Buoyancy is represented by b and Π is the normalized pressure perturbation. The Coriolis parameter is defined as $f \equiv 2\Omega \cdot \hat{k}$, where Ω is the angular velocity of Earth's rotation and $\hat{k}$ is the z -direction unit vector. The geostrophic wind associated with the perturbation pressure gradient is defined as $v_g = \frac{1}{f} \frac{\partial \Pi}{\partial x}$ and K denotes the eddy diffusivity, treated here as height independent and equal for momentum and heat. Boundary conditions at the surface are

$$u(0, t) = 0, v(0, t) = 0, b(0, t) = b_s(t), \quad (5.5)$$

where $b_s(t)$ is a diurnally periodic function. Upper boundary conditions are implemented far from the slope as

$$\lim_{z \rightarrow \infty} u = 0, \lim_{z \rightarrow \infty} v = v_{g\infty} = \frac{1}{f} \left(\frac{\partial \Pi}{\partial x} \right)_\infty, \lim_{z \rightarrow \infty} b = 0. \quad (5.6)$$

The subscript ∞ is used to clarify the difference between local geostrophic wind, v_g , and the free atmosphere geostrophic wind far above the surface, $v_{g\infty}$. The upper boundary conditions result in spatially and temporally constant $v_{g\infty}$. Taking $\frac{\partial}{\partial x}$ of eq. 5.3, dividing by f , and reordering the order of differentiation gives $\frac{\partial v_g}{\partial z} = 0$. At most, v_g could be a function of x or t . Boundary conditions in eq. 5.6 require that v_g cannot be a function of x or t , thus v_g must be equal to the free atmospheric value $v_{g\infty}$.

The buoyancy profile can be defined as

$$b(z) = \frac{g}{\theta_0} (\theta_v(z) - \theta_{v_r}(z)), \quad (5.7)$$

where g is the gravitational acceleration, θ_0 is a constant reference potential temperature, $\theta_v(z)$ is the virtual potential temperature, and $\theta_{v_r}(z)$ is a reference profile of virtual potential temperature. In this application, we find $\theta_{v_r}(z)$ by taking the average free atmosphere θ_v

across the slope and the environmental lapse rate, $\frac{\partial \theta_{vr}}{\partial z}$, that satisfies a prescribed Brunt-Vaisala frequency ($N = \sqrt{\frac{g}{\theta_0} \frac{\partial \theta_{vr}}{\partial z}}$) of 0.01. Buoyancy is an important component to NLLJ dynamics over the Great Plains because the Great Plains are sloped, leading to the tilted coordinate system shown in Fig 5.9. Buoyant accelerations still act along the true vertical direction (z^*), but in tilted coordinates buoyant accelerations have components along the slope-normal z and along-slope x directions. This can be illustrated by considering the case with no slope ($\alpha = 0$). In this case, eq. 5.1 can be written

$$\frac{\partial u}{\partial t} = -fv_{g_\infty} + fv + K \frac{\partial^2 u}{\partial z^2}. \quad (5.8)$$

Since the slope angle in this case is zero, buoyancy does not enter eq. 5.8, and the local geostrophic wind in the boundary layer, V_g , is equal to the free atmosphere geostrophic wind v_{g_∞} . In this case, the NLLJ would develop as described by Blackadar (1957). An ageostrophic wind component develops during the day due to friction force acting via eddy diffusivity. Eddy diffusivity decreases at sunset, and the ageostrophic wind oscillates around the constant geostrophic wind. In the case of an eastward-facing slope with $\alpha > 0$, eq. 5.1 becomes

$$\frac{\partial u}{\partial t} = -fv_{g_\infty} - b \sin \alpha + fv + K \frac{\partial^2 u}{\partial z^2}. \quad (5.9)$$

Here, the local geostrophic wind in the boundary layer is given by

$$V_g(z, t) = v_{g_\infty} + \frac{1}{f} b \sin \alpha, \quad (5.10)$$

the sum of the constant free atmosphere geostrophic wind and the contribution from buoyancy along the sloped surface. Since buoyancy can vary in time and height, the PBL geostrophic wind, V_g must also vary in time and height. When the NLLJ is oriented from the south (and thus, $v_{g_\infty} > 0$) the PBL geostrophic wind V_g will be at a maximum when b is at a maximum, and at a minimum when b is at a minimum.

Based on the case with an eastward-facing slope, like that of the Great Plains, two buoyancy related drivers of NLLJ evolution can be described. First, differential PBL geostrophic

wind due to gradients of buoyancy along the slope can be connected to observed and simulated NLLJ features. Second, temporal evolution of u -component velocity due to temporal buoyancy evolution can be connected to observed and simulated east-west motion of the NLLJ.

5.3.1 Buoyancy related driver I: differential PBL geostrophic wind

Observations and simulations of NLLJ cases along the slope of the Great Plains frequently showed the boundary layer to be deeper over the western portion of the slope. Perhaps related to land use and climatologically drier conditions in the west, convective mixing apparently occurs over a deeper layer in the west. Warmer conditions through the boundary layer depth allow buoyancy (defined in eq. 5.7) to reach larger magnitudes over the western portion of the slope compared to the east. This can be demonstrated via buoyancy gradients from simulations of the 14 PECAN and LABLE NLLJ cases shown in Fig. 5.10. The buoyancy gradient was computed between a west (36.5° latitude, -100° longitude) and east (36.5° latitude, -95° longitude) site. For clear cases, the mean gradient and the spread of gradient values remained negative throughout the night. This means that in the cases where the previously identified NLLJ temporal-spatial evolution was most clear, the buoyancy gradient was always negative along the slope of the Great Plains. The mean gradient value also remained negative throughout the night during cases categorized as similar, but the spread shows some periods during which the buoyancy gradient changed sign. Recognizing that several cases described in Appendix section A.3 included frontal boundaries, it is not surprising that the sign of the gradient sometimes switched.

Since x is defined as positive to the east along the slope, a negative buoyancy gradient indicates that buoyancy values are smaller in the east than in the west. Larger buoyancy magnitudes in the west contribute to greater values of PBL geostrophic wind, V_g in eq. 5.10. Stronger V_g in the west leads to a stronger inertial oscillation as described by Blackadar (1957), and thus a stronger NLLJ maximum in the west as shown in the left panel of Fig.

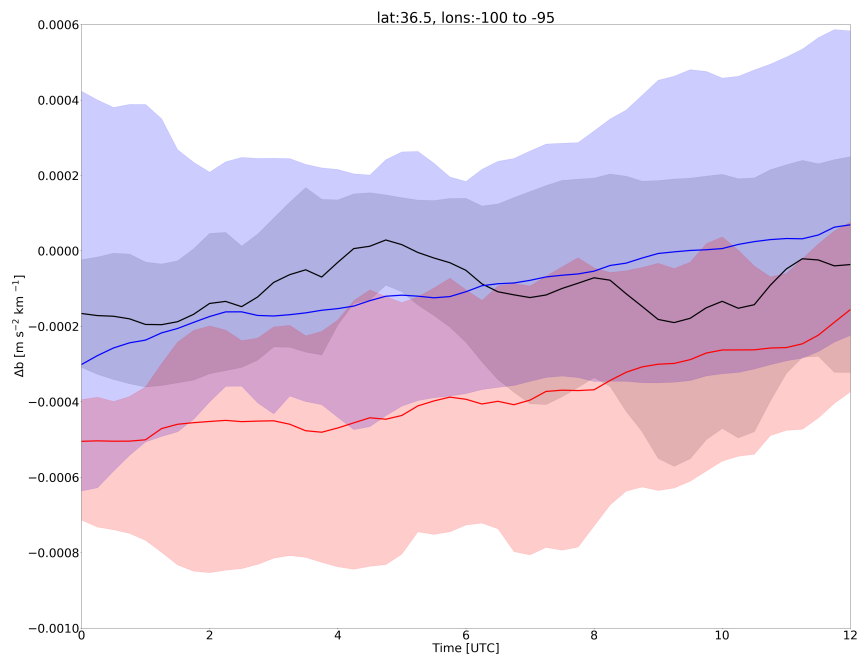


Figure 5.10: Buoyancy gradients for clear (red), similar (blue), and unclear (black) NLLJ case categories with the line denoting the average among each category and the colorfill showing the spread among the cases.

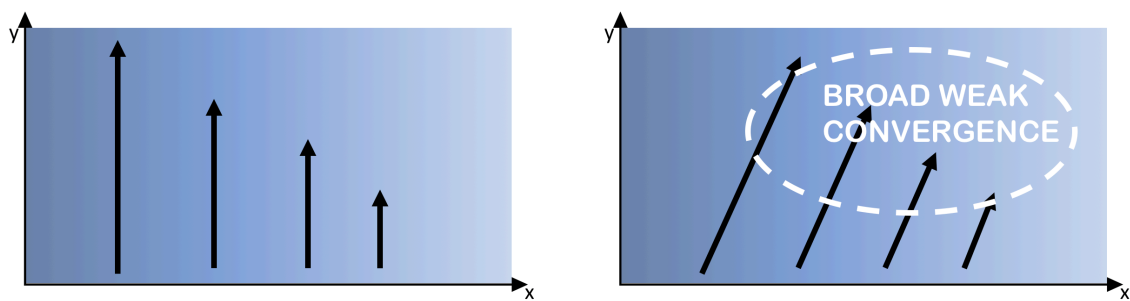


Figure 5.11: Schematic showing NLLJ vectors resulting from a differential PBL geostrophic wind overlaid on a buoyancy gradient (colorfill) where darker shades indicate greater buoyancy values just after sunset (left) and later in the night (right).

5.11. The NLLJ has been known to veer with time due to the inertial oscillation (Blackadar 1957). The associated change of wind direction combined with the differential potential NLLJ magnitude can cause broad convergent regions within the NLLJ to evolve in time as shown in the right panel of Fig. 5.11 (Bonner 1966).

5.3.2 Buoyancy related driver II: temporal u -component evolution

The time tendency of u -component velocity on an eastward-facing slope is described in eq. 5.9. The first two terms on the right hand side can be taken together as they were in eq. 5.10 as the PBL geostrophic wind. Using the definition of the background geostrophic wind, this can be rewritten as

$$V_g = \frac{1}{f} \frac{\partial \Pi}{\partial x} - b \sin \alpha, \quad (5.11)$$

where the term $\frac{1}{f} \frac{\partial \Pi}{\partial x}$ represents the background geostrophic wind as forced by the pressure gradient. For $\frac{\partial u}{\partial t}$ to be non-zero, V_g must change, assuming that eddy diffusivity (K) is constant and we consider timescales short enough to disregard turning of the v -component by the Coriolis force. If background conditions are quiescent, changes in $\frac{\partial \Pi}{\partial x}$ should remain small enough to neglect, meaning any change in V_g would be due to change in b . Moreover, if b changes at different rates at different locations along the slope, $\frac{\partial u}{\partial t}$ would evolve differently at different locations.

To evaluate evolution of the NBL and NLLJ through the night composite perturbation profiles were constructed at the same west (36.5° latitude, -100° longitude) and east (36.5° latitude, -95° longitude) sites used to compute buoyancy gradients. This method defined a perturbation as a deviation from the overnight mean state

$$A'(t, z) = A(t, z) - \overline{A(z)}, \quad (5.12)$$

where A is the time varying vertical profile of a chosen atmospheric variable, A' denotes the perturbation quantity, and $\overline{A}$ represents the temporally averaged profile for the overnight

period (00-12 UTC). These perturbation profiles are computed for buoyancy (b), virtual potential temperature (θ_v), u -component velocity, and v -component velocity. Then, perturbation profiles are composited by averaging across all cases according to case category (clear, similar, unclear). A positive (negative) perturbation tells us that the chosen atmospheric variable's magnitude is larger (smaller) than the mean state. Composite perturbation profiles for buoyancy, virtual potential temperature, u -component velocity, and v -component velocity are shown in Figs. 5.12, 5.13, 5.14, and 5.15 respectively.

First, it is clear that perturbation profiles of b and θ_v are identical. This makes sense as the definition of b (eq. 5.7) is simply a deviation from a reference state multiplied by constants. The magnitude of the reference state and constants are removed in the composite perturbation method, leaving identical composite perturbation profiles. Since temperature and perturbations to the temperature field are more tangible than buoyancy to the average reader, further discussion will focus on the change in the virtual potential temperature profiles (Fig. 5.13).

In both clear and similar cases shown in Fig. 5.13, it is apparent that the overnight cycle of virtual potential temperature near the surface is larger in the west. Strongly positive perturbations early in the night give way to strongly negative perturbations late in the night below 250 m AGL. A similar pattern (positive to negative perturbation) is apparent at the eastern site, but the magnitude of the cycle is smaller, and it takes longer for the perturbation to become negative. The main difference between clear and similar cases manifests above 250 m AGL. In the clear cases at the west site, the pattern in perturbation evolution reverses above 250 m AGL. Instead of trending from positive perturbations early to negative perturbations later, perturbations are initially negative at this level and above, trending toward positive perturbations late in the night. A similar reversal of pattern is evident in clear cases at the east site, but less pronounced in magnitude. The trend also reverses aloft for similar cases, but the range of values is much smaller and the reversal tends to occur at a level more removed from the surface.

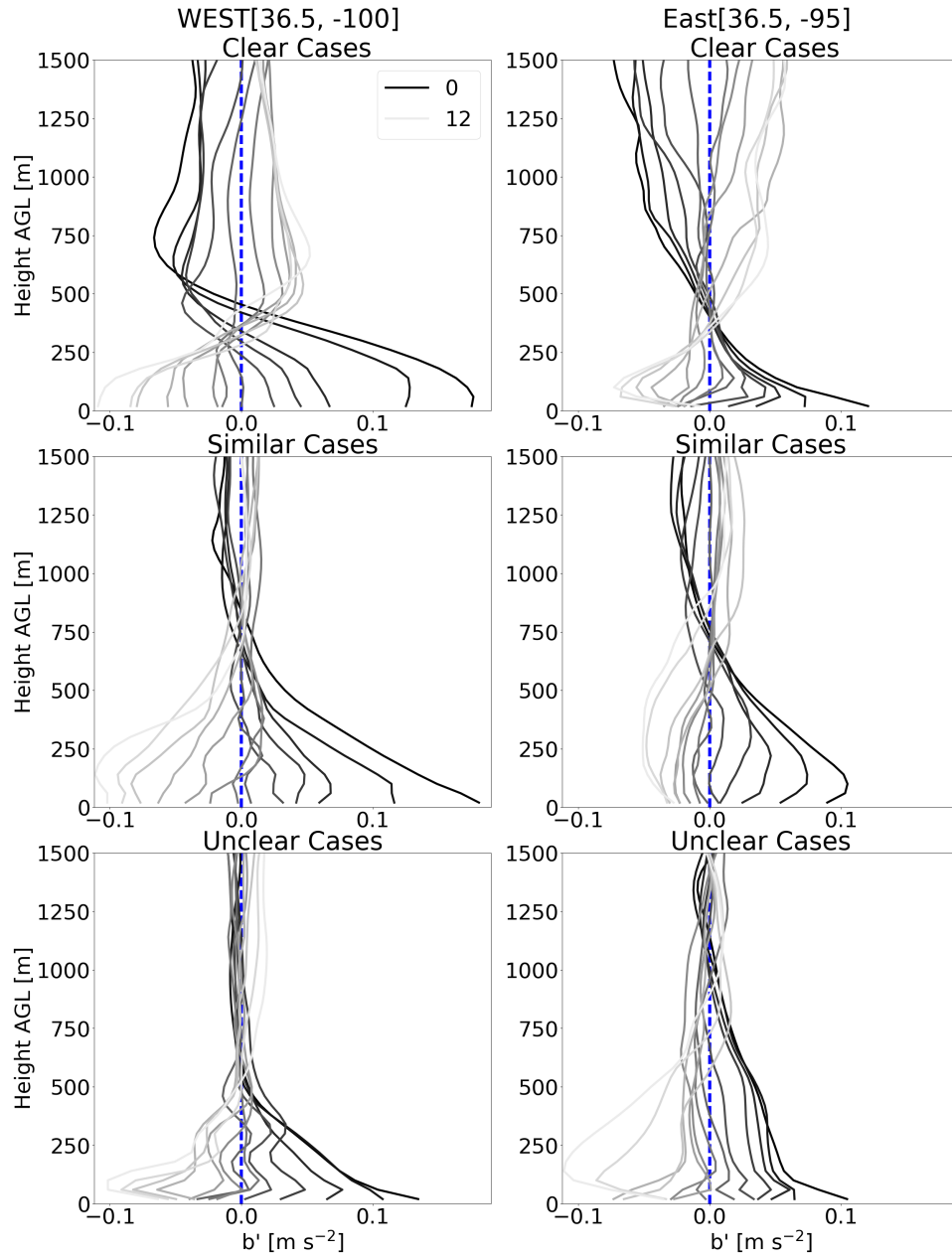


Figure 5.12: Composite perturbation profiles of buoyancy. Darker shades indicate earlier times during the night.

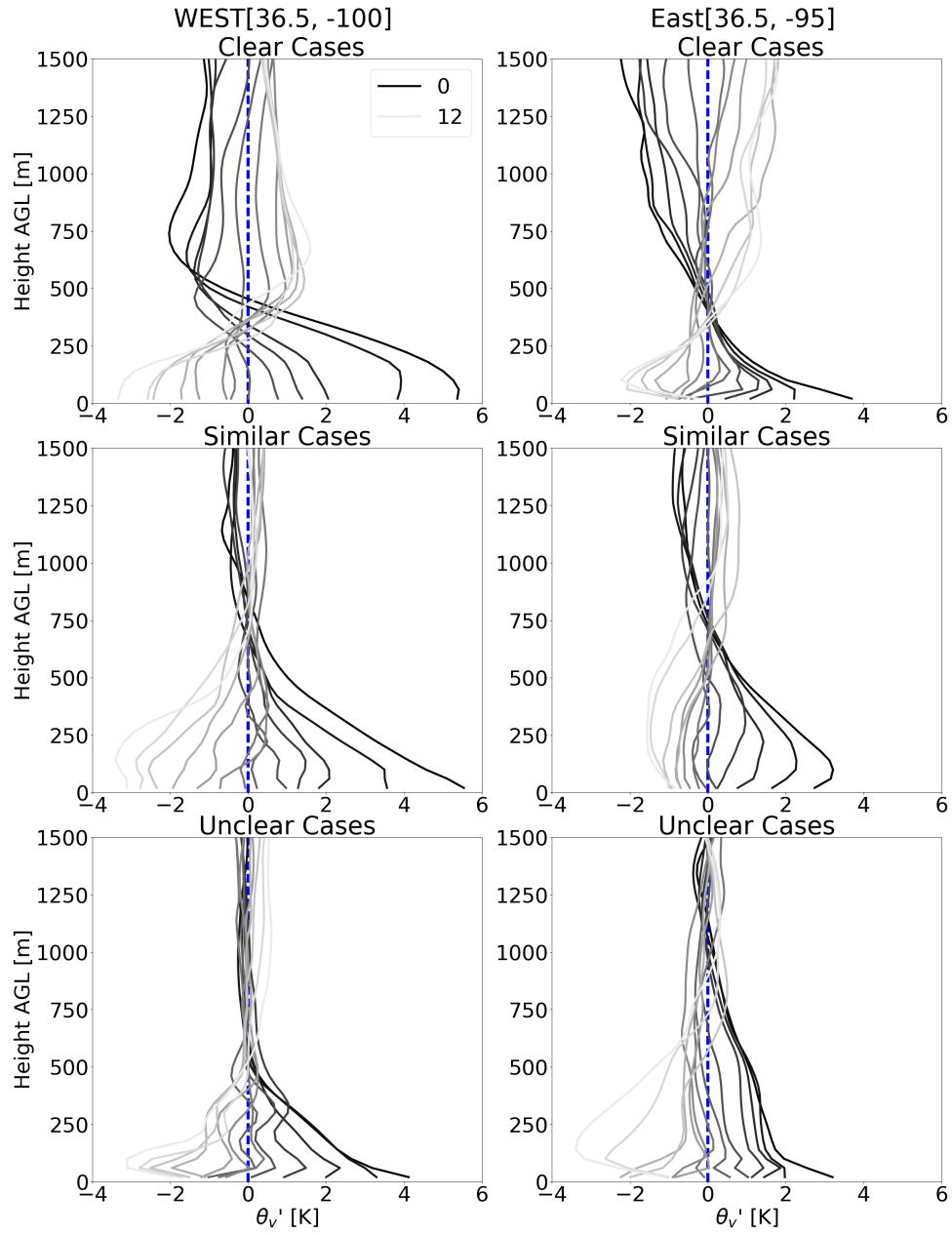


Figure 5.13: As in Fig. 5.12, but for virtual potential temperature.

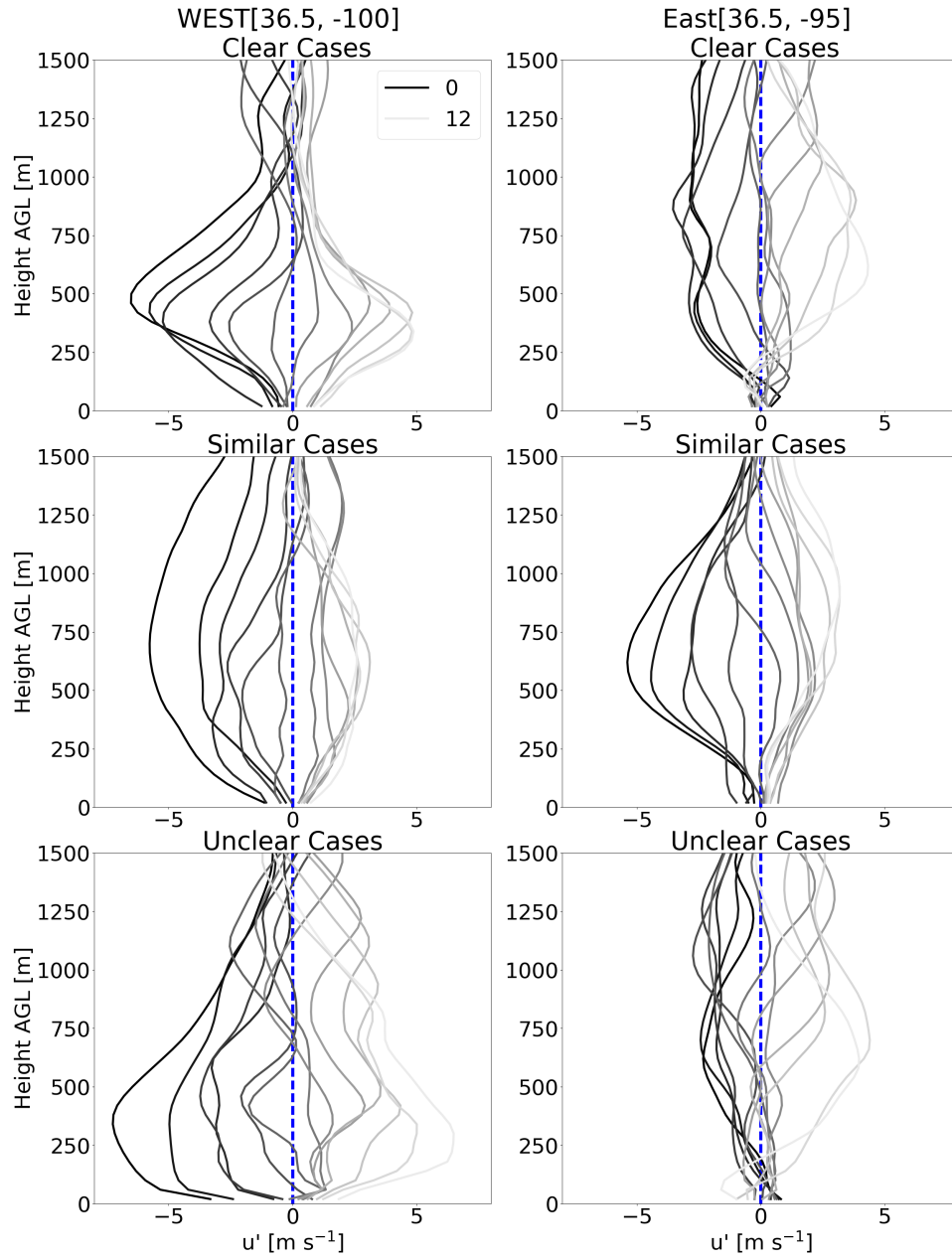


Figure 5.14: As in Fig. 5.12, but for u -component velocity.

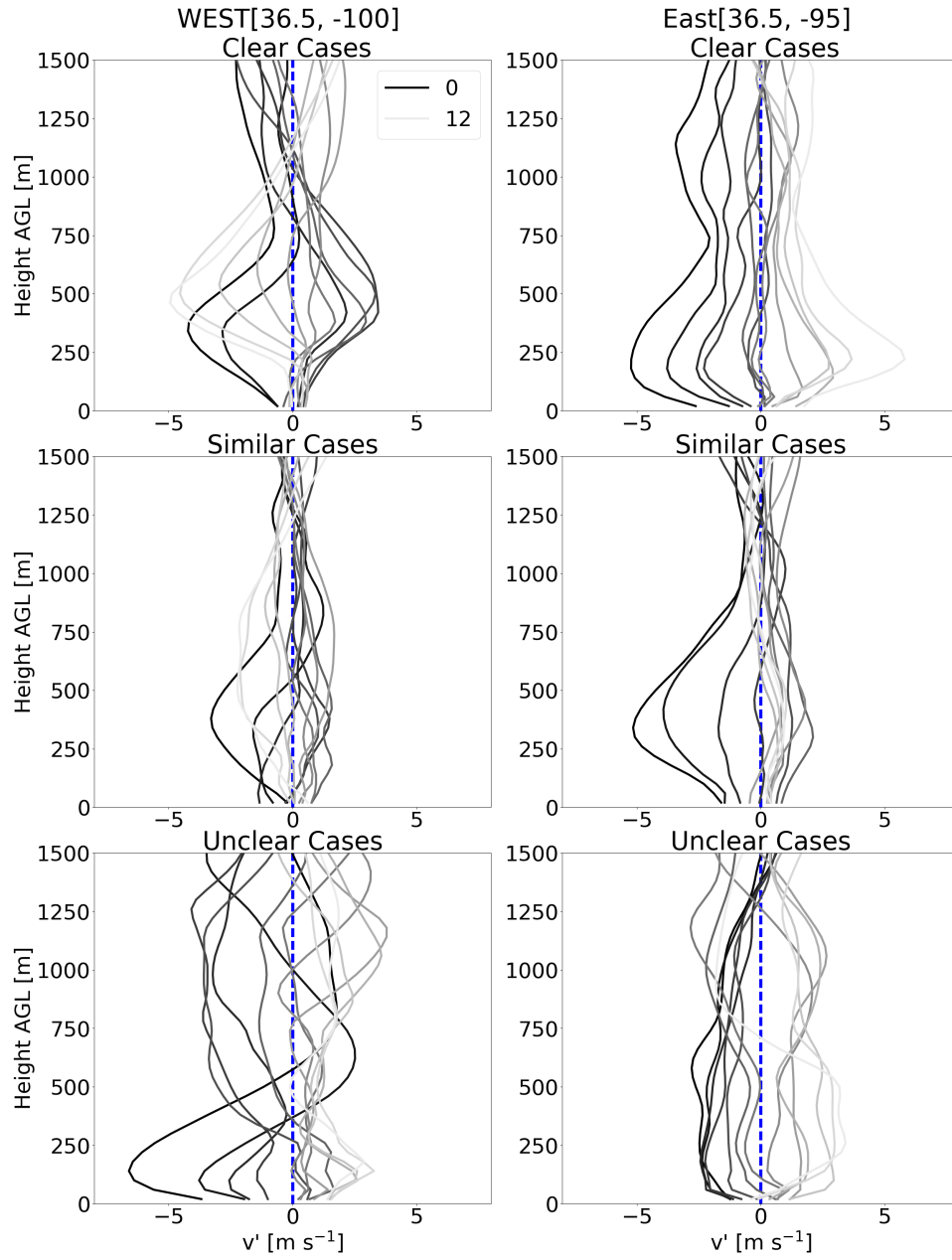


Figure 5.15: As in Fig. 5.12, but for v -component velocity.

Composite perturbation profiles for u -component velocity in Fig. 5.14 can be related to the evolution of composite perturbation profiles for θ_v in Fig. 5.13 (and thus b in Fig 5.12). In the layer between 250 and 750 m at the west site for clear cases, u' profiles show the most pronounced overnight cycle from strongly negative, to strongly positive. The same pattern, though less drastic, is evident in the same layer at the west site for similar cases. As the u -component strengthens in the layer above 250 m AGL, downslope winds increase buoyancy through advection of environmental potential temperature as required by the first term on the right hand side of eq. 5.4 ($uN^2 \sin \alpha$) leading to the more dramatic swing in θ_v' and b' profiles at the west site for clear cases. At the east site, the cycle in u' profiles is generally less pronounced, and occurs over a deeper layer from about 250 to 1000 m AGL. Since θ_v and thus b changes more rapidly in the west during the clear cases, eq. 5.11 requires that V_g would change and therefore $\frac{\partial u}{\partial t}$ in eq. 5.9 would be greater in the west than in the east. Composite perturbation profiles for v -component velocity in Fig. 5.15 do not show clear connection to temporal evolution of buoyancy, and no clear pattern is evident when comparing eastern profiles to western profiles or different categories.

It is important to note that a gradient in buoyancy should lead to the generation of positive y -component vorticity. This vorticity then leads to u -component velocity increasing with height above the surface. This can be demonstrated via the y -component vorticity equation in terms of pressure perturbations and buoyancy under the Boussinesq approximation as written in Markowski and Richardson (2011)

$$\frac{\partial \eta}{\partial t} = -\mathbf{v} \cdot \nabla \eta + \boldsymbol{\omega} \cdot \nabla v + f \frac{\partial v}{\partial z} - \frac{\partial b}{\partial x} + \hat{j} \cdot \nabla \times \mathbf{F}, \quad (5.13)$$

where $\eta = (\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x})$ is the y component of vorticity, $\mathbf{v}$ is the full velocity vector, $\boldsymbol{\omega}$ is the full vorticity vector, and F is the viscous force. The buoyancy term on the right hand side shows that a negative buoyancy gradient leads to a positive contribution to the time rate of change of y -component vorticity, η . Since $\eta = (\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x})$, we can expect that a positive rate of change of η can then lead to an increase in $\frac{\partial u}{\partial z}$, and the u -component velocity will be enhanced with height. This effect can explain why the upper portion of the NLLJ develops

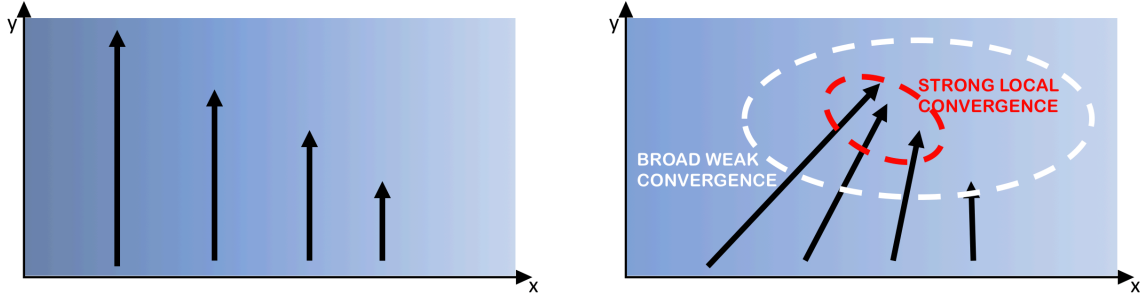


Figure 5.16: Schematic showing NLLJ wind vectors overlaid on a buoyancy gradient (col-orfill) where darker shades indicate greater buoyancy values just after sunset (left) and later in the night (right).

the stronger u -components and the top portion of the NLLJ is advected downslope earlier in the night.

Differential $\frac{\partial u}{\partial t}$ driven by temporal evolution of buoyancy along the slope of the Great Plains can act to enhance broad convergence described in Sect. 5.3.1 and Fig. 5.11. The schematic in Fig. 5.16 shows the combined effect of a background buoyancy gradient (as described in 5.3.1) and differential temporal evolution of buoyancy as described in the present section. As buoyancy (or virtual potential temperature) changes more rapidly in the west, $\frac{\partial u}{\partial t}$ becomes more significant in the west than the east leading to stronger u -component velocity earlier in the night. The wind vector, which is already stronger in the west due to the background buoyancy gradient (as shown in the left panel of Fig. 5.16), veers more in the west leading to local regions of enhanced convergence (as shown in the right panel of Fig. 5.16).

5.4 Conclusions

Analysis in Chap. 4 identified the connection between spatial and temporal characteristics of NLLJs via detailed analysis of PECAN IOP12 and comparison to additional PECAN cases. In the present chapter, this spatial-temporal evolution was explored in a broader

case set including four PECAN cases and ten LABLE cases using high-resolution simulation data. These 14 cases were first categorized based on how well they represented the identified spatial-temporal resolution; clear cases showed most or all features of the spatial-temporal evolution, similar cases showed some features but were often disturbed by larger scale features, and unclear cases showed no evidence of the identified spatial-temporal evolution. These categories were used to elucidate bulk features and behaviors of Great Plains NLLJs and to answer the following open questions:

- How common is the described spatial-temporal NLLJ evolution?
- What is the source of spatial heterogeneity in the NLLJ?
- What are the impacts of local changes in buoyancy?
- How do buoyancy gradients impact NLLJ evolution?

Time series analysis showed that different NLLJ categories tended to have different evolution. In the clear cases, NLLJ magnitude was shown to increase to a maximum before plateauing and eventually decreasing at western sites. At eastern sites, these cases showed local NLLJ magnitude to continually increase through the night. Likewise, clear cases showed static stability to increase early in the period before becoming constant or decreasing in the west, while eastern sites showed slow and steady increase in static stability. These local temporal evolution features were connected to the larger spatial evolution of the NLLJ. In clear cases, the NLLJ is expected to move from west to east down the slope overnight. As this occurs, the core zone of strongest NLLJ winds moves as well. Locally, this means western sites would experience their maxima earlier and then expect a decline in wind speed while eastern sites continually increase until the strongest winds arrive late in the night. As the NLLJ veers, westerly advection is also expected to become significant, bringing in warmer potential temperatures from upslope regions in the layer above the NLLJ maximum. This advection can be directly related to static stability increases. As was the case for NLLJ peak winds, it is expected that westerly advection would reach a

maximum earlier in the night in the west while continuing to increase to a late maximum in the east. Static stability was also shown to be potentially enhanced in the east since those sites have time to form a classic SBL before the NLLJ (a producer of shear turbulence) becomes strong as opposed to the west where the NLLJ is strong soon after sunset. This analysis showed that the spatial-temporal NLLJ evolution and associated characteristics identified in Chapter 4 are not rare.

To answer the remaining open questions, two buoyancy drivers were identified and described: differential geostrophic wind and temporal u -component evolution. The differential geostrophic wind driver related climatologically warmer conditions and deeper boundary layers in the western Great Plains to buoyancy gradients along the slope. Assuming background large-scale geostrophic wind is unchanged, higher magnitudes of buoyancy in the west result in stronger PBL geostrophic wind. Based on inertial oscillation theory, stronger PBL geostrophic wind leads to stronger NLLJ magnitudes in the west. Thus, spatial heterogeneity of the NLLJ can be connected to buoyancy gradients. The second buoyancy driver is forced by more rapid local changes in buoyancy in the west compared to the east. As buoyancy changes more quickly, the time rate of change of u -component velocity must change in response, leading to enhanced turning of (already stronger due to the first driver) NLLJ winds in the western portion of the Great Plains. This enhanced veering can lead to heterogeneity in the NLLJ, locally strong convergence regions, and associated vertical motions.

Chapter 6

Summary and Conclusions

The boundary layer is a complex and still poorly understood portion of our atmosphere. Complexity of the boundary layer is due in part to the broad range of important scales of motion. Boundary layer features are critically important as human life exists in this layer and it remains as a source of error and uncertainty in atmospheric prediction. The NLLJ is a boundary layer feature which forms in several locations around the globe, but has a maximum frequency in the United States Great Plains. NLLJs are important to local climatology, daily weather, atmospheric transport, and several human industries such as aviation and wind energy. NLLJ and, more generally, boundary layer studies have historically lacked in either temporal or spatial resolution. These limitations were due in part to the lack of developed observation and simulation systems allowing for high spatial and temporal resolution together. Most of the body of literature to date has focused on NLLJs either as a bulk mesoscale feature or as a local phenomenon. Rarely have studies investigated the nature of the NLLJ in the Great Plains as a spatially and temporally dynamic feature. In broad terms, this dissertation set out to expand the current understanding of NLLJs in the Great Plains. Using high resolution observations and simulations together, this dissertation documented, described, and analyzed spatial and temporal characteristics of the Great Plains NLLJ.

First, the ability of the WRF model to reproduce NLLJs was evaluated. Using high resolution observations from the LABLE campaign, sensitivity tests were conducted to understand the impact of horizontal grid spacing, vertical grid spacing, and PBL parameterization scheme. Results from this study showed that horizontal spacing finer than 4-km did not offer enough improvement to the resulting simulation to justify computational expense. In some instances, decreasing horizontal spacing degraded the predicted atmospheric state.

Using finer vertical spacing did improve simulations of NLLJ cases. In particular, using a finely spaced non-stretched vertical grid showed large improvements in the simulated NLLJ and PBL structure. This improvement was limited by model stability and computational expense. Finally, aside from a particular sensitivity to model top height in the MYNN scheme, sensitivity to PBL parameterization scheme was generally small. The three evaluated schemes produced statistically similar results. Based on the conducted sensitivity tests, the optimal WRF configuration for NLLJ studies was identified as using a grid with 4-km horizontal spacing, 40-m vertical constant spacing, and using the QNSE PBL parameterization scheme. While the sensitivity to the choice of PBL schemes was small, QNSE's relevant depiction of SBL physics showed additional skill in representing NLLJ evolution. These analyses were covered in Chapter 2, and have been published in Smith et al. (2018a).

Even the best observations and simulations still have their own limitations. Using high resolution and observations as complementary datasets can lead to a more robust analysis. To confirm that the identified optimal WRF configuration can be used in NLLJ analyses, simulations using this configuration were validated against PECAN observations. These NLLJ observations were collected in different locations, during a different season, and using different platforms than the observations used to identify the model configuration. Through this study, interesting NLLJ features were also identified. Simulated NLLJs formed earlier than observations and were too strong early in the night and too weak late in the night. However, the WRF model was able to successfully represent the general structure and evolution of NLLJs and reproduce sudden variation in boundary layer winds, including diagonal striation features in the time-height wind profile. NLLJ height and depth of the NLLJ core were well captured in the simulations, as were potential temperature fields with warm air advection above the NLLJ maximum. The WRF simulations produced similar sudden vertical motions as were found in the observations. This analysis lead to high confidence in using optimally configured WRF simulations alongside high resolution observations for studies of NLLJ features such as those identified above. These analyses were

covered in Chapter 3 and have been adapted as part of a publication in review in Smith et al. (2019).

To better understand the features identified during PECAN NLLJ cases used to validate the optimal WRF configuration, the high resolution simulation data was used alongside high resolution PECAN observations in an in-depth analysis of PECAN IOP12. This case study suggested spatial evolution of the NLLJ could be responsible for sudden changes in NLLJ local structure (e.g., diagonal striations, sudden vertical motions, warm air advection). Plan-view analyses of simulated data showed the NLLJ was moving from west to east down the slope of the Great Plains overnight. This momentum advection was associated with increasing westerly components as the NLLJ veered. Cross-sections along the slope of the Great Plains showed the NLLJ was veering in time and also in height. The veering first occurred near the top of the boundary layer, then proceeded through a deeper layer. This time-height veering was connected to diagonal striations observed from point locations. The NLLJ was shown to be heterogeneous in depth, wind speed, and wind direction. This heterogeneity combined with the motion of the NLLJ was identified as a potential source of localized convergence and associated vertical motion. The spatial and temporal characteristics of the NLLJ were shown to be deeply connected. These analyses were covered in Chapter 4 and have been adapted as part of a publication in review in Smith et al. (2019).

After finding the connection between spatial and temporal features of NLLJ in PECAN IOP12 (and similar features in 2 additional PECAN cases), more cases were investigated in detail to understand how often the identified spatial-temporal NLLJ evolution occurs and to more fully describe characteristics of this evolution. The ten LABLE cases first introduced in Chapter 2 and four PECAN cases were categorized based on similarity to the identified spatial-temporal evolution as either clear, similar, or unclear cases. Time series analyses showed that the identified spatial-temporal NLLJ evolution resulted in differing local NLLJ evolution at different locations along the slope. Finally, buoyancy considerations

were presented to connect NLLJ dynamics to NBL thermodynamic characteristics. Two buoyancy drivers were identified and described: differential geostrophic wind and temporal u -component evolution. The differential geostrophic wind driver can explain greater NLLJ magnitudes in the west based on buoyancy's contribution to PBL geostrophic wind and inertial oscillation theory. The temporal u -component evolution driver can explain enhanced veering in the west based on rapid buoyancy changes in the west forcing the time rate of change of u -component velocity to change in response. When these two drivers are combined, the NLLJ is expected to first veer near the top of the boundary layer in the west. As the u -component increases, non-linear momentum advection (i.e., the $u\frac{\partial u}{\partial x}$ term in advection) can result in the motion of the NLLJ from west to east along the slope. This enhanced veering can also lead to heterogeneity in the NLLJ, locally strong convergence regions, and associated vertical motions. These analyses were covered in Chapter 5 and are planned for limited inclusion in Smith et al. (2019) and in a future publication.

This dissertation used high resolution observations and simulations to describe new spatial and temporal characteristics of the NLLJ. Through this approach, we have learned about the motion of the NLLJ as a dynamic feature moving from west to east down the slope of the Great Plains. We have also documented heterogeneity in NLLJ depth, wind speed, and wind direction. This combined motion and heterogeneity is thought to be a potential source of local convergence and vertical motion which could be connected to nocturnal convection initiation, especially in otherwise pristine cases. To better describe the mechanisms behind these newly identified NLLJ features, buoyancy-related drivers were presented that could explain why NLLJ motion and heterogeneity occurs in the context of existing NLLJ theory.

Unanswered questions remain about what implication these spatial and temporal NLLJ characteristics have on our understanding of turbulence regimes in nocturnal boundary layers. For example, in the included buoyancy considerations, it was generally assumed that eddy viscosity was spatially homogeneous. Of course, this assumption is likely not true

for the real environments considered in this dissertation. Eddy viscosity, and more specifically the rapid reduction in it during the evening transition, is an important component for understanding NLLJ development. Spatial variability in eddy viscosity and how it evolves throughout the night remains poorly understood. The theory on which the buoyancy considerations are based (Shapiro et al. 2016) also has some inherent limitations. A one-dimensional theory cannot represent all features of full physical atmospheric flows. In specific terms, the model is not equipped to include spatial gradients of parameters such as buoyancy. Ongoing work by the authors of Shapiro et al. (2016) hopes to expand the theory to two dimensions and include a prescribed buoyancy gradient. Even with this addition, the theory still will not be able to fully represent true environmental conditions in which gradients themselves may commonly vary across the Great Plains, with multiple maxima and minima. Buoyancy and eddy viscosity may be connected in the NBL, where buoyancy may modulate the spatial and temporal variability of eddy viscosity.

To better understand the physical conditions to inform theoretical and numerical approaches to improve our understanding of NLLJ physics, better observations are needed. In particular, more focused field observations are necessary with a turbulence-oriented measurement strategy on a large spatial scale. Observations like these would allow us to understand how eddy viscosity behaves in time and space before, during, and after the evening transition. Carefully configured observations could also document common buoyancy distributions in the Great Plains and how these relate to NLLJ spatial and temporal evolution. Such data would provide the necessary field data to document phenomena and inform numerical simulation studies including mesoscale simulations, LES, and DNS to begin to address some of the uncertainties described above.

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Appendix A

LABLE Case Descriptions

A.1 Unclear Cases

LABLE cases that took place on 15 October and 23 October 2012 were categorized as unclear cases, meaning they may have locally exhibited NLLJ like features at the SGP/FP1 site, but otherwise do not appear to have NLLJ features on the larger spatial scale. LABLE observations and WRF simulations for each case will be shown to support this categorization.

A.1.1 15 October 2012

Wind speed observed by Doppler lidar and AERI on 15 October is shown in Fig. A.1. At about 0730 UTC, wind speed in the low levels increase and form a very weak NLLJ-like signature lasting to 12 UTC with a maximum wind speed around 12 m s^{-1} . From a point observation, this case could be considered a weak NLLJ that formed late. However, spatial considerations show this case was not a traditional NLLJ. Simulated wind speed at 500 m AGL is shown in Fig. A.2. There was no evidence of a NLLJ forming in the Great Plains on this night. Archived synoptic charts (Fig. A.3) show that the period between 00 and 12 UTC on 15 October 2012 was dominated by a post-frontal air mass over the Great Plains behind a cold front. Winds were oriented mostly from the north as high pressure built into the region. The NLLJ-like signature late in the period over the SGP/FP1 site was related to locally stronger winds moving over the site, not the formation of a NLLJ. As such, this case should not be expected to match the previously identified spatial-temporal NLLJ evolution.

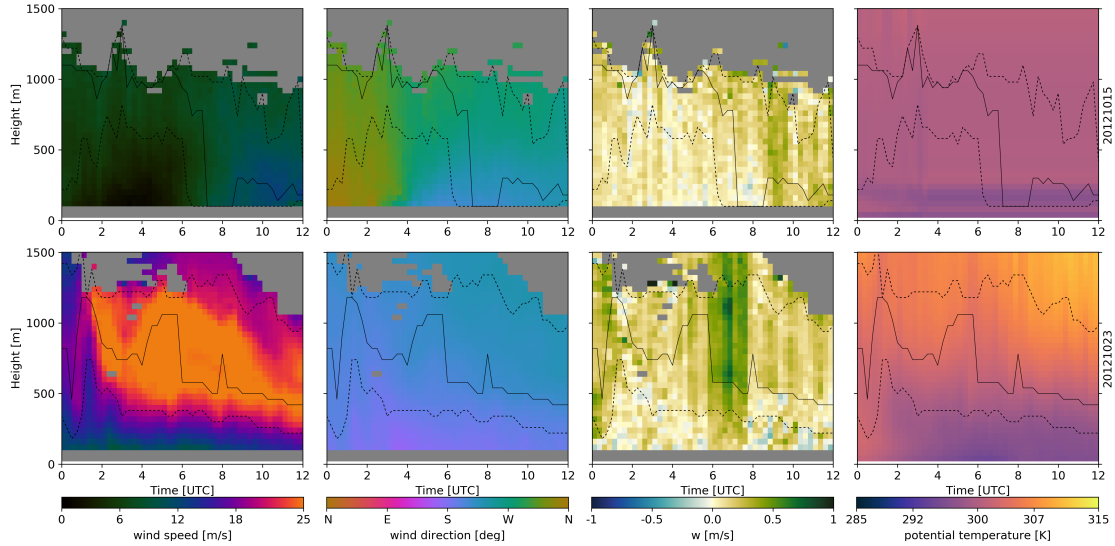


Figure A.1: LABLE observations of wind speed, wind direction, vertical velocity, and potential temperature for cases categorized as unclear.

A.1.2 23 October 2012

Unlike the 15 October case, the Doppler lidar and AERI observations from 23 October 2012 (shown in Fig. A.1) show a clear and strong NLLJ signature throughout the night. Again, simulated wind speed at 500 m AGL on 23 October is shown in Fig. A.4. At 00 UTC, the wind field shows the classic signature of a low pressure system with associated fronts. The center of the low pressure was located near Salina, KS with a cold front draped southward to the west of the SGP/FP1 site and a warm front stretching northeast toward the KS/NE/MO border. A similar signature is evident in the simulated potential temperature field at 00 UTC (Fig. A.5). Throughout the night, the low pressure system migrated east and a secondary low pressure center formed west of the domain. In the region south of the low pressure (i.e., in OK), some evidence of the expected NLLJ evolution (strengthening wind speed and developing westerly component) was apparent in the simulation, but it is unclear if this occurred due to NLLJ physics or synoptic forcing.

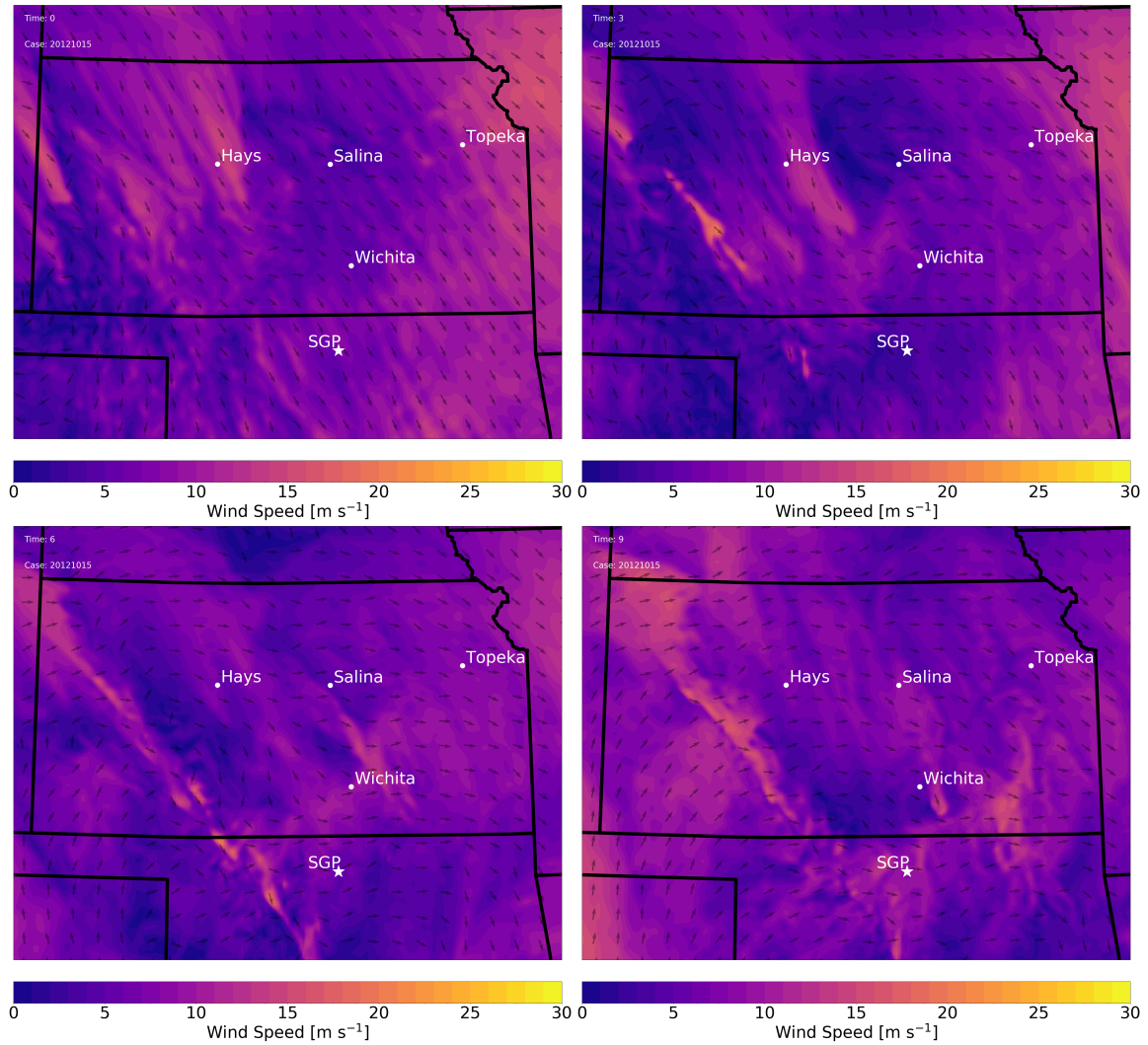


Figure A.2: WRF simulated wind speed at 500 m AGL on 15 October 2012 at 00, 03, 06, and 09 UTC.

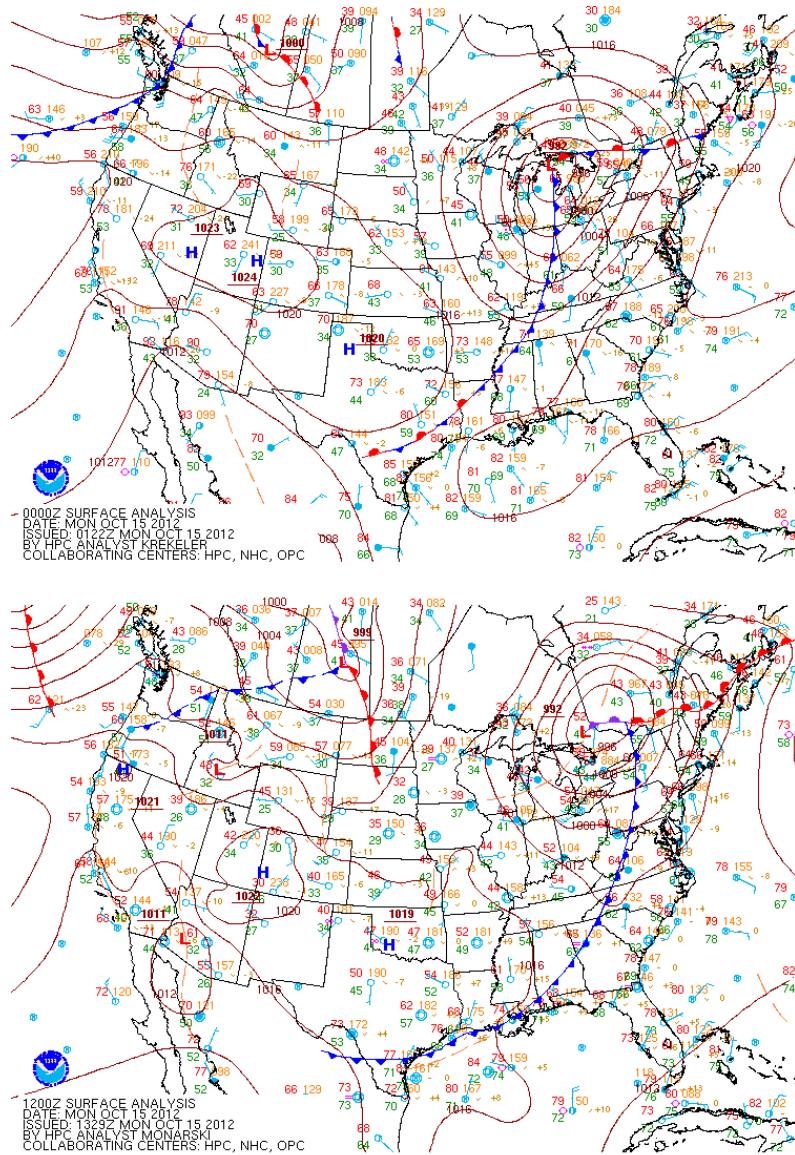


Figure A.3: Surface analyses for 00 and 12 UTC on 15 October 2012 from NOAA's Weather Prediction Center (previously the Hydrometeorological Prediction Center).

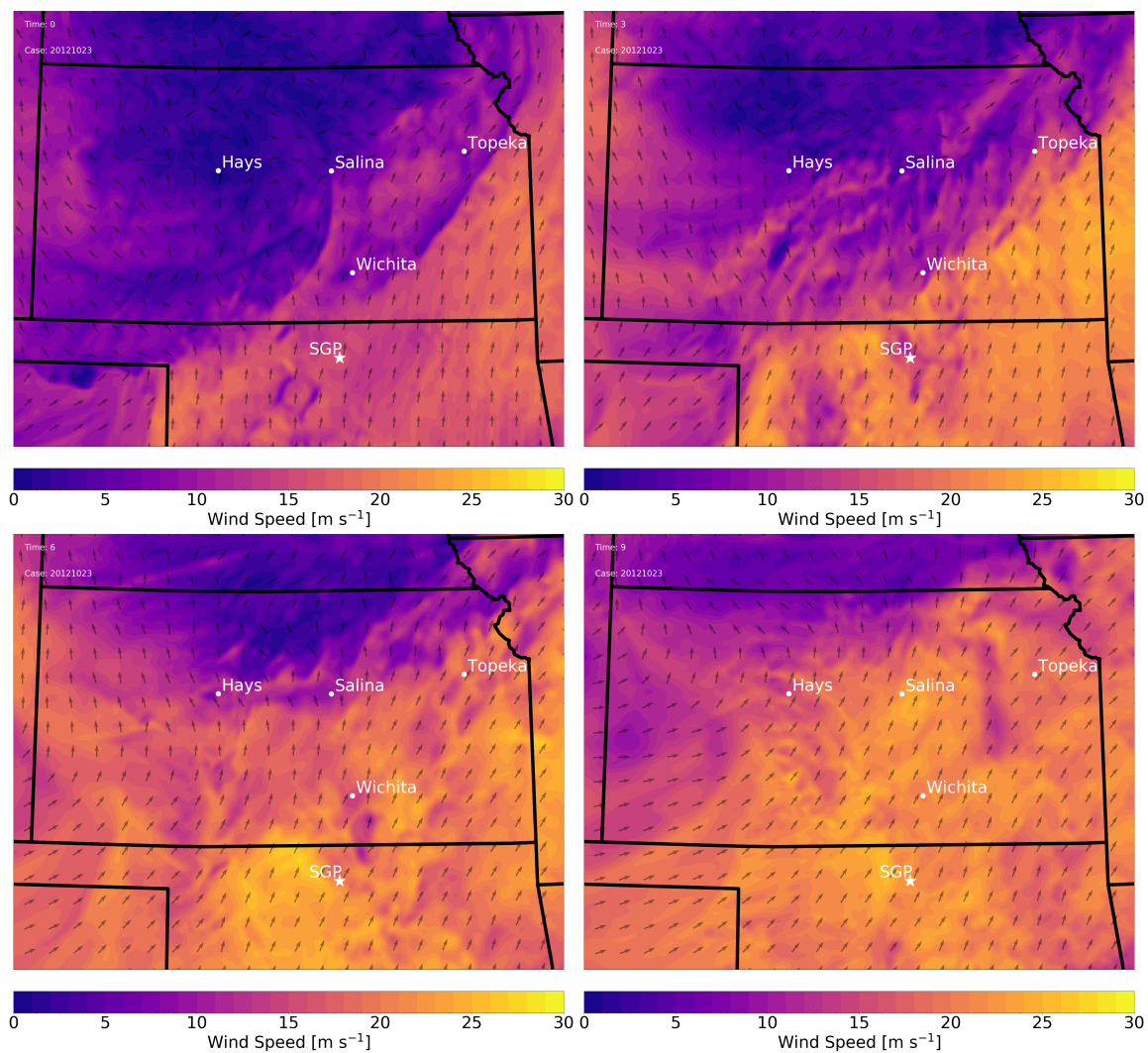


Figure A.4: WRF simulated wind speed at 500 m AGL on 23 October 2012 at 00, 03, 06, and 09 UTC.

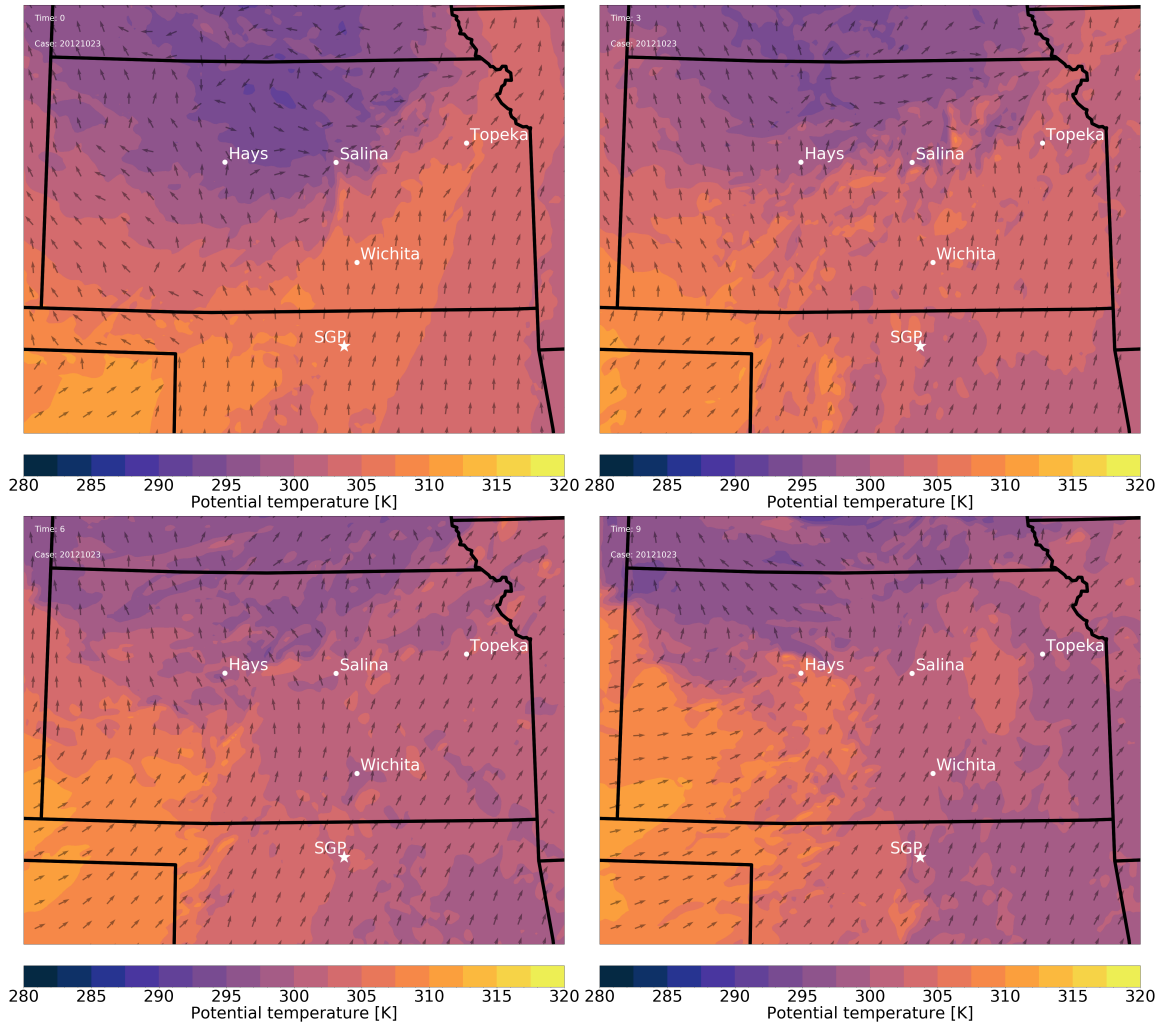


Figure A.5: WRF simulated potential temperature at 500 m AGL on 23 October 2012 at 00, 03, 06, and 09 UTC.

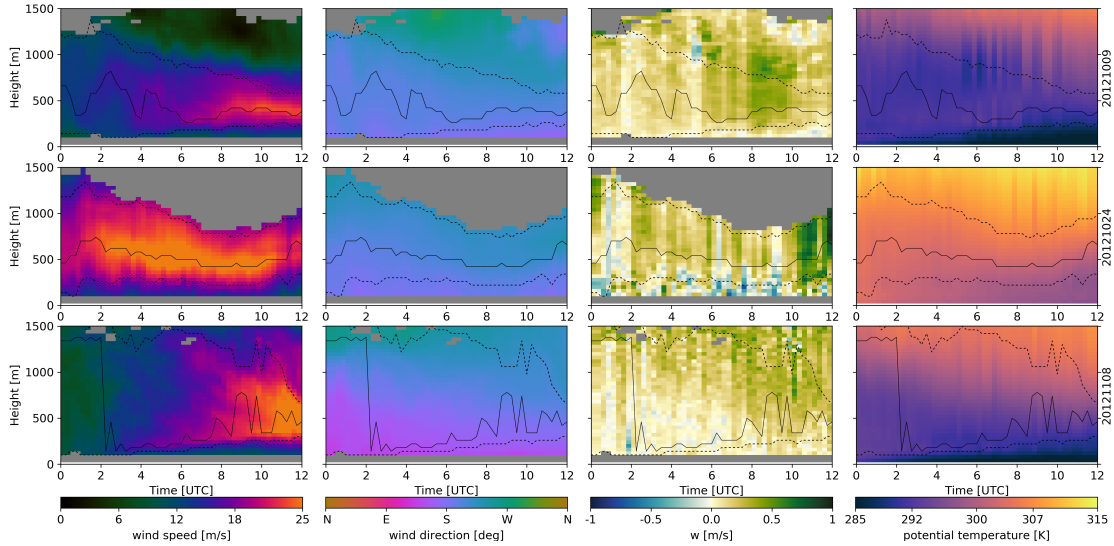


Figure A.6: As in Fig. A.1, but for cases categorized as clear.

A.2 Clear Cases

TABLE cases that took place on 09 October, 24 October, and 08 November 2012 were categorized as clear cases, meaning they have strong similarity to the spatial-temporal NLLJ evolution identified from the PECAN cases including east-west NLLJ motion, local convergence zones, sudden vertical motions, and westerly advection. LABEL observations and WRF simulations for each case will be shown to support this categorization.

A.2.1 09 October 2012

Doppler lidar and AERI observations from 09 October 2012 (Fig. A.6) show a weak broad NLLJ forming around 04 UTC that becomes narrower and stronger overnight. A diagonal striation-like feature is apparent between 04 and 07 UTC in the zone from 900 m to 250 m AGL. An additional similar but smaller (in depth and duration) signature appears between 07 and 08 UTC in the layer between 500 and 300m AGL. After 08 UTC a 2-hour period of weak vertical motion was observed. Wind direction was observed to become more westerly with time and height. The strong warm air advection above the NLLJ noted in PECAN cases was not evident in this case.

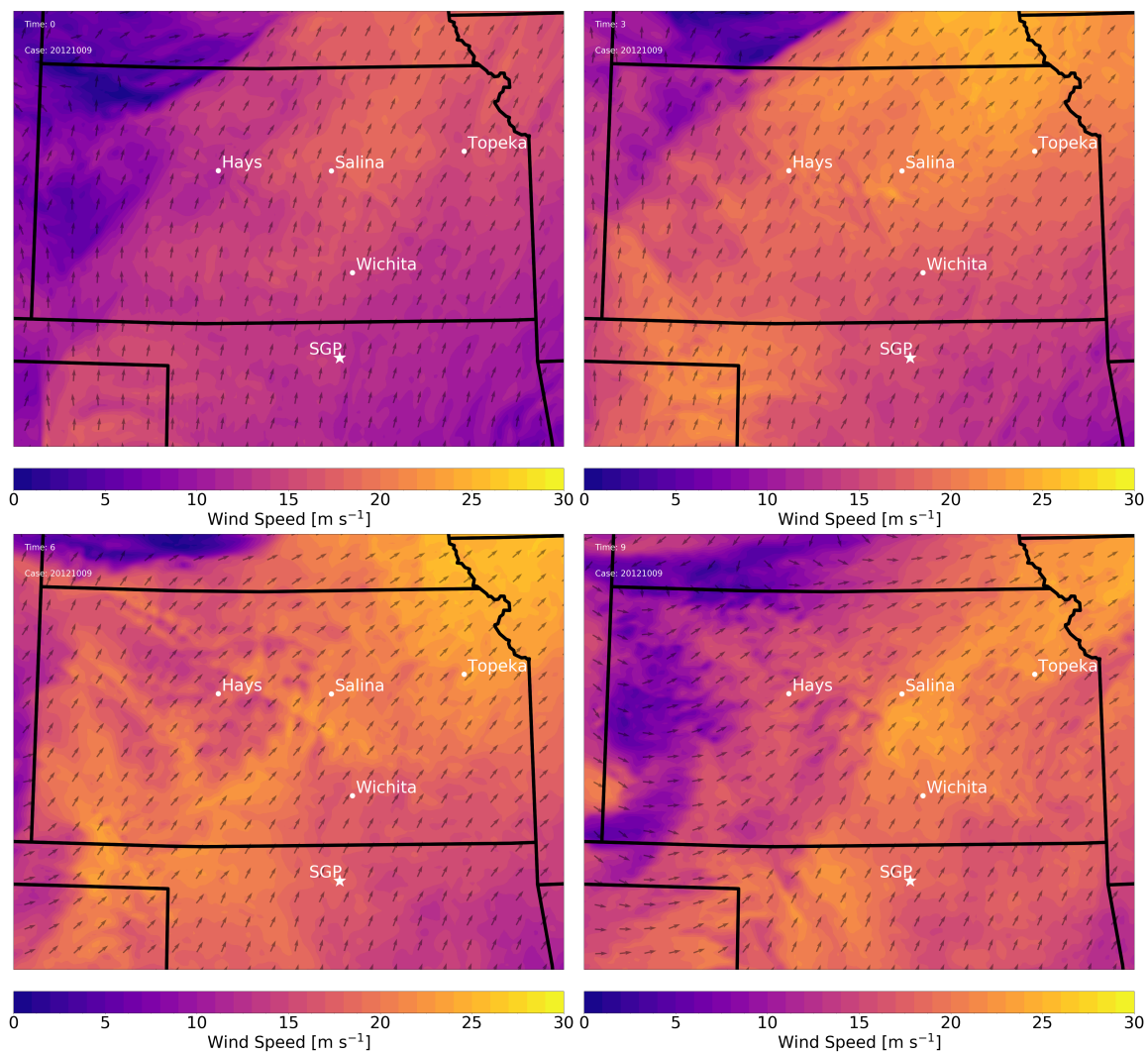


Figure A.7: WRF simulated wind speed at 500 m AGL on 09 October 2012 at 00, 03, 06, and 09 UTC.

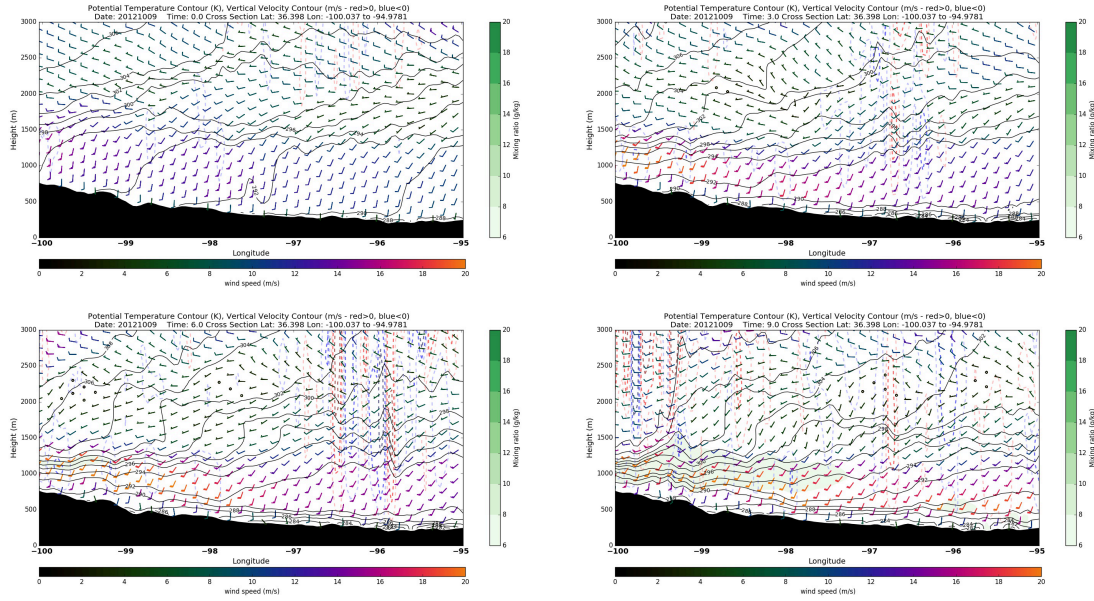


Figure A.8: As in Fig. 4.3 but for 09 October 2012 at 00, 03, 06, and 09 UTC.

Simulated wind speed at 500 m AGL is shown in Fig. A.7. At 00 UTC, winds were southerly and fairly uniform across most of KS and OK. By 03 UTC, the NLLJ had formed in a corridor from the panhandles of TX and OK stretching toward the northeast into the southeast corner of NE. At 06 UTC, NLLJ winds developed a westerly component, and the region of strongest wind speeds expanded east toward Wichita. By 09 UTC, the zone of strongest NLLJ winds was located over the eastern half of the domain with weaker and more westerly winds in the west. This spatial evolution explains the local temporal evolution seen at the SGP/FP1 site in Fig. A.6. At 00 and 03 UTC, Fig. A.7 shows that the core zone of the NLLJ was located west of the SGP/FP1 site. This means locally observed winds would be weak and would not present much of an NLLJ signature. By 06 UTC, the edge of the region of strongest winds was located at the SGP/FP1 site, leading to increased wind speed. Finally, by 09 UTC, the SGP/FP1 site was located within the core of the NLLJ which lead to the strong NLLJ signature with increased westerly component observed at the site late in the night.

Cross-sections along the slope of the Great Plains are shown in Fig. A.8. At 00 UTC, the cross-section shows that the CBL was more shallow and dry than the CBL preceding PECAN cases. By 03 UTC, the NLLJ formed over the western portion of the slope and lead to some speed-based convergence just east of 97° W and an associated positive vertical motion. Later at 06 UTC, the NLLJ strengthened and the strongest portions moved east, and the wind developed a westerly component across the domain. The local zone of convergence and associated vertical motion also moved east close to 96.5° W. By 09 UTC, the strongest zone of the NLLJ had moved further west. Convergence at the edge of this zone of stronger winds brought rising motion back near 97° W. A small amount of moisture advected in over the western-most portion of the domain. Spatial evolution of the water vapor mixing ratio field at 500 m (Fig. A.9) show that moisture was transported from the south and west toward the north and east, confirming that westerly advection was not negligible.

The spatial and temporal evolution observed and simulated on 09 October 2012 matches the NLLJ evolution identified from PECAN cases. While the single point observations did not show the obvious diagonal striations and positive vertical motions identified in IOP12, analysis of this case's three-dimensional evolution showed it was similar to the PECAN evolution. The NLLJ – in this case the strongest portion of the NLLJ – was shown to move from west to east across the slope of the Great Plains. This motion and heterogeneity in the structure of the NLLJ resulted in local convergence regions and associated vertical motion. This suggests that the identified spatial-temporal NLLJ evolution may be common enough to occur during different years and seasons.

A.2.2 24 October 2012

Observations from Doppler lidar and AERI on 24 October 2012 are shown in Fig. A.6. Of the clear cases, this was the strongest observed NLLJ. During the period between 07 and 10 UTC, the NLLJ core narrows and the NLLJ height decreases slightly. This period also

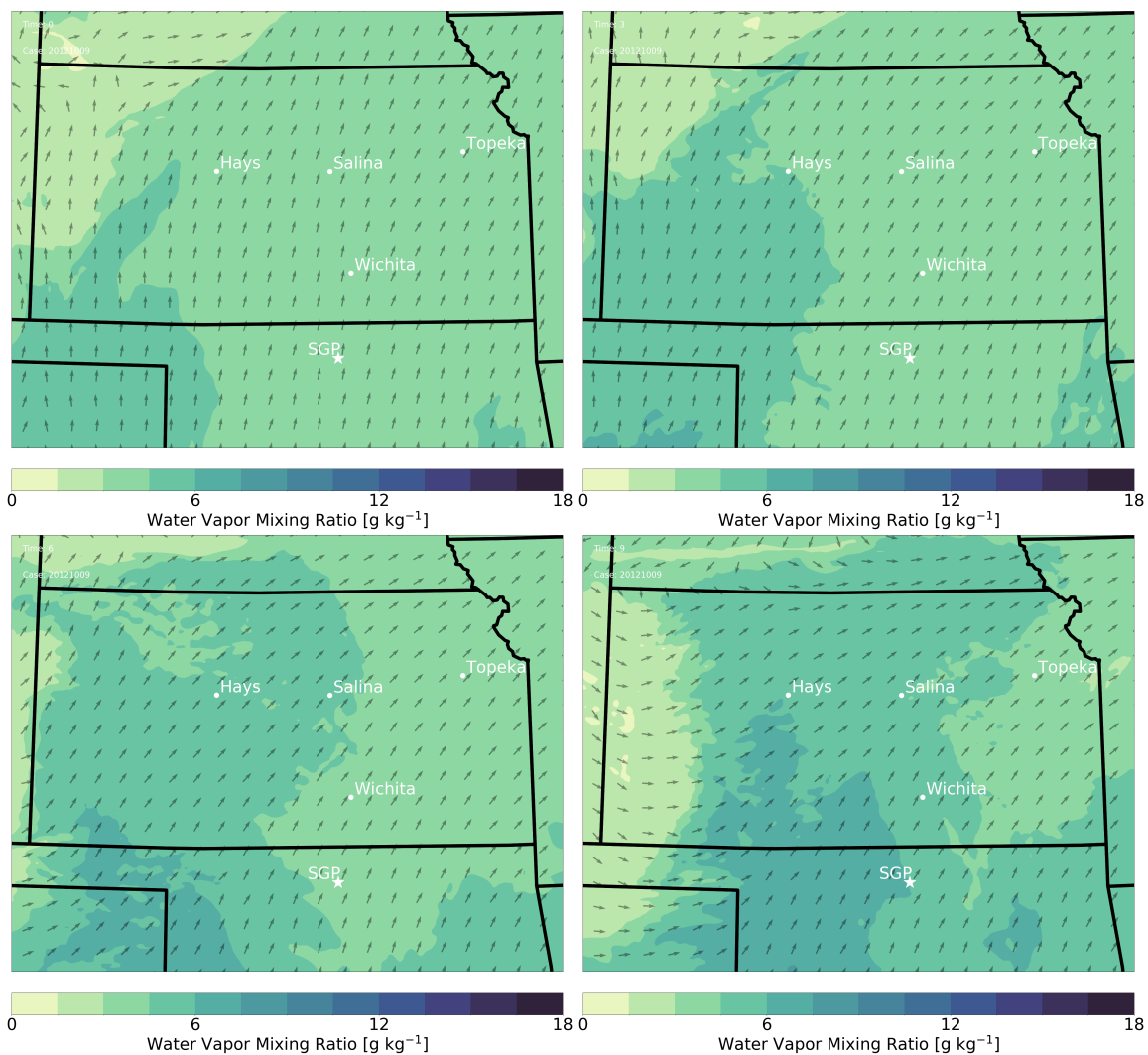


Figure A.9: WRF simulated water vapor mixing ratio at 500 m AGL on 09 October 2012 at 00, 03, 06, and 09 UTC.

showed an increasing westerly component at the level of the NLLJ maximum and above. Observations of potential temperature show warming in the region where the wind direction was more westerly.

Simulated 500 m AGL wind speed (Fig. A.10) show that the NLLJ first formed ahead of a boundary across central KS by 03 UTC. Synoptic archived charts (Fig. A.11) show a dryline-like feature associated with a cold/stationary front draped across west and central KS. The progression of this boundary in Fig. A.10 is consistent with the expected retreat of a dryline overnight (see e.g., Markowski and Richardson 2011) and the temperature gradient across the boundary was fairly weak. By 06 UTC, the NLLJ had strengthened and began to modulate the shape of the boundary southwest of Hays. At this time, a westerly component had become evident in the wind direction. Finally at 09 UTC, the NLLJ covered most of the domain ahead of the boundary now situated further northwest. Wind direction everywhere within the NLLJ were south-southwesterly.

Cross-sections across the slope of the Great Plains (Fig. A.12) still show the NLLJ moved from west to east overnight even as the boundary and any forcing associated with it retreated from southeast to northwest. At 00UTC the location of the boundary is apparent from the sharp edge of the moisture field near 99.5° W. East of this boundary, relatively strong southerly flow covered much of the domain and was likely at least partially forced by the nearby boundary. By 03 UTC, the boundary had retreated to the east and more NLLJ-like flow (a more defined low-level maximum) was simulated over most of the domain. At 06 UTC, the strongest zone of NLLJ wind was located over the eastern most part of the domain and winds had begun to develop a westerly component. By 09 UTC, the NLLJ was nearly confined to the eastern portion of the domain and winds over the western portion slowed. During the entire night, there was active vertical motion in the region above the SBL (marked by horizontal isentropes and the depth of the moisture field). In a few instances, vertical motion appeared to originate from within the SBL – for example, near 96.5° W at 03 UTC at about 750 m. Some of these instances appear to be associated

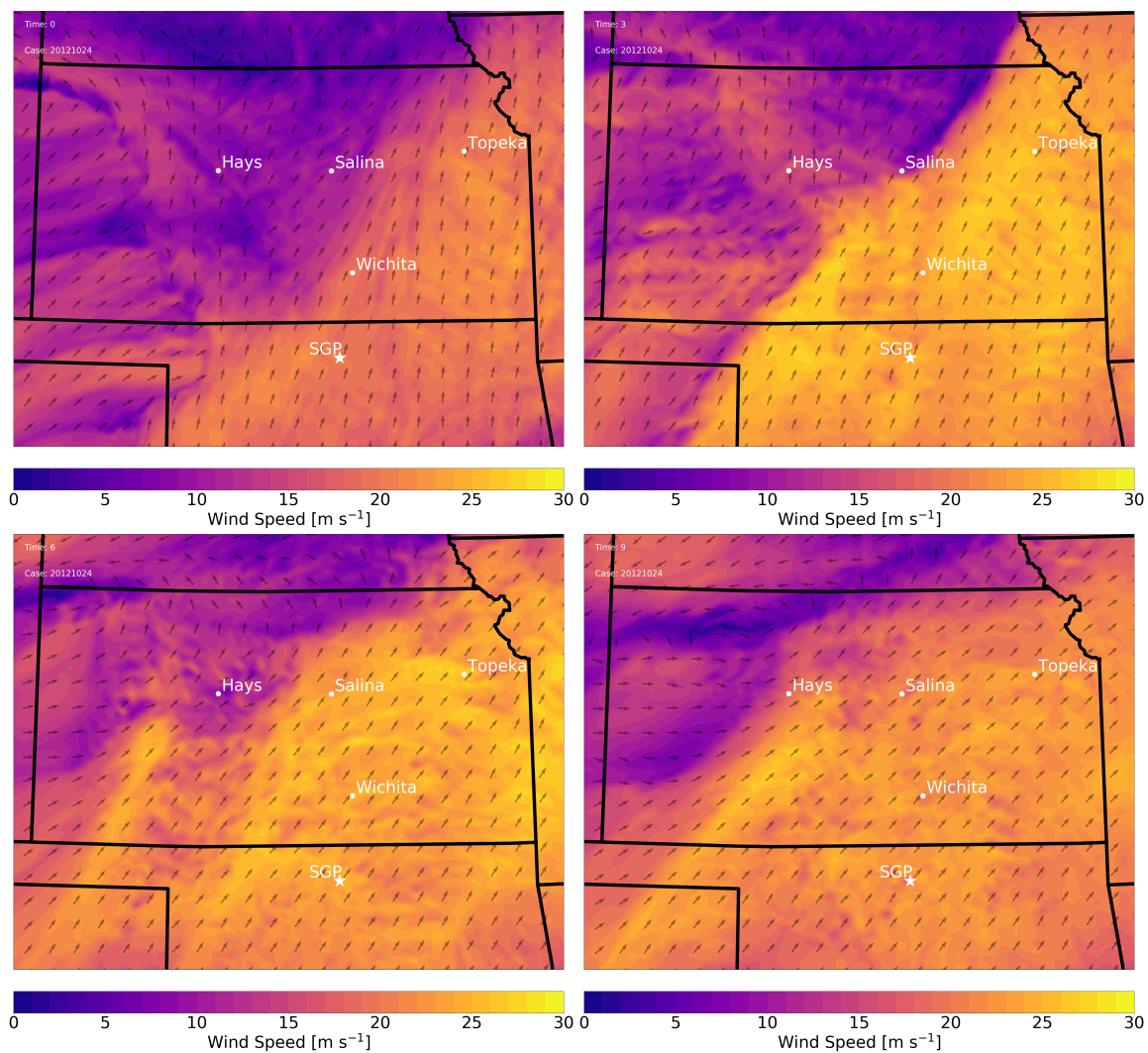


Figure A.10: WRF simulated wind speed at 500 m AGL on 24 October 2012 at 00, 03, 06, and 09 UTC.

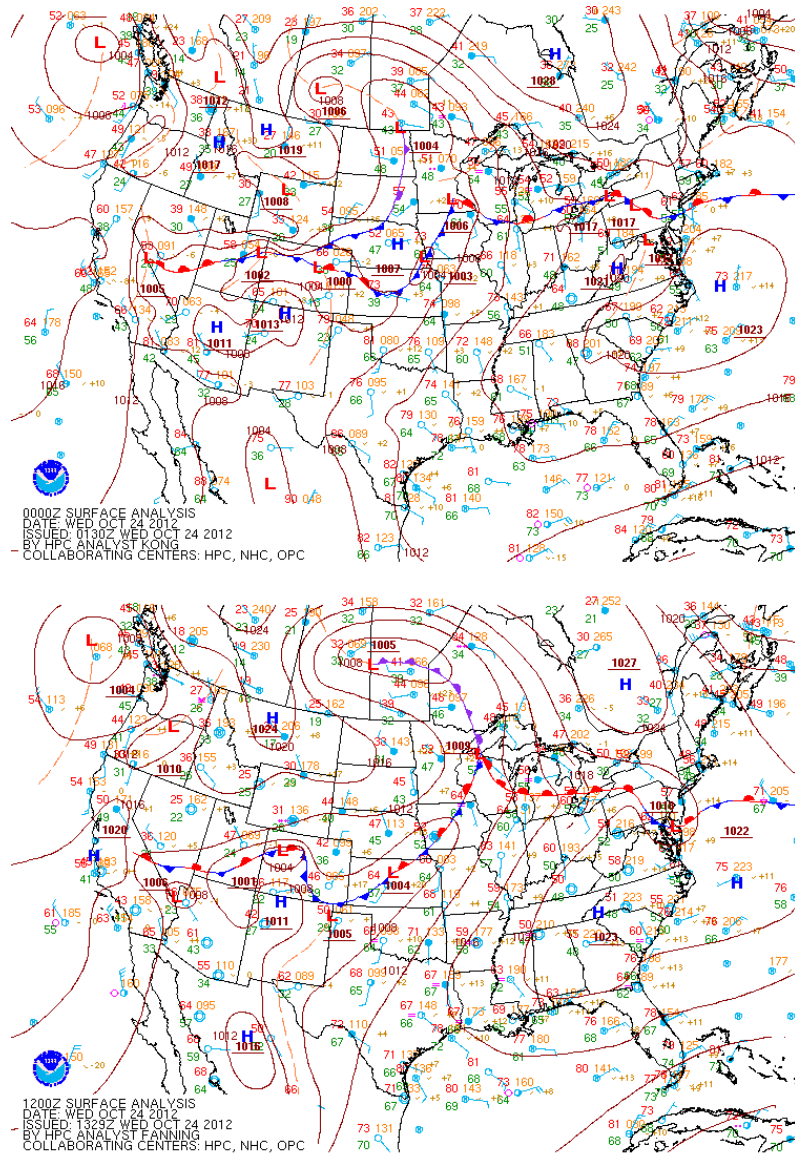


Figure A.11: As in Fig. A.3, but for 24 October 2012.

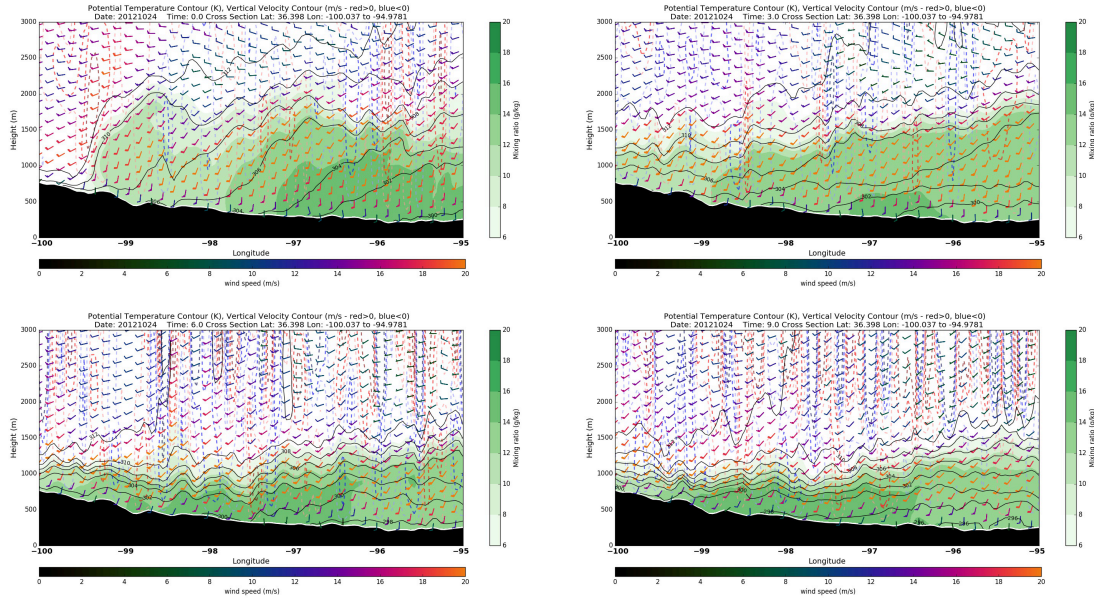


Figure A.12: As in Fig. 4.3 but for 24 October 2012 at 00, 03, 06, and 09 UTC.

with local convergence due to heterogeneity in NLLJ wind speed and direction across the slope.

In this case, the NLLJ was shown to still exhibit most of the features identified in the spatial temporal NLLJ evolution from PECAN. The core region of the NLLJ moved from west to east even as a nearby boundary and the forcing associated with it propagated to the northwest. Also, the wind veered in time and in height (apparent in Fig. A.12) resulting in heterogeneity in NLLJ wind speed and direction. In some instances, vertical motion may have been triggered by convergent motion associated with this heterogeneity. While a less clean example than 09 October 2012, the NLLJ on 24 October 2012 still suggests that identified NLLJ evolution may be common even when large scale conditions and associated forcing are different.

A.2.3 08 November 2012

Doppler lidar and AERI observations from 08 November 2012 are shown in Fig. A.6. A deep region of slightly increased wind speed formed around 03 UTC with the strongest

winds at low levels near 250 m AGL. Between 04 and 08 UTC multiple small diagonal striation-like features were observed in the wind speed field. A major diagonal striation feature was observed between 06 and 10 UTC starting at 1300 m AGL and descending to nearly 500 m AGL. This case has a more easterly component than others, so veering of the wind results in more south-southwesterly wind directions coincident with the diagonal striation features in wind speed. Sudden instances of vertical motion were not observed, but during the period in which the most obvious diagonal striation was observed vertical velocity showed increased upward motion. While not as drastic as in some other cases, upper level warming was observed in the region where winds veered and obtained a more south-southwesterly direction.

Simulated 500 m AGL wind speed is shown in Fig. A.13. At 00 UTC winds over the western half of the domain are stronger than winds over the eastern half, and a slight easterly component is apparent in the wind direction. Vertical profiles in Fig. A.6 suggest that this eastern component is stronger below this level. By 03 UTC, wind speed over the western portion of the domain increased with the formation of the NLLJ. Winds were more southerly at this time, but some locations still showed a slight easterly component. At 06 UTC, the NLLJ had moved from west to east with the edge over the SGP/FP1 observation site. Winds over the western-most portion of the domain developed westerly component. Finally at 09 UTC, the core region of the NLLJ had moved further west. More of the domain was covered by winds with a westerly component, while winds over the eastern half of the domain continued to be southerly.

Cross-sections along the slope are shown for 08 November 2012 in Fig. A.14. At 00 UTC, the dry CBL was characterized by vertical isentropes and south-southeasterly winds. CBL wind speed was slightly stronger over the western portion of the slope. By 03 UTC, the NLLJ formed over the western portion of the slope with a more southerly direction. Winds over the eastern portion of the slope were still weaker. At 06 UTC, the NLLJ had strengthened and spread further to the east. This is a good example for NLLJ

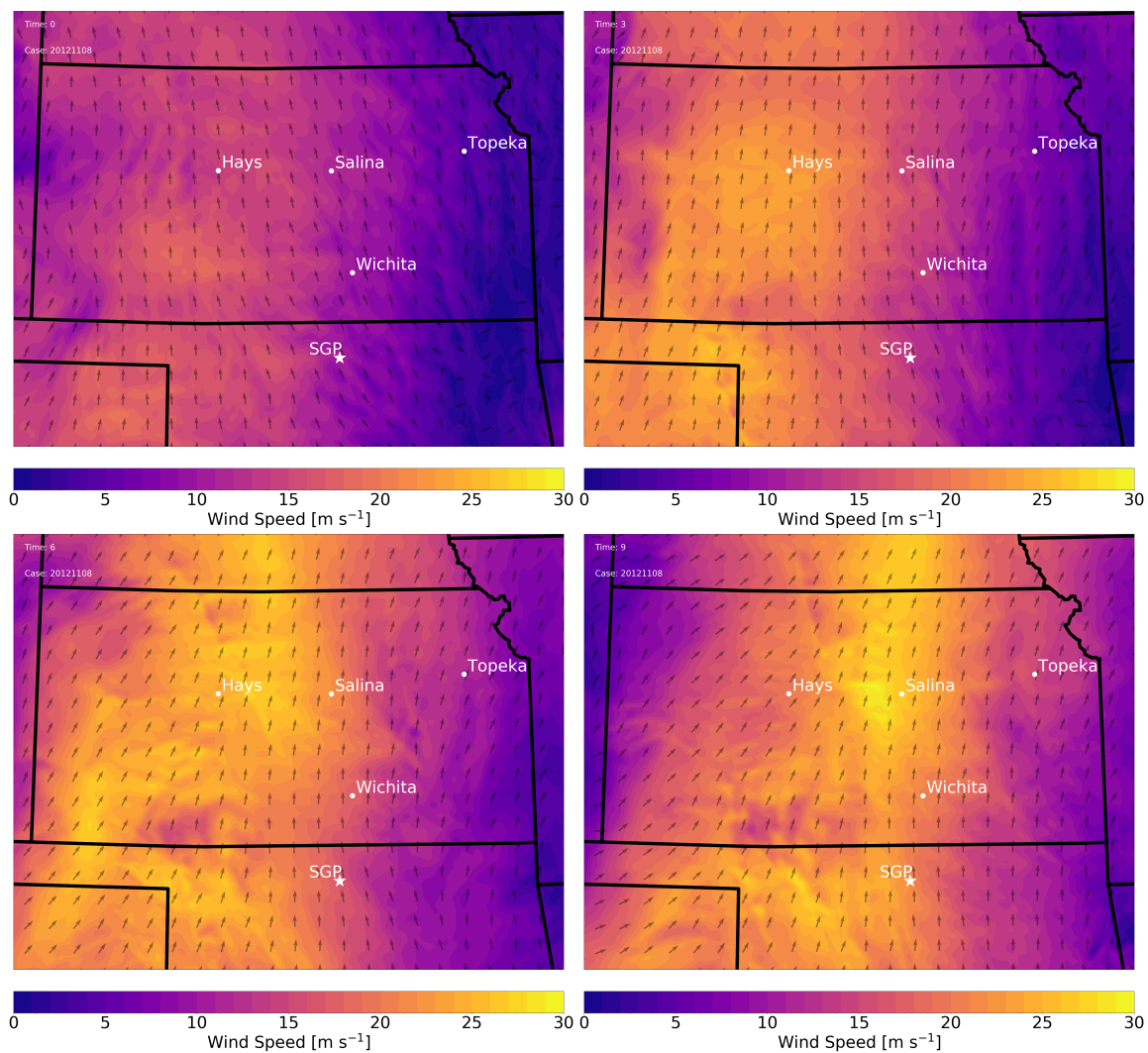


Figure A.13: WRF simulated wind speed at 500 m AGL on 08 November 2012 at 00, 03, 06, and 09 UTC.

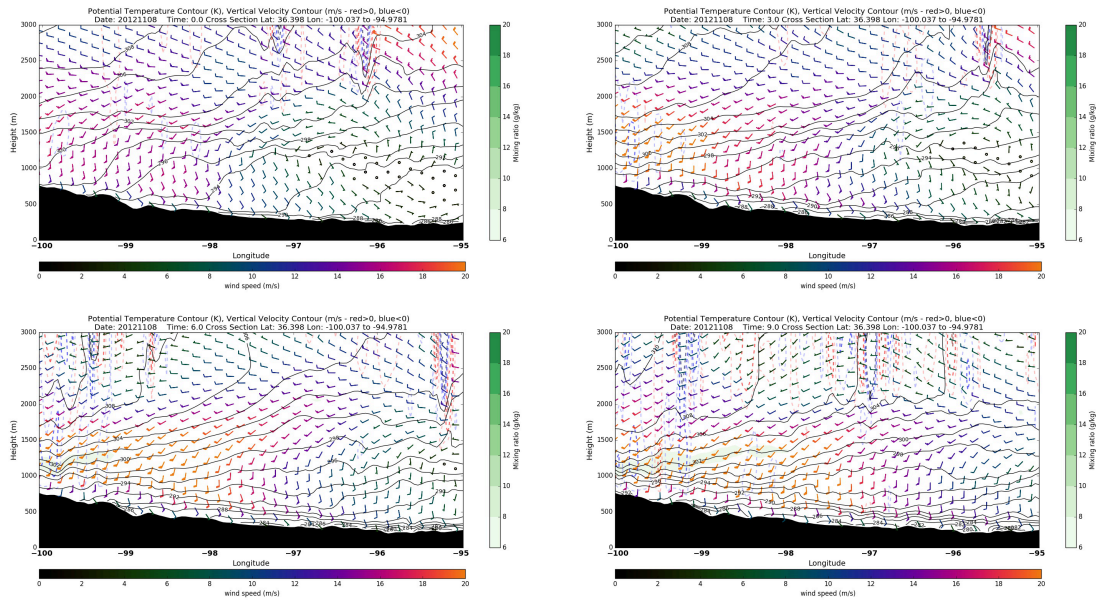


Figure A.14: As in Fig. 4.3 but for 08 November 2012 at 00, 03, 06, and 09 UTC.

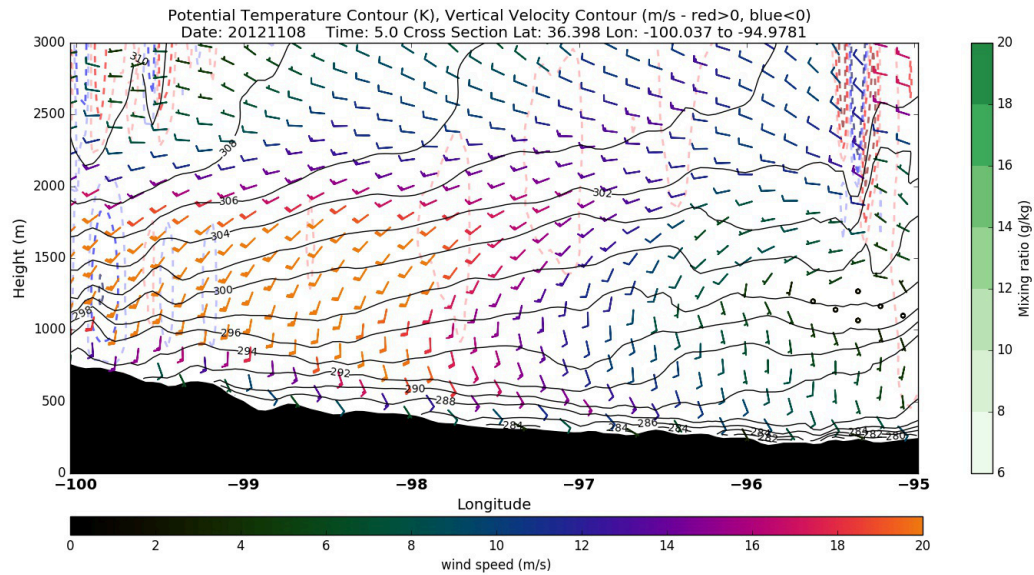


Figure A.15: As in Fig. 4.3 but for 08 November 2012 at 05 UTC.

winds veering in height. Near 97.5° W, winds were weaker and more south-southeasterly near the surface. Between 1000 and 1500 m above sea level, winds became stronger and veer with a more south-southwesterly direction. This shows that the NLLJ first develops stronger and more westerly winds near its top which leads to a diagonal striation in local profile observations (see Fig. 4.4). While Fig. A.14 does not show any sudden instances of vertical motion associated with convergence zones, such motions were simulated in this case. Fig. A.15 shows the same cross section but at 05 UTC as an example. Wind speed and direction associated with the heterogeneous NLLJ lead to a region of convergence between 98 and 97° W in the layer between 1000 and 1500 m above sea level. Within this zone of convergence, positive vertical motions were simulated as noted in other cases.

The NLLJ observed on 08 November 2012 was shown to have many features similar to PECAN IOP12. Observations showed a late forming NLLJ with obvious diagonal striation features. While occurring in the fall season in a different year, this NLLJ was shown to move from west to east, exhibit heterogeneous wind speed and direction, and lead to convergence supporting positive vertical motion.

A.3 Similar Cases

LABLE cases that took place on 13 October, 16 October, 21 October, 22 October, and 09 November 2012 were categorized as similar cases, meaning they have some similarity to the spatial-temporal NLLJ evolution identified from the PECAN cases, but may not show all features or may be impacted by synoptic patterns in the larger domain. LABLE observations and WRF simulations for each case will be shown to support this categorization.

A.3.1 13 October 2012

Observations from Doppler lidar and AERI on 13 October 2012 are shown in Fig. A.16. A NLLJ formed around 02 UTC around 500 m AGL. The NLLJ height descended until about

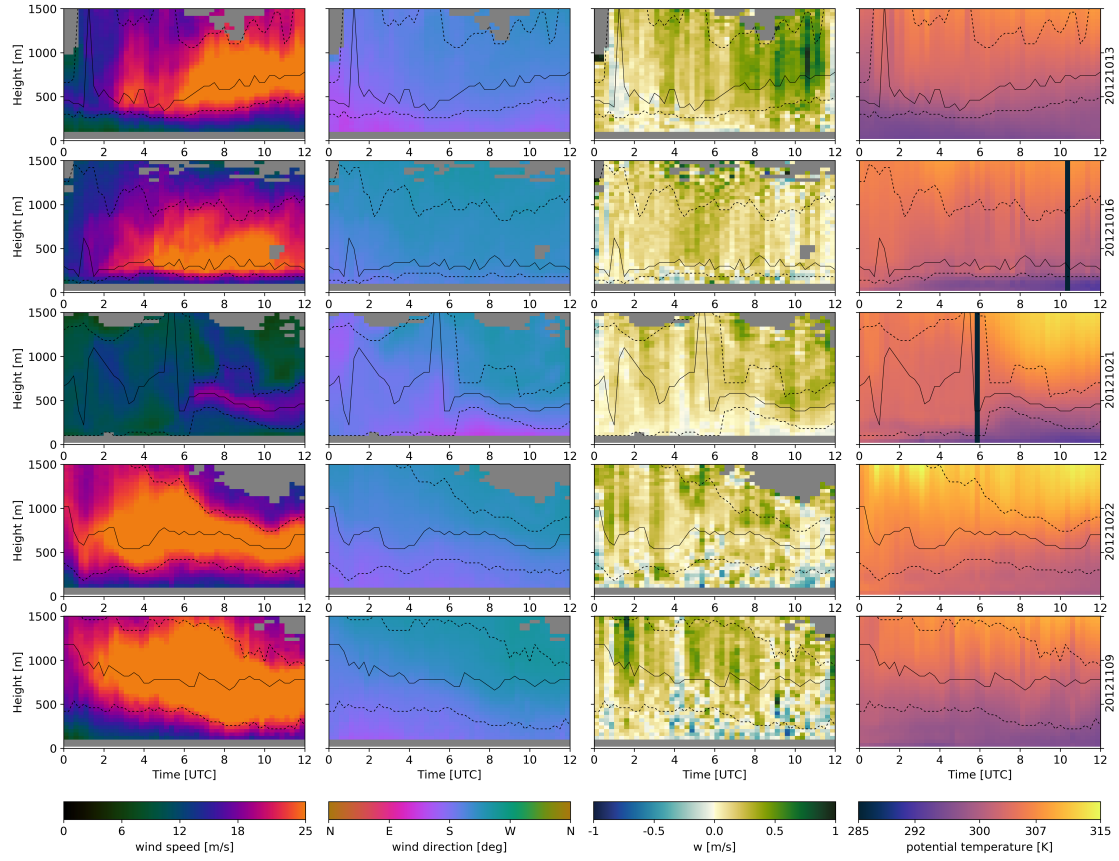


Figure A.16: As in Fig. A.1, but for cases categorized as similar.

05 UTC when the NLLJ strengthened and the height began to increase. This strong NLLJ continued with slowly increasing NLLJ height throughout the night. Near the surface, winds had a slight easterly component. In the layer where the NLLJ formed, wind direction was more southerly with some slight western components above the NLLJ maximum after 05 UTC. Whole isolated sudden instances of vertical motion were not observed, broad upward motion was observed after 07 UTC. Potential temperature observations show the formation of a SBL between 00 and 05 UTC. After 05 UTC, the SBL seemed to decay and become more neutral. The decay of the SBL resulted in an elevated NLLJ and explains the observed increase in NLLJ height.

Simulated 500 m AGL wind speed on 13 October 2012 is shown in Fig. A.17. At 00 UTC weak, non-uniform winds were simulated across the domain. A boundary-like feature was stretched from the OK panhandle to the KS/MO/NE border marked by weaker wind speed and more easterly wind direction. West of this feature, a region of stronger southerly winds were simulated. Surface analysis valid for 00 UTC on 13 October 2012 (Fig. 4.15) shows a warm/stationary front in the area of interest, but a bit further south and east than the simulation suggests. By 03 UTC, NLLJ like winds became apparent over most of OK. Winds over KS were still weaker, but the boundary-like feature became less apparent. West of the boundary, a region of increased wind speed was still present. By 06 UTC, NLLJ winds strengthened and expanded across most of OK and KS. The boundary-like feature had lifted to the north and west now located near Hays, KS. In the region where NLLJ winds had formed, wind direction was dominantly southerly. At 09 UTC, NLLJ winds became quite strong. The boundary like feature was now further north and west. NLLJ winds had developed a westerly component.

Cross-sections along the slope of the Great Plains are shown in Fig. A.19. At 00 UTC, simulated winds were generally weak. Over the eastern half of the domain winds were generally southerly. Over the far western portion of the domain wind speed was stronger associated with the zone of strong wind speed north and west of the boundary feature (see

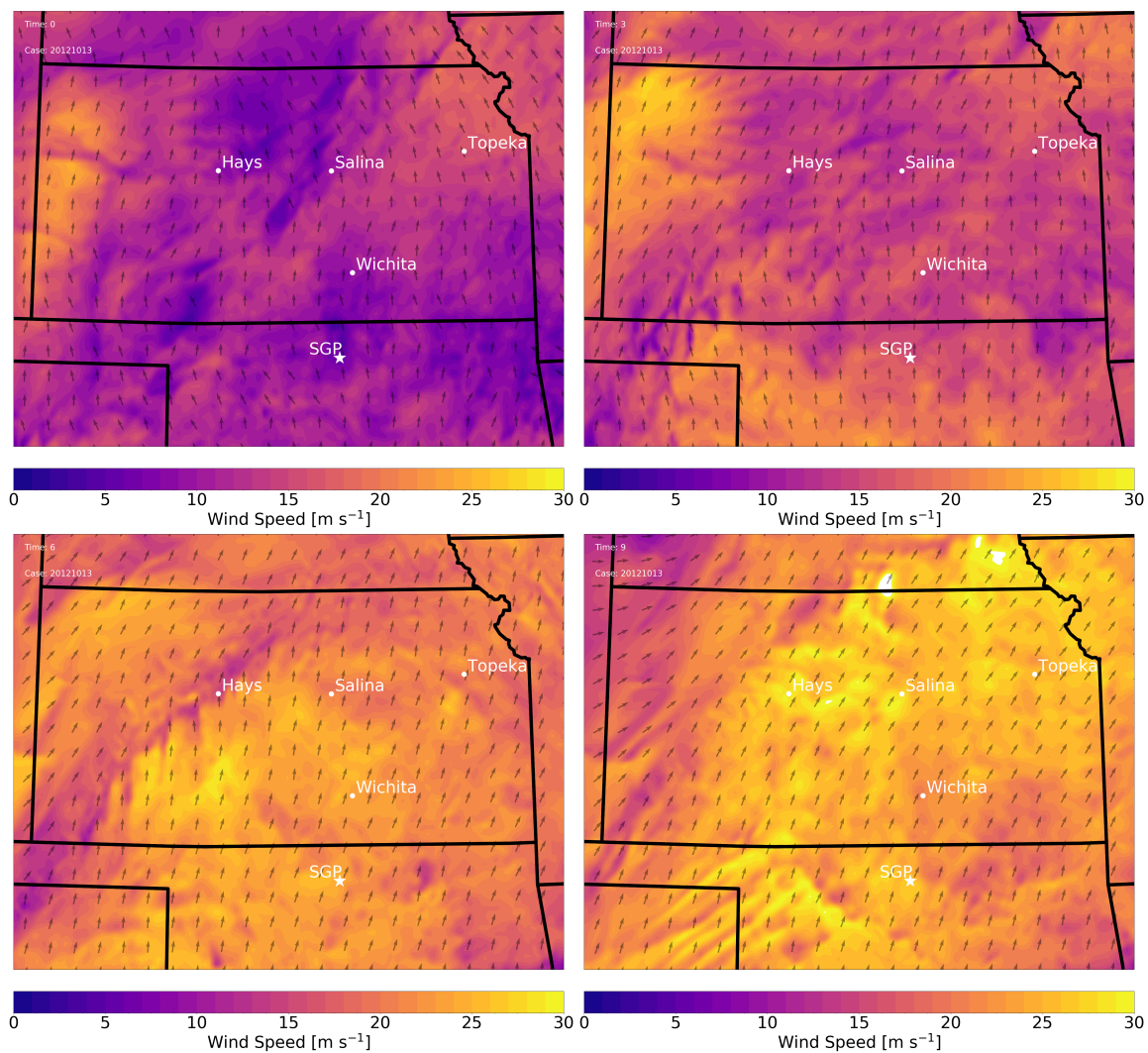


Figure A.17: WRF simulated wind speed at 500 m AGL on 13 October 2012 at 00, 03, 06, and 09 UTC.

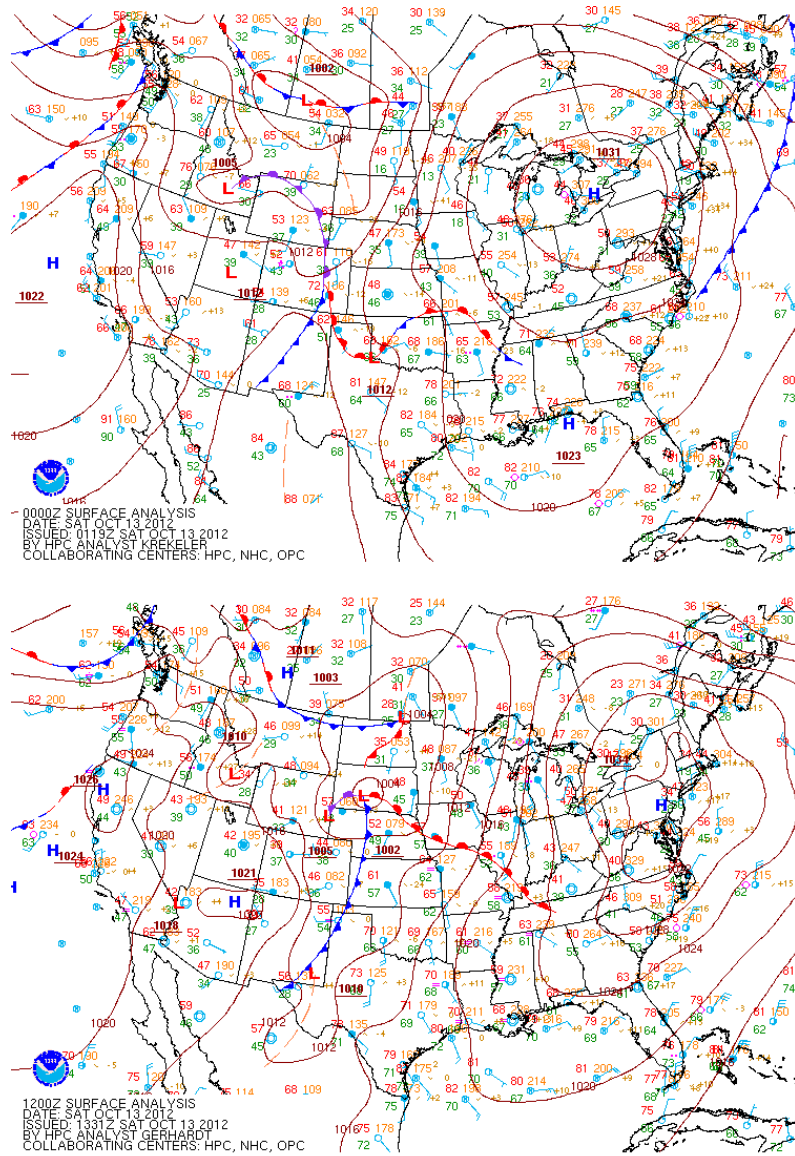


Figure A.18: As in Fig. A.3, but for 13 October 2012.

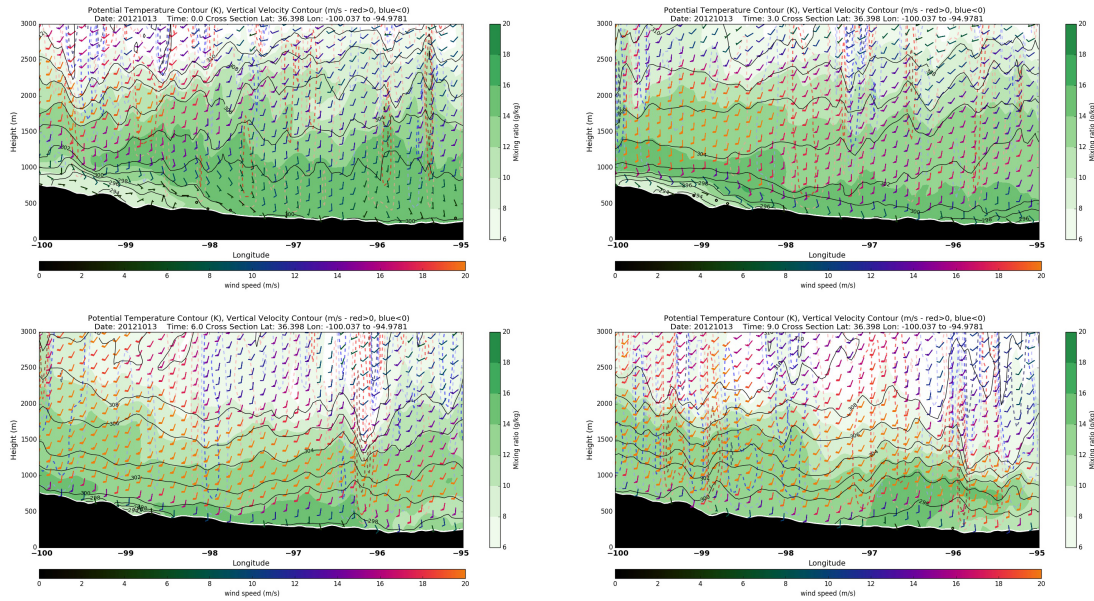


Figure A.19: As in Fig. 4.3 but for 13 October 2012 at 00, 03, 06, and 09 UTC.

Fig. A.17). In the low levels west of 98° W, a shallow layer of dry air with easterly winds was simulated. This region was likely associated with dry cool air in the airmass behind the aforementioned boundary feature. By 03 UTC wind speed increased across much of the domain. The strongest winds were over the western portion of the domain. With the exception of the shallow layer of dry air near the surface west of 98° W, wind direction was generally southerly. Later at 06 UTC, strong southerly wind was simulated across the entire domain. The extent of the strong NLLJ winds reached to the eastern bound of the cross-section. At 09 UTC NLLJ winds were still simulated across the entire domain and the wind direction had begun to develop a westerly component.

Similar to cases covered in Section A.2, the NLLJ on 13 October 2012 moved from west to east through the night. This movement took place while a boundary feature moved north and west away from the area of interest. The western edge of the NLLJ was not apparent in this case as in clear cases. Winds within the NLLJ developed a westerly component as the jet veered in time and in height. As compared to the cases covered in Section A.2, this case did not develop strong stability as evidenced by isentropes in Fig. A.19. Prior to 06

UTC, stability was stronger in the western portion of the domain in the lower levels, likely related to the airmass behind the boundary feature. Throughout the period, the vertical motion field shown in Fig. A.19 was active. While some instances of vertical motion may have been related to local convergence in the wind field, it is difficult to discern if that convergence is due to NLLJ effects or to the boundary feature nearby.

A.3.2 16 October 2012

Doppler lidar and AERI observations of the NLLJ on 16 October 2012 are shown in Fig. A.16. A broad, generally weak jet formed at 01 UTC. By 02 UTC the NLLJ strengthened with a maximum near 250 m AGL. The NLLJ height gradually increased until about 0430 UTC, when the height decreased and the NLLJ magnitude increased. A diagonal striation feature was observed starting at about 900 m AGL just before 03 UTC and descending to the height of the NLLJ maximum at 04 UTC. After 05 UTC, the NLLJ remained strong with the height of the exact maximum fluctuating between 250 and 400 m AGL. The core zone of strong wind deepened with time until 11 UTC. After this point the NLLJ began to weaken. Wind direction was south-southwesterly throughout the night with slightly more westerly direction later in the period and higher in the domain. No sudden instances of vertical motion were observed, but broad weak upward motion was observed after the diagonal striation feature between 04 and 06 UTC. Potential temperature observations show that a SBL formed after 02 UTC and reached its maximum depth at about 04 UTC, which it maintained throughout the night.

Simulated wind speed at 500 m AGL on 16 October 2012 is shown in Fig. A.20. At 00 UTC a boundary feature was located over the southwest quarter of KS starting in Salina and curling south and west. Throughout the night this feature slowly lifted north and west until 09 UTC when a cold front passed through the domain from northwest to southeast. At 00 UTC the only region of enhanced wind speed was located just ahead of the boundary feature. Thus, we assume this flow is forced and not NLLJ-like. By 03

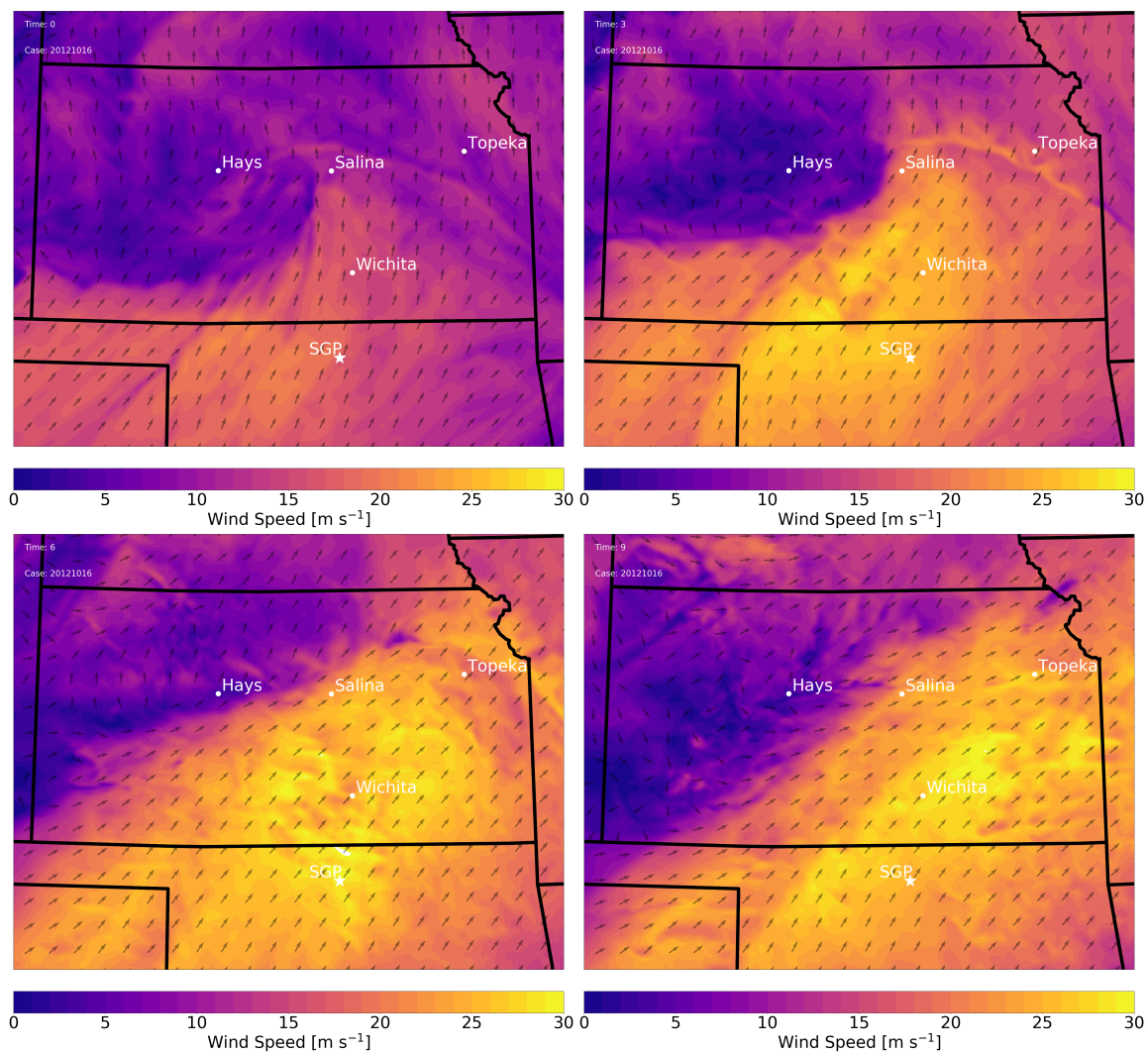


Figure A.20: WRF simulated wind speed at 500 m AGL on 16 October 2012 at 00, 03, 06, and 09 UTC.

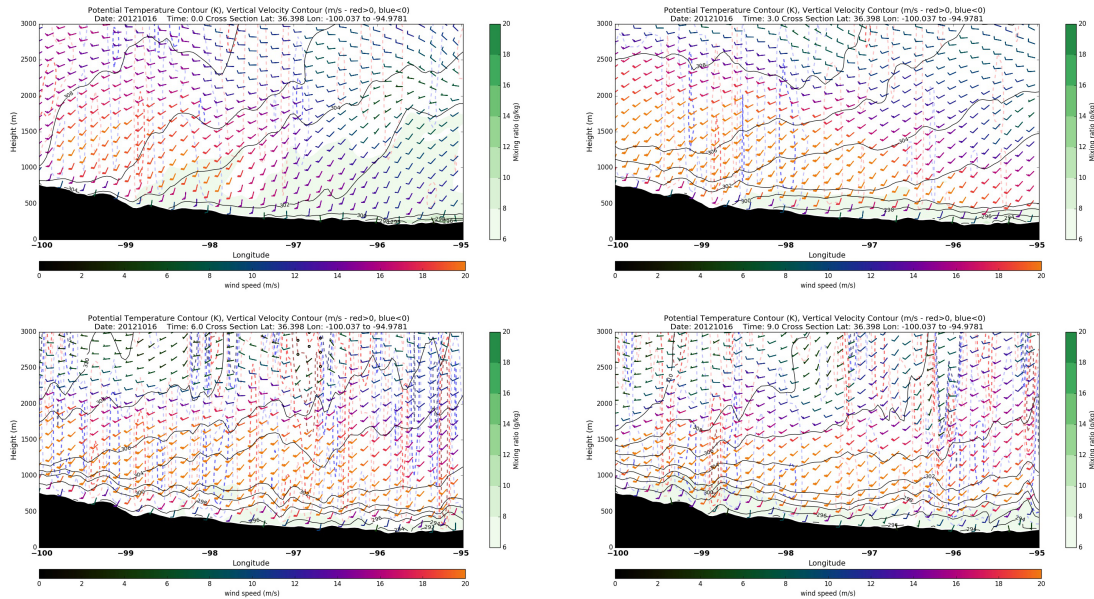


Figure A.21: As in Fig. 4.3 but for 16 October 2012 at 00, 03, 06, and 09 UTC.

UTC, the boundary feature moved north and west while strong southerly winds developed over OK and south central KS. These winds were likely more NLLJ-like since wind speed and coverage increased while the boundary feature retreated. At this time the core zone of strongest NLLJ winds was located along a SW-NE axis south of Salina and west of SGP/FP1 and wind direction was south-southwesterly. At 06 UTC, NLLJ winds reached further east with a broader core region centered over Wichita. Wind direction became more westerly than at 03 UTC. By 09 UTC, the cold front was between Hays and Salina. The core NLLJ winds were still over Wichita, but the western edge of this zone moved further east.

Cross-sections along the slope of the Great Plains are shown in Fig. A.21. At 00 UTC, strong wind speeds were simulated over the western portion of the slope. Considering the placement of the boundary feature at 00 UTC in Fig. A.20, we assume this is forced flow associated with that boundary instead of NLLJ flow. By 03 UTC, a zone of enhanced wind speed with a more defined vertical maximum reached further east. These winds are considered to be more NLLJ-like and less forced since the boundary feature retreated. At

06 UTC, NLLJ winds reached further east. The vertical motion field was very active at this time. As on 13 October 2012, it is difficult to discern if these vertical motions were associated with NLLJ features or other forcing. It is worth noting that while stability (as indicated by isentropes) increased in the low levels at 06 UTC, a layer of elevated instability remained between 700 and 1500 m above sea level. Finally at 09 UTC, the NLLJ moved even further east with the core of strongest winds located over the eastern most portion of the domain. Activity continued in the vertical motion field and elevated instability remained.

In this case, NLLJ motion from west to east was clear in Fig. A.20 in the region not impacted by the early boundary feature or later cold front. Due to the synoptic setup and nearby boundaries and fronts, winds were always south-southwesterly. Some veering in time was apparent in Fig. A.20, but veering with height was hard to diagnose from A.21. An observed diagonal striation feature occurred during the period in which winds became more NLLJ-like as opposed to boundary forced. Increased vertical motion was observed after the diagonal striation, but the source of simulated vertical motion was difficult to diagnose from Fig. A.21.

A.3.3 21 October 2012

Observations from Doppler lidar and AERI of the NLLJ on 21 October 2012 are shown in Fig. A.16. At the SGP/FP1 site, the NLLJ did not form until after 06 UTC and was much weaker and shallower than other cases in the similar category. Previous to 06 UTC, a narrow region of increased wind speed (15 m s^{-1}) was observed with frequently changing height. After 06 UTC, the NLLJ formed just above 500 m AGL and the NLLJ height gradually descended through the rest of the period. While not as clear as other instances of diagonal striations, an area of increased wind speed was observed beginning around 07 UTC at the top of the observation domain. It rapidly descending to the level of the NLLJ from 08-10 UTC. During this same time period, wind direction became much more

westerly compared to the south-southeasterly wind direction observed previous to 06 UTC. A thin layer of easterly winds were observed throughout the period just above the surface. After about 09 UTC weak and broad positive vertical motion was observed at the height of the NLLJ, coincident with the end of the descending region of increased wind speed above the NLLJ. Potential temperature observations prior to 06 UTC show a fairly mixed layer above a shallow stable layer. After 06 UTC the stable boundary layer deepened, filling the region below the NLLJ. Above the NLLJ, higher potential temperatures were observed in the same region where wind direction became more westerly.

Simulated 500 m AGL winds are shown in Fig. A.22. At 00 UTC, no NLLJ-like feature was simulated in the domain. Flow was generally weak and southerly. By 03 UTC, increased wind speed was apparent in the south-eastern portion of the domain. The rest of the domain showed either weak winds with some small pockets of increased wind speed to the north. At 06 UTC, the western two-thirds of the domain showed weak winds, but the eastern portion exhibited more NLLJ-like flow, including the SGP/FP1 site. This region also began to develop a westerly component in the wind direction. The strongest region of wind speed appeared south of the SGP/FP1 site. By 09 UTC, the NLLJ region developed more of a westerly component. The zone of strongest winds moved east, now located south-east of the SGP/FP1 site.

Cross-sections of the simulation data along the slope are shown in Fig. A.23. At 00 UTC, the cross-section shows a deep mixed boundary layer across the slope with net southerly flow. Throughout the night, the moisture field was transported from west the east. By 03 UTC, wind speed increased as an NLLJ formed only over the eastern portion of the domain, consistent with what was shown in Fig. A.22. By 06 UTC the NLLJ moved east and the upper portion of the NLLJ developed a westerly wind component. At 09 UTC, the strongest NLLJ winds moved further east and winds developed a more westerly component. A convergent zone and weak associated zone of vertical motion was simulated near -95.5° W.

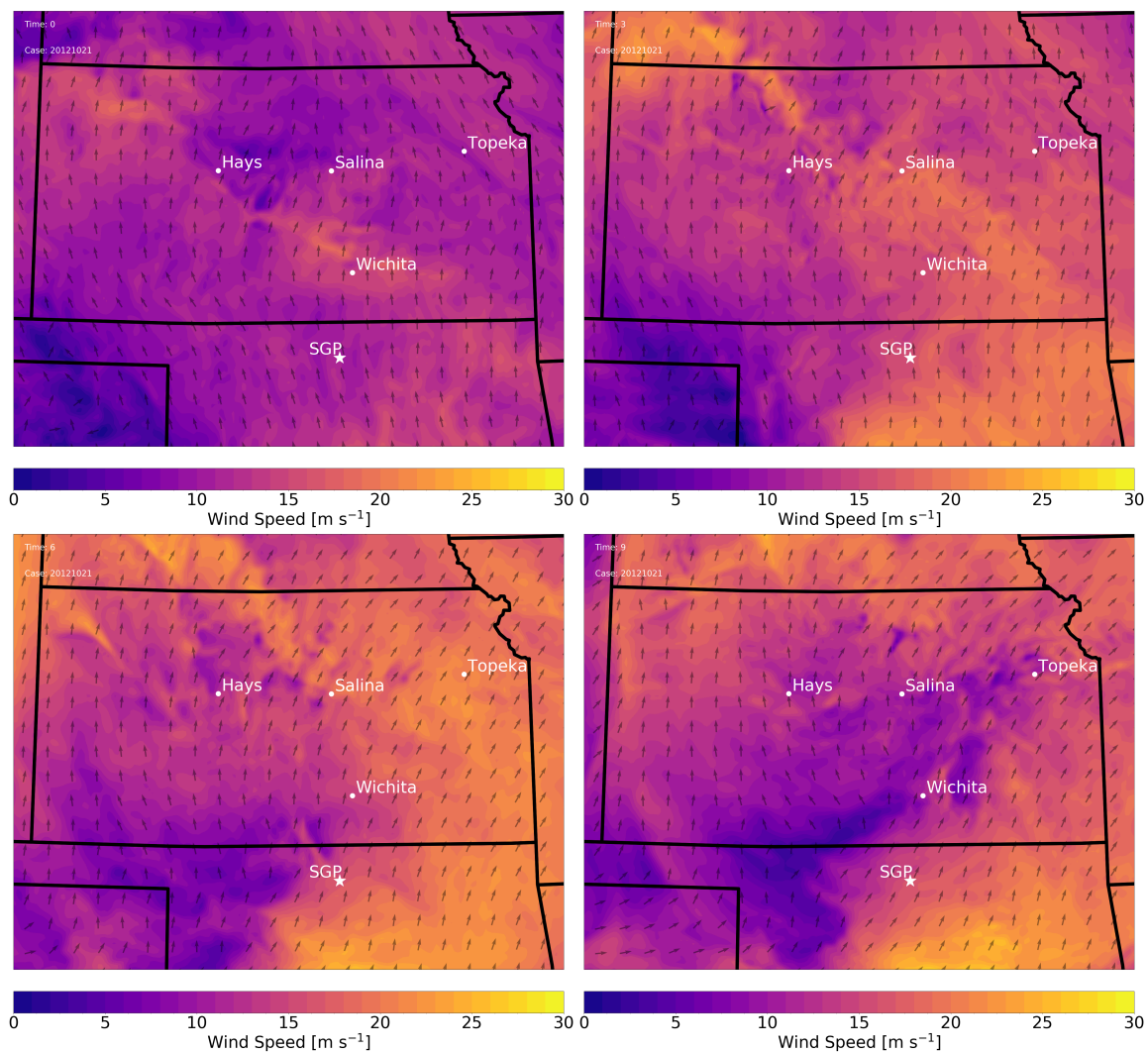
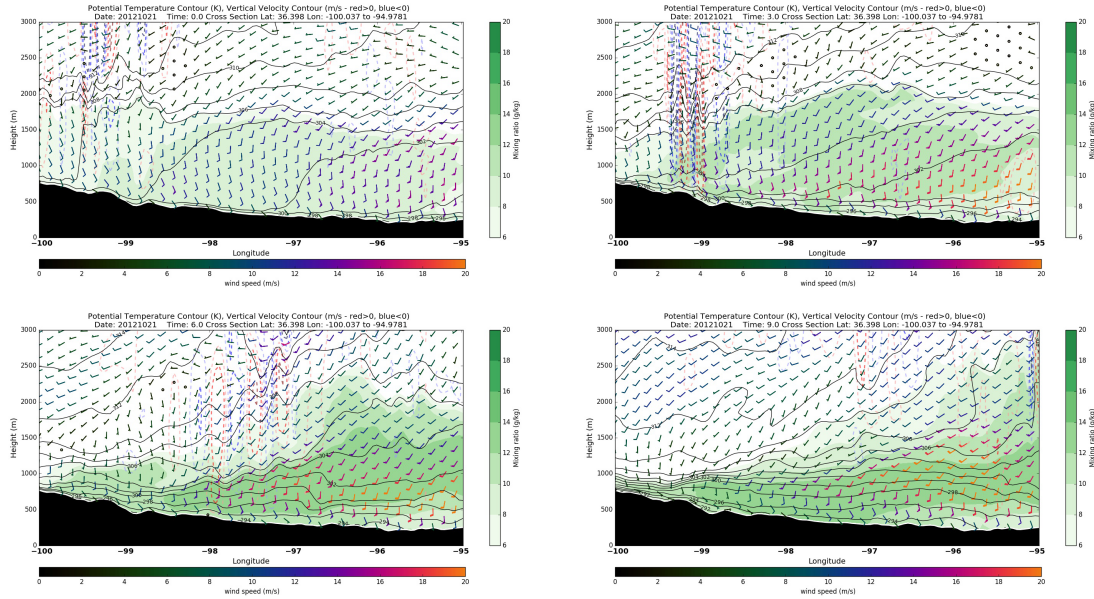


Figure A.22: WRF simulated wind speed at 500 m AGL on 21 October 2012 at 00, 03, 06, and 09 UTC.



strong. Once the NLLJ formed, it persisted through the night just above the 500 m AGL level. Starting around 06 UTC, the upper part of the NLLJ began to descend resulting in a much more shallow NLLJ by 08 UTC. During this time, winds above the NLLJ maximum gained a westerly component, and the vertical velocity field became more active, with positive vertical motions occurring through 10 UTC. Warm potential temperatures were observed as the westerly component increased above the NLLJ height.

Simulated 500 m AGL wind speed is shown in Fig. A.24. At 00 UTC, a boundary was simulated across the western part of KS. Archived synoptic surface analyses (Fig A.25) show that a cold front was positioned over western KS at 00 UTC. Throughout the night, this front pushed east slightly to central KS and become a stationary front. Ahead of the front over eastern KS and OK, strong southerly flow was simulated likely associated with frontal forcing. By 03 UTC, this region of southerly flow became stronger, but the front was unchanged. Thus, the strong flow over eastern KS and OK is assumed to have NLLJ characteristics. At this time, the strongest zone of NLLJ winds was located over the SGP/FP1 site and flow was generally southerly. At 06 UTC, the NLLJ flow developed a more westerly component in regions not impacted by the frontal boundary. The strongest zone of winds now reached further east. By 09 UTC, the zone of strongest NLLJ winds had moved east leaving the SGP/FP1 site on the western edge of the NLLJ core.

Cross sections along the slope are shown in Fig. A.26. At 00 UTC, forced southerly flow was apparent across most of the domain. The position of the frontal boundary can be discerned near -99° W by the western edge of the moisture field and collocated vertical motions. By 03 UTC, this flow appeared more NLLJ-like with a more defined jet-shaped vertical profile in the low levels. Winds developed a more westerly component near the top of the NLLJ in the western portion of the NLLJ flow. A pair of local speed-based convergence zones and associated vertical motions were simulated at -97° and -96° W. By 06 UTC, the zone of strongest NLLJ winds moved to the east. At the top of the boundary

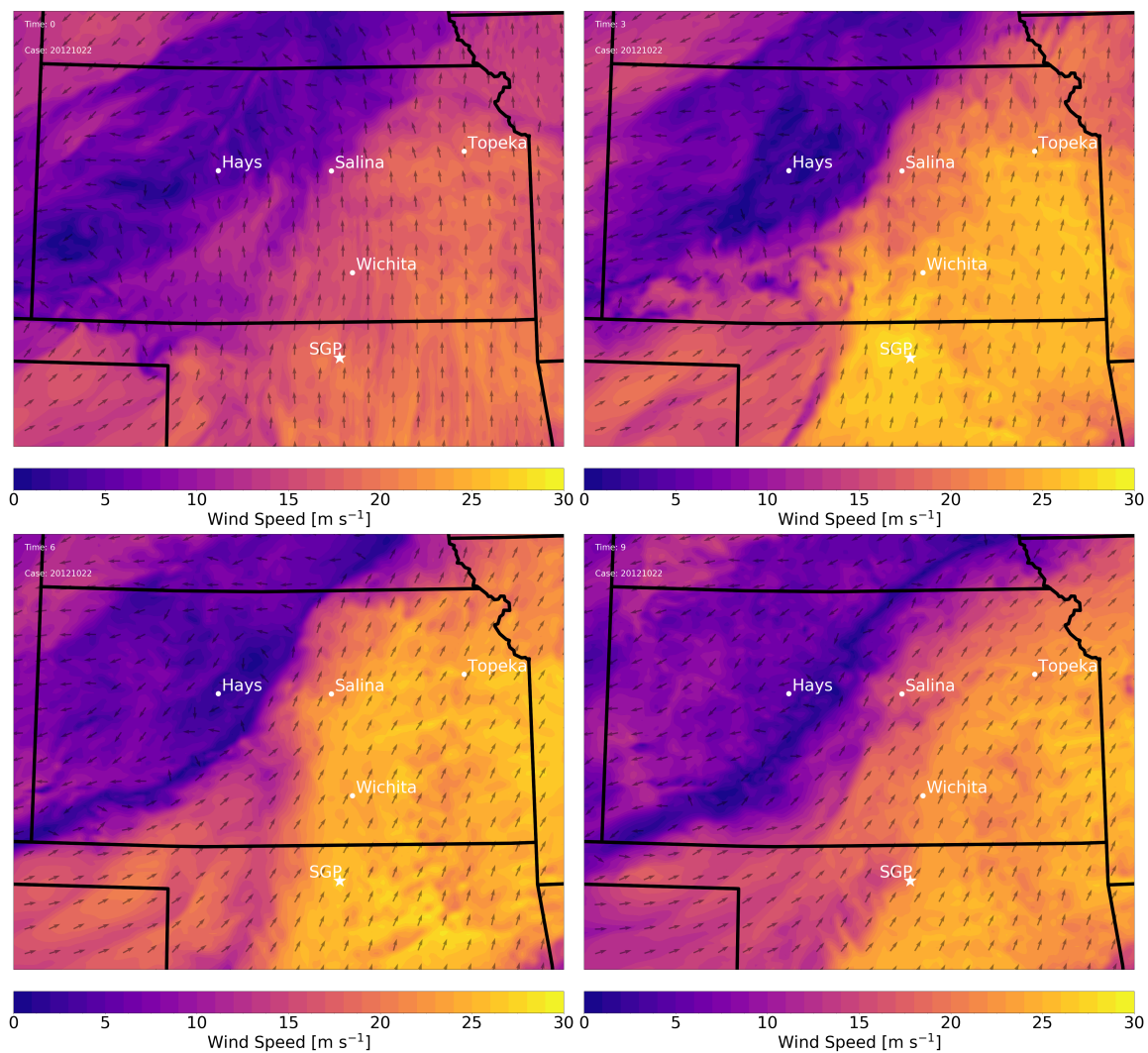


Figure A.24: WRF simulated wind speed at 500 m AGL on 22 October 2012 at 00, 03, 06, and 09 UTC.

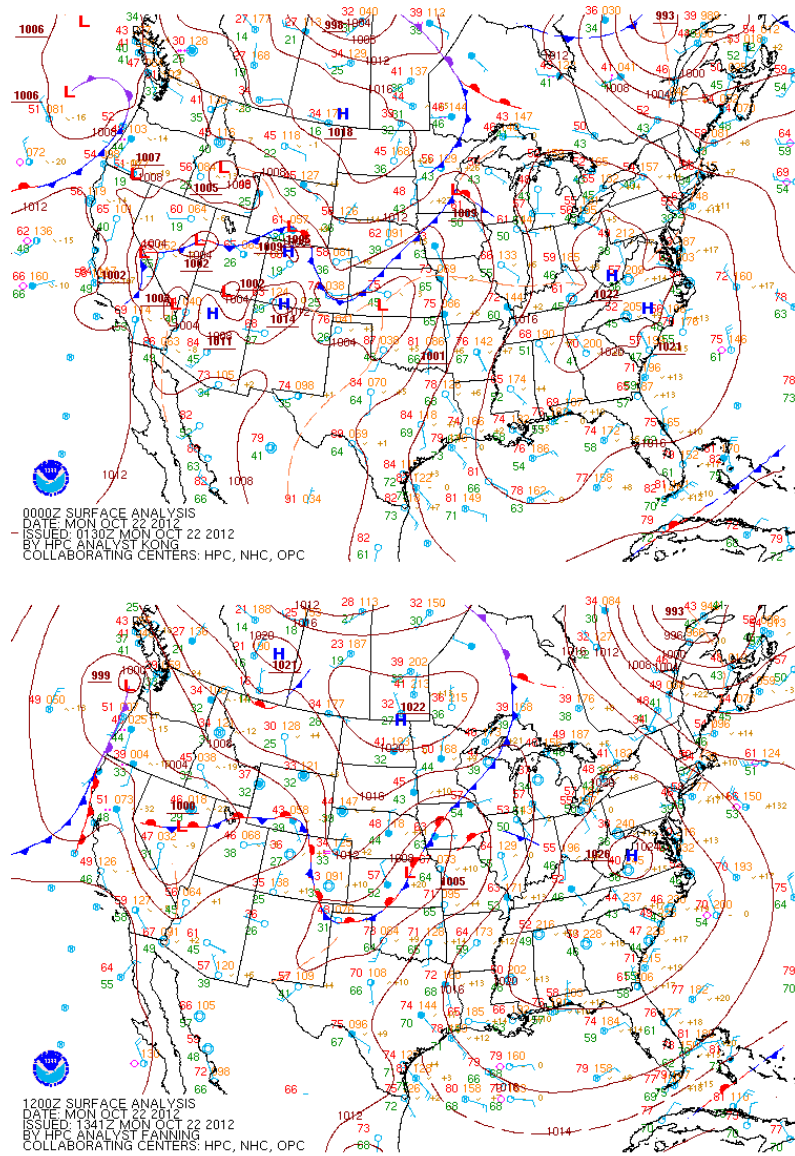


Figure A.25: As in Fig. A.3, but for 22 October 2012.

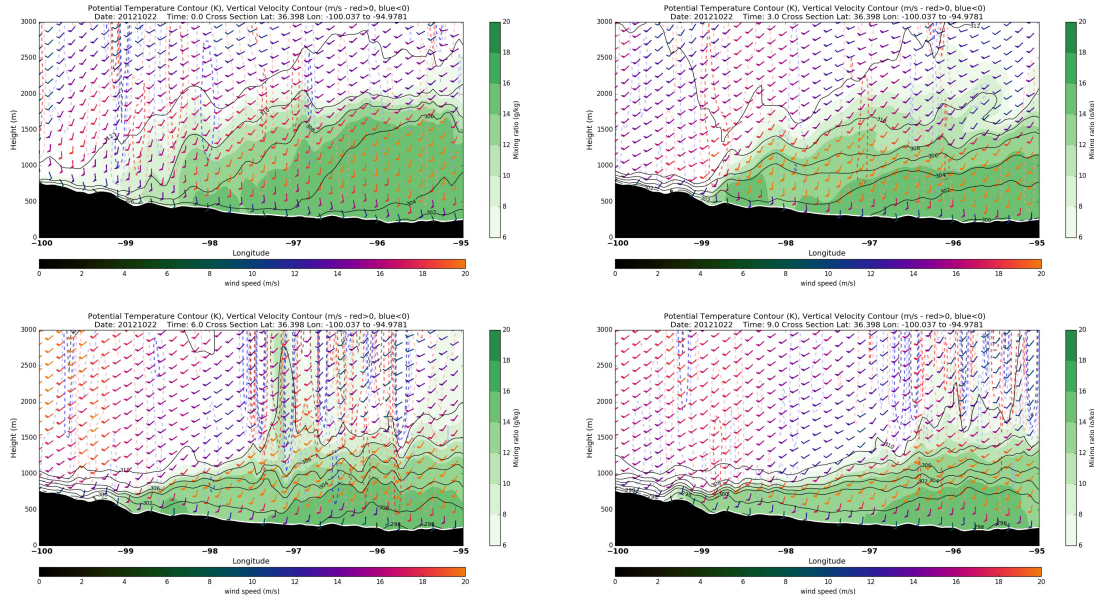


Figure A.26: As in Fig. 4.3 but for 22 October 2012 at 00, 03, 06, and 09 UTC.

layer, marked by the depth of the moist layer, the vertical velocity field became active. Potential temperature contours show a less stable residual layer remained above the boundary layer. With this level of activity, it is hard to diagnose the origins of these vertical motions. Wind direction become more westerly over a deeper layer than at 03 UTC. At 09 UTC, the zone of strongest NLLJ winds was confined to the eastern most portion of the cross section. Winds were westerly except at the lowest levels, and the increased vertical velocity activity was ongoing above the boundary layer. Archived radar data (not shown) indicated that convection began to initiate along and ahead of the frontal boundary after the sun came up, so an active residual layer with little to no stability is not surprising in this case.

This case began with strong background southerly flow forced by a frontal boundary draped across KS. After sunset, the forced flow became more NLLJ-like and exhibited some of the features of the identified NLLJ evolution. The strongest zone of NLLJ winds moves west to east overnight despite the frontal boundary remaining nearly stationary. Throughout the night, wind direction became more westerly as the NLLJ winds veered in time and height. Early in the night (e.g., 03 UTC) some vertical motions could be

associated with the development local convergence regions by NLLJ heterogeneity, but later on the vertical velocity field became quite active in the residual mixed layer above the boundary layer.

A.3.5 09 November 2012

Observations from AERI and Doppler lidar are shown in Fig. A.16 for 09 November 2012. This case appears quite similar to the case on 22 October 2012. Background flow was strong and the NLLJ formed quickly at or before sunset. The NLLJ maximum was higher above the surface than several other NLLJs with the NLLJ height remaining close to 750 m AGL throughout the night, but also had a broader jet nose. After about 08 UTC, the NLLJ depth decreased as the top of the NLLJ lowered. Simultaneously, the wind direction became more westerly. This case showed several periods of broad weak vertical motions above the NLLJ maximum. Throughout the night, a deep stable boundary layer was observed below the NLLJ maximum. It is hard to discern what the temperature profile was like above the NLLJ since the jet was so deep in this case, but observations suggest some warming may have occurred late in the period.

In this case, the synoptic setup was nearly identical to that on 22 October 2012 (see Fig. A.25). A stationary frontal boundary was draped across KS. In this case, it appeared to retreat to the north and west some overnight. Simulated 500 m AGL winds are shown in Fig. A.7. At 00 UTC, the frontal boundary is clearly evident in the wind field. South and east of the frontal boundary (including the SGP/FP1 site), strong uniform southerly flow was simulated. By 03 UTC, more NLLJ-like flow developed. The strongest zone of NLLJ winds was located over the SGP/FP1 site and slightly east. In the western portion of the NLLJ flow, wind direction began to turn westerly. At 06 UTC, the zone of strongest winds moved east. Most of area occupied by the NLLJ now had a westerly component. The frontal boundary retreated to the north and west while the NLLJ core moved to the east, suggesting that NLLJ motion was independent of frontal forcing. Finally at 09 UTC,

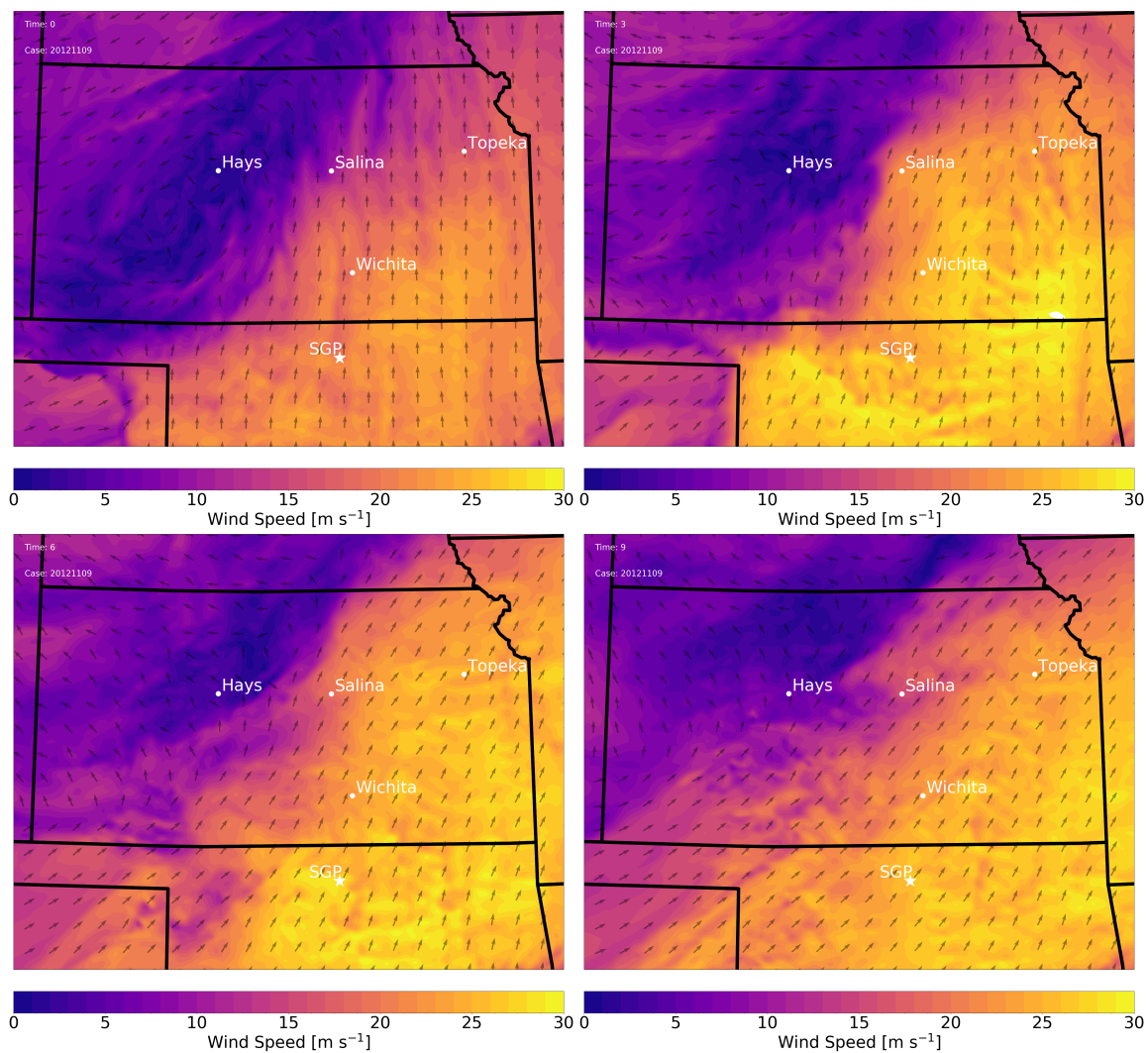


Figure A.27: WRF simulated wind speed at 500 m AGL on 09 November 2012 at 00, 03, 06, and 09 UTC.

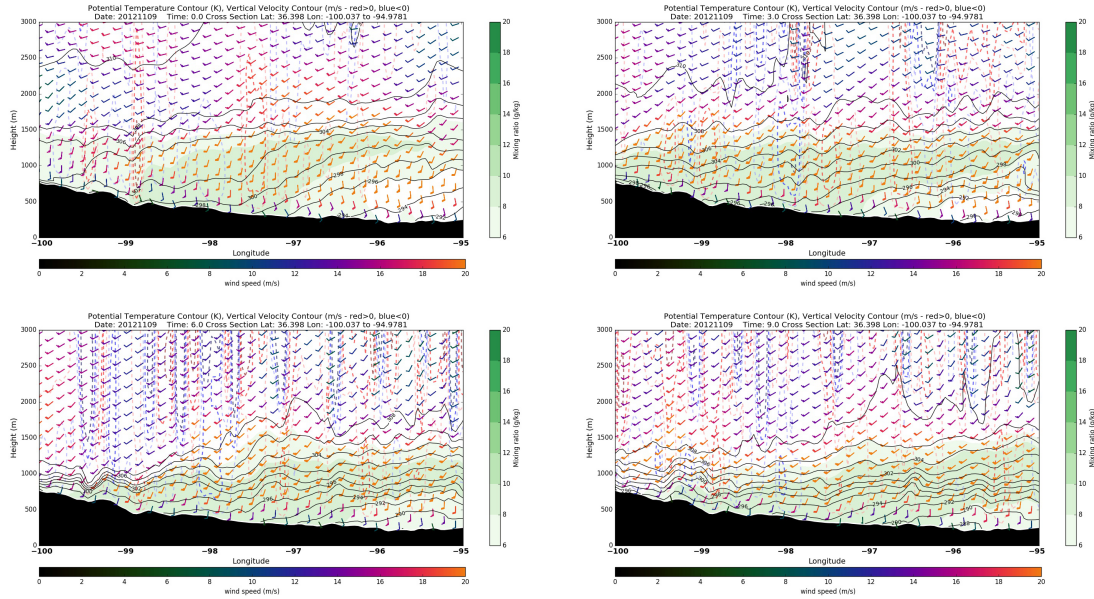


Figure A.28: As in Fig. 4.3 but for 09 November 2012 at 00, 03, 06, and 09 UTC.

the NLLJ core was located further east and winds continued to show a westerly component across the area occupied by NLLJ flow. The frontal boundary continued to retreat to the north and west.

Cross sections along the slope are shown in Fig. A.28. At 00 UTC, the frontal boundary is evident in the cross section where winds become weaker and vertical motion is strong near -99° W. East of that point winds were generally strong and southerly in the boundary layer (marked by the moisture field). In the lowest levels east of -97° W, a drier and less stable air mass was simulated. This feature persisted throughout the night and could explain why the observed NLLJ maximum (Fig. A.16) was higher than in other cases. By 03 UTC, more jet-like flow was simulated with a NLLJ maximum in the vertical profile. Over the eastern portion of the domain, westerly components were simulated near the top of the NLLJ. Well above the boundary layer the vertical velocity field was active. Within the boundary layer and away from the frontal boundary, a local speed and direction based convergence zone was simulated along with the associated vertical motion near -96.5° W. At 06 UTC, the zone of strongest NLLJ winds began to move east. This is most evident

by the NLLJ becoming deeper in the east but more shallow in the west. Wind direction developed a more widespread westerly component. At this time the region above the NLLJ had a very active vertical velocity field, making it difficult to discern if motions within the boundary layer were associated with local convergence or larger scale forcing. By 09 UTC, the NLLJ had moved even further east, again most evident by the NLLJ becoming deeper in the east but more shallow in the west. Westerly components in the wind direction were simulated throughout the NLLJ. At this time, a local speed and direction based convergence zone was simulated with a boundary layer confined vertical motion near -95.5° W.

This case showed most of the features of the identified spatial-temporal NLLJ evolution in the region not impacted by the frontal boundary. Through the night, the frontal boundary retreated to the north and west as the core of the NLLJ appeared to move from west to east. Wind direction became more westerly as the NLLJ veered in time and height. In some instances, vertical motion could be connected to local convergence due to NLLJ heterogeneity, but larger scale forcing also resulted in an active vertical velocity field in the gradually destabilizing layer above the boundary layer.