FLUX MEASUREMENTS IN THE STABLE BOUNDARY LAYER AND DURING MORNING TRANSITION

by

DAVID JOSEPH DURDEN

(Under the Direction of Monique Y. Leclerc)

ABSTRACT

The eddy-covariance technique measures fluxes of momentum and scalars fairly accurately under well mixed convective boundary layer (daytime) conditions. However, flux measurements are not accurately measured in the stable nocturnal boundary layer (NBL) or during the morning transition time without careful analysis. The impact of gravity waves on turbulence statistics and flux calculations is shown to be significant, resulting in overestimation of turbulent kinetic energy on the order of greater 50% at times. These wave events can also modulate flux calculations rendering the results erroneous. The presence of a low-level jet can also impact turbulence structure and flux calculations. It is demonstrated the decay of a low-level jet during the morning transition can influence the transport of heat and CO_2 during the morning transition. The objective of this thesis is to examine phenomena that impact these measurements and establish some quantitative estimates of the extent to which calculations are impacted.

INDEX WORDS: Errors in Flux Measurements, Bias in Flux Calculations, Stable Boundary Layer, Turbulence Inflation, Morning Transition

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DEDICATION

I would like to dedicate this work to my loving wife, beautiful family, supporting friends, and talented colleagues. Without all of their support this work would not have been possible. I would especially like to dedicate this to my Mother and Father, who believed in my abilities and nurtured my talents. I would also like to give thanks to the Lord. He gave me strength in times of weakness, fortified my beliefs, and pointed me in the right direction when I was lost.

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Tharpe, Dr. Ian Flitcroft and Dr. Chang for encouraging talks during and after these games.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The eddy-covariance technique measures fluxes of momentum and scalars fairly accurately under well mixed convective boundary layer (daytime) conditions. However, the inability to measure net ecosystem exchange accurately in the stable nocturnal boundary layer (NBL) and the morning transition is a problem that is well documented (Karipot et al., 2008; Mahrt, 1999; Mathieu et al., 2005). A lack of turbulence, stated to be approximately one tenth the turbulence intensity during daytime convective conditions, suppresses vertical transport of scalars such as water vapor and CO_2 during nighttime (Cheng et al., 2005). During a very stable night, CO_2 accumulates in the lower boundary layer as plants respire throughout the night. This phenomenon results in systematic underestimation of the CO_2 flux during the nighttime, without the introduction of a storage term or selective filtering (Baldocchi et al., 2000; Falge, 2001; Goulden, 1996).

Yet, the stable nocturnal boundary layer is characterized by these quiescent periods interrupted by sporadic, intermittent features, including eddies, roll vortices, and plumes (Cooper et al., 2006). These turbulent events can be initiated by various mechanisms, including density currents, microfronts, bores, solitary waves and low-level jets (Banta et al., 2003; Blackadar, 1957; Coleman and Knupp, 2011; Duarte et al., 2012; Karipot et al., 2006, 2008; Mahrt and Vickers, 2002; Mahrt, 2010; Means, 1952; Nappo et al., 2004, 2008, 2010; Prabha et al., 2007, 2008; Sun et al., 2004). Moreover, the processing of eddy-covariance fluxes in the nocturnal boundary layer can potentially be impacted by internal gravity waves, "submeso" motions, and advection (Mahrt, 2009; Nappo et al., 2008, Aubinet, 2010). Therefore, even with the introduction of a storage term, non-stationarity and intermittent turbulence convolute quantification of turbulent transport and storage measurements (Aubinet, 2008).

In fact, many micrometeorologists focus predominantly on fluxes during the daytime convective conditions to avoid the turbid data processing required for nighttime measurements, filling the nighttime gaps for long-term net ecosystem exchange calculations through purely empirical means. A common way to deal with the nighttime problems is to reject eddy-covariance data recorded under calm conditions including the morning transition, as determined by a threshold level of friction velocity (u_*) (Falge, 2001). Nighttime and transitional eddy-covariance data measured in turbulent conditions are then used to construct regression equations based on temperature so that ecosystem respiration can be calculated and used to replace rejected data from calm periods (Goulden et al., 1996; Baldocchi, 2003; Rannik et al., 2006). This approach is empirical lacking theoretical substance in both determining the filtering threshold and deciding on replacement data (Aubinet, 2010).

The CO_2 accumulates until suddenly being flushed by a sporadic turbulent event, whether generated by shear stress or gravity wave instability, advection through evolution of density currents, or morning transition. These turbulence events associated with gravity waves are often localized, and non-stationarity complicates quantification of their impacts. Low-level jets (LLJ) are common throughout the world and often persist into the early morning before decaying, and though extensive documentation illustrates the impact jets can have during the night, few if any studies have looked at their impact in coincidence with morning transition. There are a plethora of potential hazards when attempting to measure fluxes in the stable boundary layer and during the morning transition.

The identification of the wave component of the eddy-covariance data during the night is significant in the presence of gravity waves, as the wave signal may be mistaken for turbulence in the calculation of the fluxes. If this is the case, the wave signal should be removed to prevent “enhancement” of the turbulence fluxes being calculated (Nappo et al., 2008).This would ultimately lead to more precise estimates of net ecosystem exchange of CO_2 lending a better understanding of different ecosystems source/sink identity and the global carbon budget. Information about the flux associated with intermittent turbulence in the nocturnal boundary layer is needed to help modelers to make accurate parameterizations in their models.

The characteristics of the stable boundary layer (SBL) include sporadic turbulence, calm winds, waves, wave-turbulence interactions, and nocturnal jets. Grace et al. (1995) and more recently, Leclerc and her group found that, during very stable conditions, the overlying atmosphere is detached from the surface due to weak turbulence in stable conditions (Mathieu et al. 2005), resulting in a buildup of CO_2 in the lower region of the canopy (Grace et al. 1995; Karipot et al., 2006). Under these conditions, the analysis of eddy-covariance flux data is complicated by the intermittency generated by the breaking of atmospheric waves, flow meandering associated with the presence of jet and density currents (Hopfinger, 1987; Smedman et al., 1995).

In the application of the nocturnal boundary-layer budget technique, Mathieu et al. (2005) noticed that the presence of a jet core leads to confinement of gases beneath it within the nocturnal boundary layer thus providing the conditions required to calculate nocturnal fluxes using the NBL budget technique. In the presence of a low-level jet (LLJ), flux measurements in the stable boundary layer are influenced by upside-down boundary layer effect (Mahrt, 1999; Balsley et al., 2006; Banta et al., 2006). During such periods, turbulence is detached from the surface results in downward transport of turbulent kinetic energy (Banta et al., 2002). If the conditions result in a buildup of CO_2 during the night, what happens to this CO_2 in the morning as the jet decays?

This study evaluates the impact that two common nocturnal boundary layer phenomena have on turbulence statistics and flux calculations. Chapter 2 assesses the magnitude of inflation/modulation of the turbulence statistics and flux calculations in response to the passage of a large amplitude gravity wave. Chapter 3 examines the potential impact of the decay of an LLJ during the morning transition on turbulence and flux calculations. Finally, Chapter 4 extracts lessons and new knowledge drawn from these studies.

CHAPTER 2

ON THE IMPACT OF ATMOSPHERIC WAVES ON FLUXES AND TURBULENCE STATISTICS DURING NIGHTTIME CONDITIONS: A CASE STUDY [1]

[1] Durden, D.J., C.J. Nappo, M.Y. Leclerc, H.F. Duarte, G. Zhang, L.B.M. Pires, M.J. Parker, and R.J. Kurzeja. Submitted to *Biogeoscience*, 12/07/12

Abstract

The interpretation of flux measurements in the stable boundary layer is typically fraught with difficulties. This paper reports on how the presence of waves in a time series leads to overestimation of turbulence statistics and errors in fluxes calculations. Using time series of the pressure signal from a microbarograph, the presence of waves at a flux measurement site near Aiken, SC is identified and removed. Our findings suggest that filtering of eddy-covariance data in the presence of wave events prevents both an overestimation of turbulence statistics (inflated) and errors in flux calculations (modulated) which frequently arise in nocturnal measurements of fluxes and turbulence variables. This preliminary case study examines the variation of the wave signal and subsequent impact on both turbulence parameters and fluxes in two contrasting nights as a function of measurement level and different averaging times. The results showed that large amplitude wave-like events occurred on 31% of the nights considered in the present study. Remarkably, in low-turbulence environments, the presence of a gravity wave can enhance the turbulence statistics more than 50%. The presence of the wave modulates the calculated fluxes of CO_2, resulting in erroneous flux calculations of the order of 10% depending on the averaging time and pressure perturbation threshold criteria. In addition, u_* was affected by the presence of the wave, and in at least one case, a 10% increase caused u_* to exceed the oft-used arbitrary 0.25 ms^{-1} threshold used in many studies. These preliminary results suggest that biases due to nocturnal atmospheric phenomena can easily creep unnoticed into flux data. The impact of different averaging periods was variable dependent. This product of the amount of the wave cycle contributing to various averaging periods and dealt with the phase relationship of the variables being analyzed;

hence, these errors are primarily introduced through our processing methods. Better, more robust fluxes can be calculated when flux sites add an inexpensive microbarograph as part of their routine measurements.

Introduction

The eddy-covariance technique measures fluxes of momentum and scalars accurately in well-mixed convective boundary layer conditions (Aubinet, 2010; Falge et al., 2001; Goulden et al., 1996). However, challenges in measuring net ecosystem exchange, i.e. the net carbon dioxide taken up or released to the atmosphere, accurately in the stable nocturnal boundary layer have been reported (Aubinet, 2010; Karipot et al., 2008; Mahrt, 1999, 2010; Mathieu et al., 2005). The nocturnal boundary layer (NBL) is characterized by quiescent periods interrupted by sporadic, intermittent features, including eddies, roll vortices, and plumes (Aubinet, 2008, 2010; Balsley et al., 2002; Blumen et al., 2001; Cooper et al., 2006; Darby et al., 2002; Mahrt, 2010; Nappo, 1991; Nieuwstadt, 1984; Newsom and Banta, 2003; Salmond, 2005; Sun et al., 2002). Such turbulence events can be initiated by various mechanisms including density currents, microfronts, bores, solitary waves and low-level jets (Banta et al., 2003; Coleman and Knupp, 2011; Karipot et al., 2008; Mahrt and Vickers, 2002; Mahrt, 2010; Sun et al., 2004). Moreover, eddy-covariance fluxes in the nocturnal boundary layer can be impacted by internal gravity waves, “sub-meso” motions, and advection (Aubinet, 2010; Mahrt, 2009; Nappo et al., 2008). Therefore, even with the inclusion of a mean storage term, both non-stationarity in the time series and intermittent turbulence make the quantification of turbulent transport and storage difficult and prone to large errors (Aubinet, 2008).

Robust determinations of fluxes and turbulence statistics pose challenges in the stable nocturnal boundary layer. Though the properties and propagation of gravity waves have been extensively studied (Chimonas, 1993, 1999; Einaudi and Finnigan, 1981, 1993; Einaudi et al., 1984; Finnigan and Einaudi, 1981; Hooke et al., 1973; Nappo, 2002), less than a handful have examined the impact of waves on turbulence statistics and fluxes (Nappo et al., 2008; Viena et al., 2009).

Waves are ubiquitous in the nocturnal boundary layer (Gossard and Hooke, 1975; Grivet-Talocia et al., 1999; Nappo, 2002; Rees et al., 2000) and can be generated by a number of mechanisms, including thunderstorms, orographic excitation (terrain induced), and shear instability (Chimonas, 1993; Emmanuel, 1973; Gedzelman, 1983; Hooke et al., 1973). Ducted waves are bound between the ground surface and some atmospheric reflecting layer above (Cooper et al., 2006; Fritts et al., 2003; Newsom and Banta, 2003; Rees and Mobbs, 1988), thus producing a wave guide allowing propagation to occur over long distances and time periods.

Gravity waves and turbulence can easily be mistaken in turbulence statistics and fluxes due to the absence of a spectral gap between waves and turbulence (Finnigan, 1999; Viana et al., 2009). If this is the case, the wave signal should be removed to prevent errors in turbulence statistics (Nappo et al., 2008; Viana et al., 2009). This additional step in the signal processing of fluxes and turbulence statistics can lead to more accurate parameterizations of net ecosystem exchange of CO_2 and a better understanding of ecosystem exchange during periods of intermittent turbulence in the nocturnal boundary layer.

The present study investigates the effect of a large amplitude wave event on turbulence statistics and fluxes. A triple decomposition of eddy-covariance data is used to identify waves in the original signal (Hauf et al., 1996; Nappo et al., 2008). Our study assesses the magnitude of the overestimation (inflation) in turbulence statistics and errors in flux calculations on two nights in contrasting atmospheric conditions. In this paper, the variation of the wave signal and subsequent impact on both turbulence parameters and fluxes are evaluated in two contrasting nights as a function of measurement level and different averaging times.

Measurements

Site Description

Turbulence and eddy-covariance data were obtained from instruments located at 34, 68, and 329 m above ground level on a tower located near Beech Island, SC (33^{o}24'21" N, 81^{o}50'02" W) (Fig. 1). The tower is positioned on a rural ridge, at an elevation of ~116 m, overlooking a mixture of mixed pine forests and agricultural fields. Each eddy-flux system consisted of a fast-response omnidirectional three-dimensional sonic anemometer (Applied Technologies, Inc., Longmont, CO, Sx (34 m level) and A (68 and 329 m levels) models) and a fast-response open path CO_2/H_2O gas analyzer (Li-Cor Biosciences, Lincoln, NE, Model 7500). Measurements were collected at 10 Hz.

To detect wave-like activity, a microbarograph (Setra Systems, Boxborough, MA, Model 270) with static pressure disks (Vaisala, Helsinki, Finland, SPH10) was used to measure static atmospheric pressure at the surface. The pressure transducer continuously collected data at 20 Hz to a data logger (model CR5000, Campbell Scientific, Logan, UT) located at the base of the tall tower. The data were averaged to 0.1 Hz for the purpose of wavelet analyses.

Figure 1.1: (a) A microbarograph station and (b) the tall tower with flux measurement levels at 34, 68, and 329 m

Data Processing

A challenge in analyzing turbulent fluxes in the presence of waves resides in the recognition and subsequent separation of the wave from the turbulence signal (Finnigan, 1988). Previous studies used phase averaging to separate waves from turbulence (Einaudi and Finnigan, 1981, 1984, 1993; Finnigan and Einaudi, 1981). However, phase averaging requires a monochromatic wave that persists for more than several cycles, a rare occurrence in the NBL. Waves observed in the atmosphere are typically non-linear and persist for only a few cycles. Therefore, the method applied by Hauf et al. (1996) and Nappo et al (2008) using band-pass filtering to separate waves from turbulence was used. The first step in the analysis consists of identifying periods of wave activity using wavelet analysis of surface pressure data to determine time, duration, and period/frequency ranges of wave-like activity. The data are then band-passed filtered to estimate the amplitude of wave-like perturbations of wind components (*u*, *v*, and *w*), temperature, water vapor, and carbon dioxide. These wave perturbations are then removed from the original time series, and the remaining signal is considered to be the 'true' turbulence signal, i.e. Reynolds decomposition. The original unfiltered signal is referred to as the "wave inflated" signal.

The Morlet wavelet was chosen in our study for its high resolution in frequency space, which is instrumental in accurately determining the period/frequency range of the wave events (Nappo, 2002; Torrence and Compo, 1998). Once the frequency range of the wave, its duration, and the start time of the individual wave episodes are determined, the data is then detrended and band pass filtered. This process is repeated for each variable at each of the three levels on the tower. The 10 Hz eddy-covariance data selected includes one hour before and after the wave event in the band-pass filter to prevent edge effects from being introduced into the turbulence and flux calculations. A three-dimensional rotation, forcing the vertical and lateral wind components to zero, was performed on the entire time series (i.e. a four hour period) before filtering the three-wind components. Therefore, a triple decomposition of a given variable $q(z,t)$ is performed as follows:

$$q(z,t) = \bar{q}(z) + q'(z,t) + \tilde{q}(z,t), \tag{1}$$

where the terms on the right-hand-side represent the mean, turbulence, and wave components respectively. If the wave signals are not removed, then the resulting flux would be:

$$\overline{w'q'}^{original} = \overline{(w - \bar{w})(q - \bar{q})}. \tag{2}$$

Using this triple decomposition on *w* and *q*, the vertical flux of *q* is given by:

$$\overline{w'q'}^{corrected} = \overline{(w - \bar{w} - \tilde{w})(q - \bar{q} - \tilde{q})}, \tag{3}$$

where Eq. (3) is the turbulence flux with the wave signals removed taken to be the true Reynolds flux. The Webb, Pearman, and Leuning (1980) correction was applied to flux measurements, for both the original flux signal and the wave corrected signal. This process illustrates the effect of a gravity wave on fluxes calculated in the customary way, such as with an automated routine.

Data Selection

Only large-amplitude events in the pressure data were investigated in this study. To detect large amplitude events, the pressure signal for 38 nights from 00:00 to 06:00 EST was band-pass filtered so that the residual signal was composed of frequencies corresponding to contributions from 3 to 30 min periods. The standard deviation (σ_p) of the static pressure was calculated from this residual signal and $3\sigma_p$ was determined to be the detection threshold of large amplitude events. The $3\sigma_p$ threshold was chosen to include the events that would have the most impact on turbulence statistics and flux calculations. Assuming that σ_p is calculated over a long enough period to provide a normal distribution, using a $3\sigma_p$ threshold would render only the top 0.3% of cases as large amplitude events. However, the nature of the wave-like disturbances is such that the crests and troughs are the major contributing factors to the large σ_p and the majority of the body of the wave falls within a single standard deviation.

The number of large amplitude events, both wave-like and otherwise, was determined for the period April 22nd to June 9th, 2009. During this period, 11 days were disregarded due to rain or erroneous data. At least one large amplitude event occurred during 16 of the remaining 38 nights. Using the wavelet transform, 12 of the 16 events were considered wave-like. The other cases were indicative of large amplitude events that occurred over many frequencies and did not display a cyclic nature. It should be noted here that not all of the identified events may be attributed to gravity waves, as other phenomena e.g. Kelvin Helmholtz instabilities, density currents, and solitary waves, may also contribute to the large amplitude events observed; yet, all are expected to influence turbulence statistics and flux calculations.

Wave-like motions were observed on most nights of the 38 nights examined, many times the amplitude of the event was small or the period of the wave event was larger than the period of interest, i.e., 30 min. The present analysis was restricted to waves with a period less than 30 minutes, a typical averaging time scale used for flux calculations. However, both turbulence statistics and fluxes are calculated over various averaging periods to assess their impact on the calculations.

Two nights, April 23rd and December 3rd, 2009 were selected for this study to evaluate wave contributions to turbulence statistics and flux calculations for contrasting nights, one quiescent and one turbulent night. These two nights were also selected due to wave propagation through all three levels of the tall tower.

Results and Discussion

Detection of Wave Events

The morning hours (00:00 to 06:00 Eastern Standard Time (EST)) of April 23rd and December 3rd, 2009 exhibited well-defined wave episodes as shown in Fig. 2. Between 02:30 and 04:30 on April 23rd, one wave disturbance occurred with an approximate period of 7 min and another with an approximate period of 4 min. On December 3rd, 2009, a wave disturbance between 03:30 and 05:30 occurred with an approximate period of 8 min and another with an approximate period of 12 min. Both nights consisted of multiple events that persisted only several cycles with non-constant amplitudes. Summarizing, the average wave periods and durations of these selected episodes was 5.5 min from 02:30 to 04:30 on April 23rd and 10 min from 03:30 to 05:30 on December 3rd.

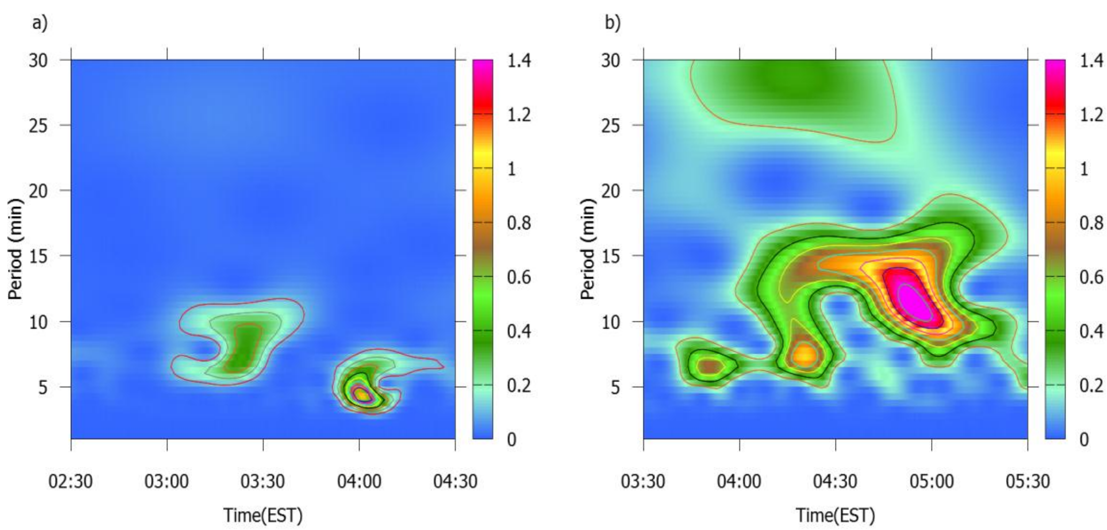

Figure 1.2: Wavelet analysis of surface static pressure data from the microbarograph sensor for (a) April 23rd and (b) December 3rd, 2009. Increases in

wavelet energy density during periods of wave-like activity are used to identify wave period and duration.

Since the wave introduces an error in the analysis of the time series overestimating turbulence properties, it follows that an uncorrected signal will lead to errors being introduced throughout all calculations, including the stability parameter (Ri_f) and u_*. Thus, the nights are characterized by the Bulk Richardson number (Ri_B) between the 68 and 329 m levels. April 23rd was a calm quiescent night with an average Ri_B of 2.64 and friction velocities (u_*) less than 0.2 ms^{-1} during the passage of the wave events. A triple decomposition (Eq. (1)) of the eddy-covariance data was applied to the periods identified in the wavelet analysis using the wave period range in a bandpass filter to obtain the wave signal for all variables. The quiescent night was disrupted by the passage of the wave, which induced large fluctuations in the time series as seen in Fig. 3 at the 34 m level. These fluctuations are observed in both the velocity components and scalar quantities beginning slightly before 04:00 and persisting until approximately 04:30. This coincides with the strongest event detected using the wavelet analysis. These fluctuations create non-stationarity in the signal that can be resolved by removing the wave (Fig. 3c).

December 3rd presents a different set of atmospheric conditions. During that night, the average Ri_B was 0.13 and u_* exceeded 0.25 ms^{-1} for all heights on the tower throughout the night. The impact of the wave on the atmospheric variables can be seen; nevertheless, the impact observed is modest when compared to April 23rd. This is in part due to the larger amount of turbulence present simultaneously with the wave: the degree of error is proportional to the turbulence levels present in the signal. The difference in the period of the waves observed on the two nights may also contribute differences observed.

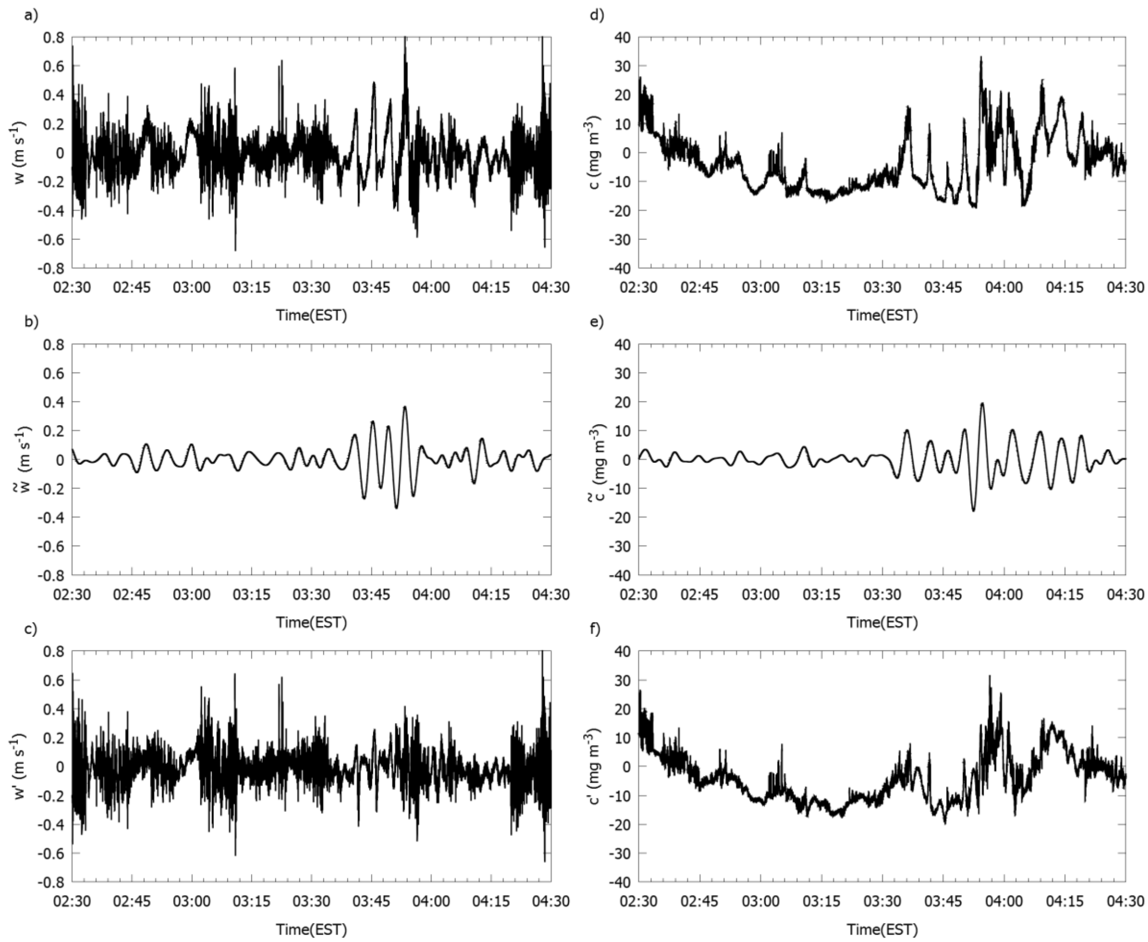

Figure 1.3: Triple decomposition of variables *w* and *c* are represented as detrended signals (a) *w* and (d) *c*, wave signals (b) $\tilde{w}$ and (e) $\tilde{c}$, and turbulence signals (c) *w*' and (f) *c*' at the 34m level on the tall tower on the night of April 23rd. Bottom figures represent the "corrected" turbulence signal.

Using the triple decomposition, the phase relationship between $\tilde{w}$ and $\tilde{T}$ at 34, 68, and 329 m for the observed periods is evaluated to identify whether the wave-like disturbance is indicative of a gravity wave. Also evident are the differences in amplitude, timing, and structure of the wave event with measurement level. Large differences in wave amplitudes and structures for each of these observation periods can be seen in Fig. 4a-f. Waves observed on April 23rd have a higher frequency and amplitude. Figure 4 represents $\tilde{w}$ and $\tilde{T}$ for the three heights of the TV tower (34, 68, & 329 m). The phase relationship between $\tilde{w}$ and $\tilde{T}$ at the beginning of the wave activity is approximately 90^{o} on both April 23rd and December 3rd, 2009 attesting to the presence of gravity waves each night. It is also evident that the waves are present at the 329 m level, suggesting that waves propagate throughout the nocturnal boundary layer.

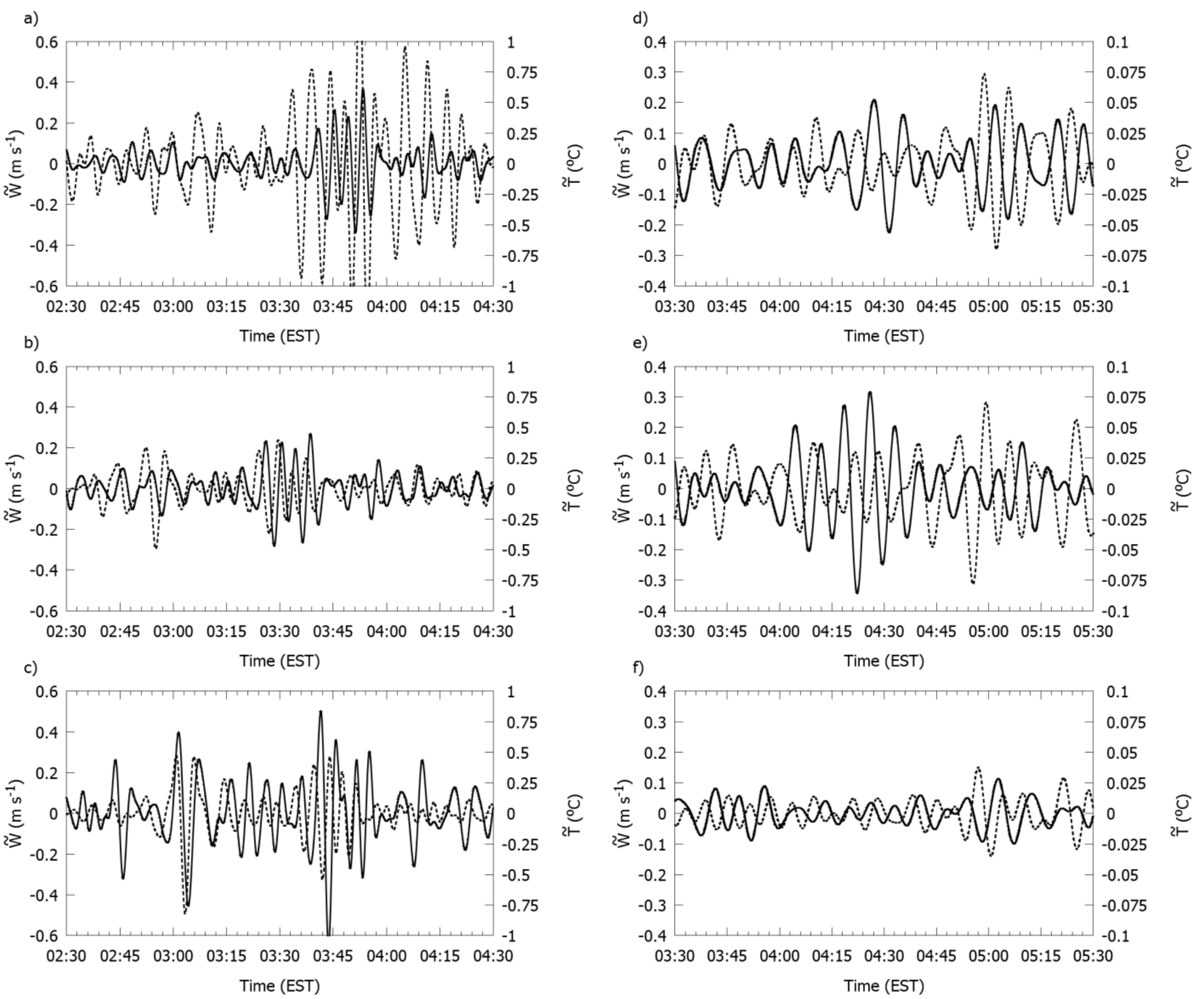

Figure 1.4: $\tilde{w}$ (solid) and $\tilde{T}$ (dashed) at 34, 68, and 329 m for April 23rd (a, b, and c) and December 3rd, 2009 (d, e, and f). The phase relationship between $\tilde{w}$ and $\tilde{T}$ is observed to be ~90^o out of phase during the wave activity, except during the large amplitude event occurring around 05:15 on December 3rd where $\tilde{w}$ and $\tilde{T}$ appear to be 180^o out of phase.

Wave-modified Turbulence Statistics and Fluxes

Nappo et al. (2008) found turbulence statistics to be consistently larger in the presence of gravity waves. Hence, the term "turbulence inflation" was ascribed to the phenomenon. The percent of turbulence inflation is defined as:

$$\% \text{ Error} = \left(\frac{\text{"inflated" flux} - \text{"de-waved" flux}}{\text{"inflated" flux}}\right). \tag{4}$$

Fluxes were calculated using different averaging blocks. These calculations reveal the potential differences varying averaging blocks can have when calculating fluxes in the presence of wave phenomena and provide a quantitative estimate of the impact the wave event has throughout the duration of the event.

Turbulence statistics and fluxes were calculated using averaging blocks of 5, 10, 15, 30 and 60 min. Values of "inflated" TKE from the original signal, "corrected" TKE, and percent error are given for April 23rd at 34m (Fig. 5a-d) and 329m (Fig. 5e-h). The turbulence statistics calculated in the presence of a wave are consistently inflated if the averaging time is longer than the wave period for the cases presented (Fig. 5), corroborating the findings of Nappo et al (2008). However, Nappo et al. (2008) also found that for averaging times less than the wave period, wave perturbations had little impact on turbulence calculations. As shown in Fig. 5, it can be seen that inflation is present for averaging times longer than the period of wave event. For shorter averaging times, modulation of the signal is observed with inflation observed in the form of localized bursts during the time of the wave events. It is interesting to note that the percentage turbulence inflation was consistent with height despite much larger TKE values at the top measurement level. To further evaluate the impact of different averaging times, ensemble averages of turbulence statistics and fluxes for the entire wave event were calculated for the different averaging periods.

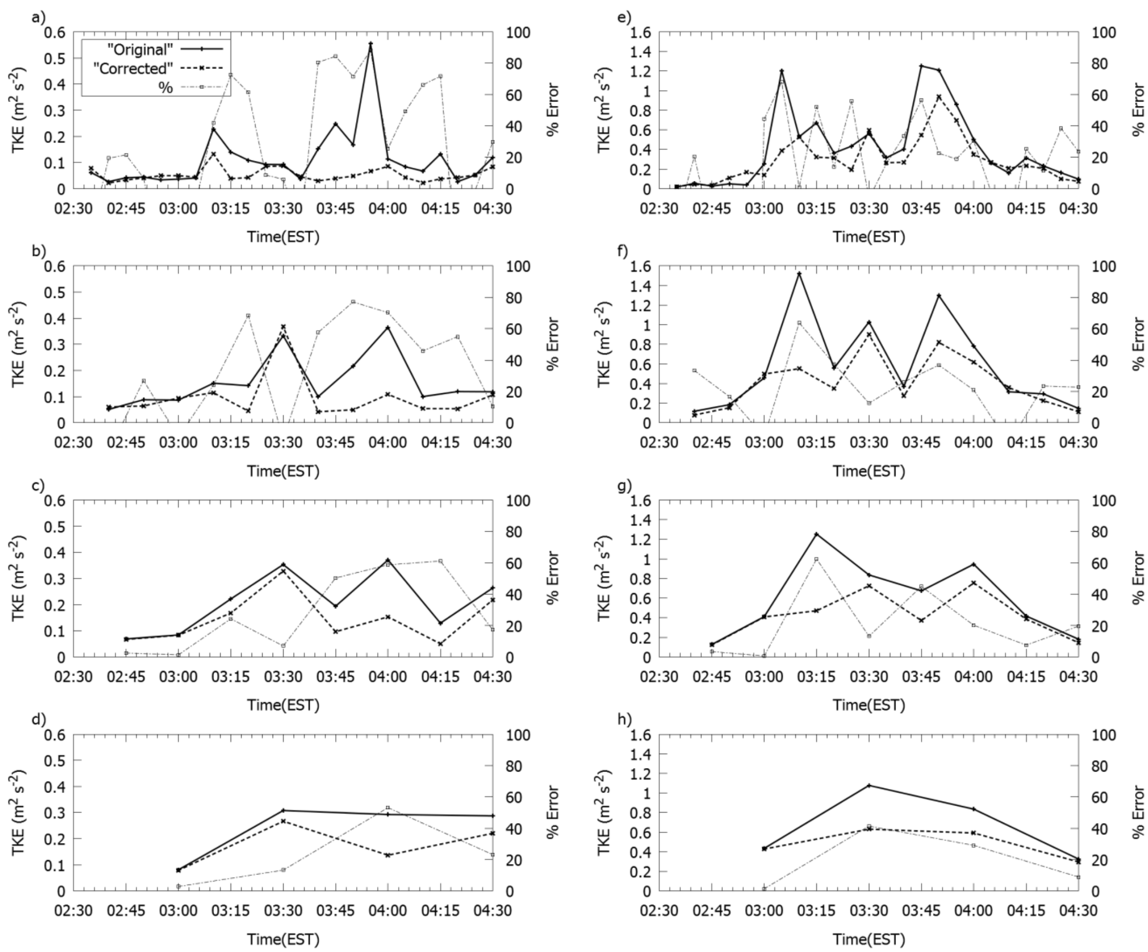

Figure 1.5: Turbulent kinetic energy calculations using the original signal ("original") and the corrected signal after wave removal ("corrected") from the time series at 34 (a, b, c, and d) and 329 m (e, f, g, and h) levels on the tall tower using different averaging periods (5, 10, 15, and 30 min) on April 23rd, 2009. The degree of overestimation ("% Error") is also presented.

Fluxes of heat, momentum, water vapor, and CO_2 are not consistently inflated the way turbulence statistics are. Instead, fluxes are often modulated depending on the phase relationship of the calculated variables. Therefore, average "original" and "corrected" fluxes for the duration of the wave events were calculated, and an average percent difference was calculated:

$$\text{Average \% Error} = \left(\frac{\text{"original" flux} - \text{"corrected" flux}}{\text{"original" flux}}\right), \tag{5}$$

where the overbar represents averaging over the duration of the wave event. The averaged turbulence kinetic energy (<TKE>), friction velocity (<u_* >), and CO_2 flux (<F_c>) are presented in Figs. 6a through f and 7a through f, for the 34 and 329 m levels on the nights of April 23rd and December 3rd, 2009, respectively.

The turbulence kinetic energy is overestimated on both nights for all averaging periods, but the percent error is far greater on April 23rd, due to less ambient turbulence during the passage of the wave. u_* is also overestimated for all averaging times throughout all levels of the tall tower for each night as well, except for the 60 min average at the 329m level on April 23rd and 5 min average on December 3rd. The inflation observed at the 329m level when shorter averages were used lead to u_* exceeding the

0.25 ms^{-1} friction velocity threshold, of significance to the flux community. This arbitrary threshold is often used in determining the validity of data in the nocturnal boundary layer (Aubinet, 2008, 2010; Falge et al., 2001; Goulden, 1996). The impact of the wave on u$_*$ is present at all heights on the tower producing differences of up to 30% for the shorter averaging periods at the 34 and 68 m levels on April 23rd. The difference is smaller with longer averaging periods, but nonetheless yields a difference of 10% for the 30 min average at both the 34 and 329 m levels. In contrast, December 3rd is only marginally impacted due to large contributions from high frequencies and the mildly stable conditions.

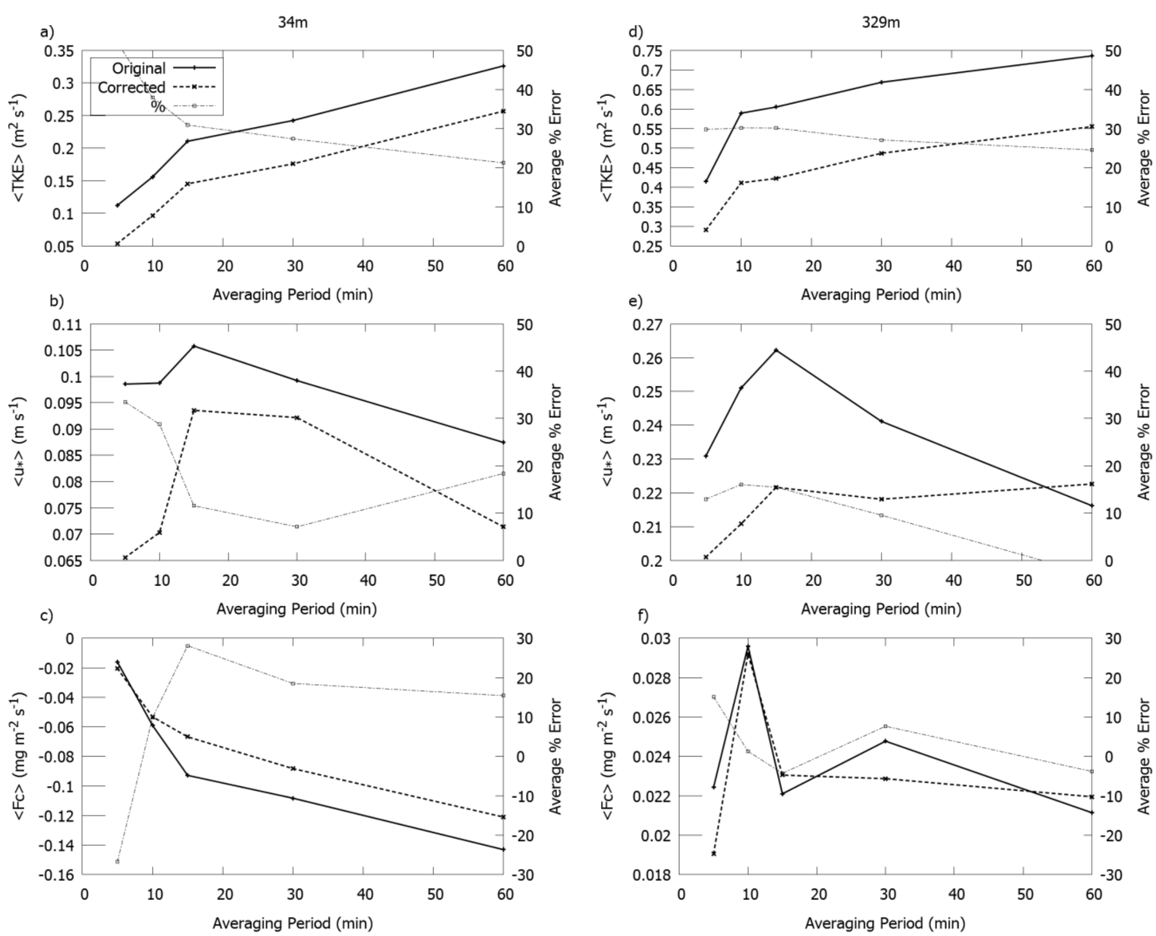

Figure 1.6: Average turbulent kinetic energy (<TKE>) , u_* (<u_* >), and CO_2 flux (<F_c>) in the “original” and “corrected” time series during the wave event on April 23^{rd} at the 34 (a, b, and c) and 329 m (d, e, and f) levels on the tall tower are depicted using different averaging periods. The average percent error introduced by the absence of such corrections is also displayed.

On December 3^{rd}, 2009, the CO_2 and sensible heat fluxes (not shown) are inflated for all averaging times at all levels on the tower by relatively small amounts (< 5%), though the degree of inflation is consistent amongst all variables evaluated (Fig. 7a-f). April 23^{rd} presents a somewhat special case as the sensible heat flux at the 34m level is positive (not shown) and the CO_2 flux is negative, in contrast with typical nighttime flux tendencies (Fig. 6c). Zeri and Sa (2010) observed similar behavior during the passage of a wave event in their study, which they attributed partially to the horizontal flux of CO_2 induced by the wave. In our study, the magnitude of the negative CO_2 flux is amplified by 15-30% for the longer averaging times (15, 30, and 60 min). This could contribute considerably to the nighttime net ecosystem exchange for this night as the rest of the night produced little transport of CO_2. These data suggest that a “contamination” of the signal by wave events leads to erroneous turbulence statistics and fluxes.

The variability in the amount of overestimation of turbulence statistics and errors in flux calculations varies little with height considering the percentage error. However, when the difference in the values of the turbulence statistics and fluxes are considered the amounts changed significantly. For instance, on December 3^{rd} the TKE values at the 34 m level were nearly double that measured at the 329 m level. Yet, the percentage inflation was very similar between the two levels, within 1% difference. Similar results were found on April 23rd with the percentage of overestimation for the two measurement heights being similar, while the values of TKE are nearly double at the 329 m level.

For the two nights studied the impact of averaging time on the error observed in the calculations varies with the choice of the variables. Consistently, it was observed that taking longer averaging periods results in more robust estimations of TKE, with the exception of 5 min averaging at both levels on December 3rd. The degree of error in F_c varies both nights with averaging time. The error is generally small for averaging periods of 5 min and at its maximum for 10 to 15 min averaging periods. The error decreases for the longer averaging periods ranging between 30 to 60 min. These results suggest that the wave frequency/period and its relation to the averaging period is important in determining the errors produced. The amount of the wave included in the averaging period varies as we typically tend to calculate data at easy discernible time periods, such as the beginning of the hour (i.e. 04:00). These errors are primarily introduced through our processing methods. This suggests that waves of different periods impact the turbulence statistics and flux calculations differently. Further studies will be needed to assess the degree to which the calculations are.

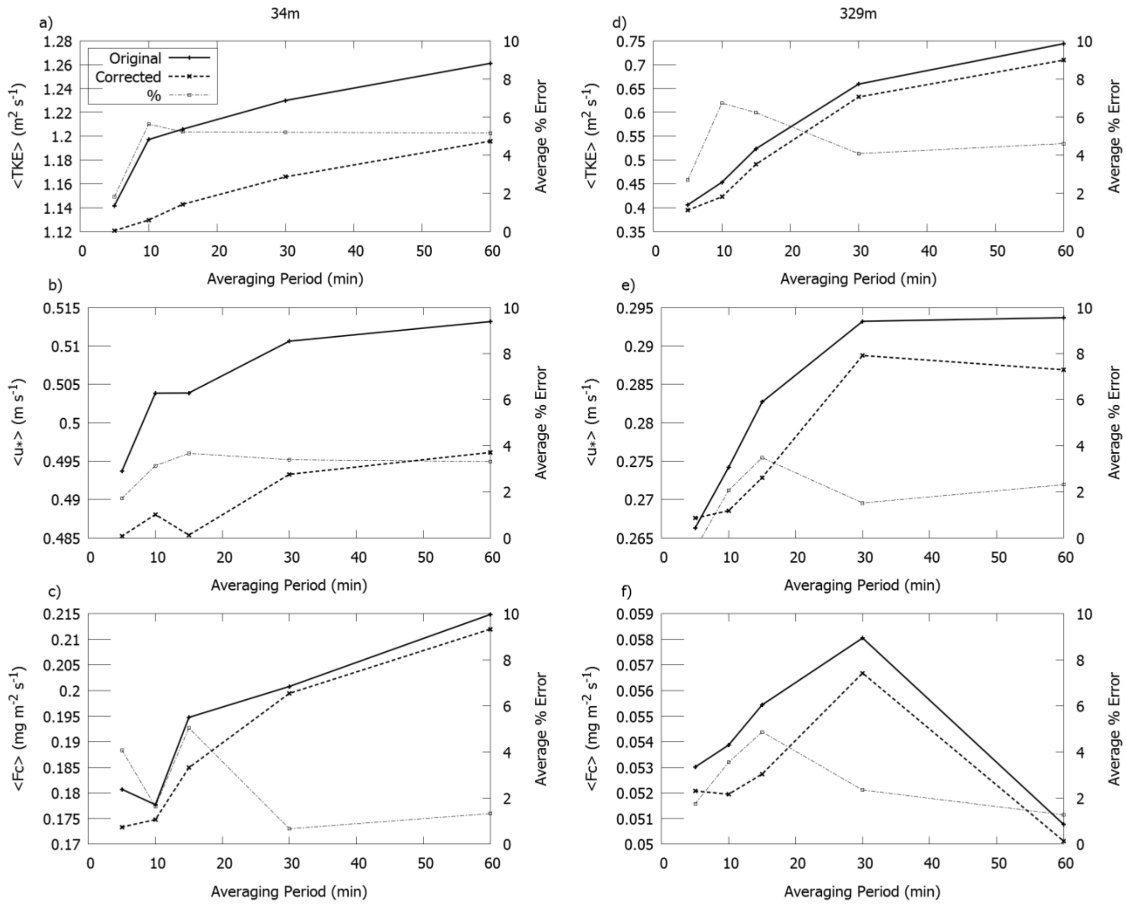

Figure 1.7: Average turbulent kinetic energy (<TKE>) , u* (<u* >), and CO_2 flux (<F_c>) for the "original" and "corrected" time series during the wave event on December 3rd, 2009 at the 34 (a, b, and c) and 329 m (d, e, and f) levels on the tall tower are depicted using different averaging periods. The average percent error introduced by the absence of such corrections is also displayed.

Conclusions

Our findings suggest that, without proper filtering, turbulence statistics would be overestimated due to the presence of wave phenomena as found by Nappo et al. (2008) and Viena et al. (2009). Our study has also examined the role of filtering the wave component and has assessed the magnitude of errors introduced in turbulence statistics and fluxes on two nights with contrasting atmospheric conditions. On relatively quiescent nights, large overestimates of TKE and modulation of fluxes have been found to occur during large amplitude wave activity. The extent of the inflation and the sensitivity of the turbulence statistics and fluxes to various wave periods and amplitudes is unknown thus suggesting a more exhaustive analysis. The data used in the present study demonstrate that nights characterized by large TKE and u_*(~0.5ms^{-1}) values are only slightly impacted by the presence of the wave (<5%). Therefore, particular attention must paid to cases close to the typical u_* threshold of 0.25 ms^{-1}, when using u_* threshold as a filtering parameter in net ecosystem exchange calculations.

In addition, results suggest that large amplitude wave-like events can occur frequently at certain sites, and should be removed from the signal during the processing of eddy-flux algorithms. The present study has shown that the presence of large amplitude wave-like events occurred on 31% of the nights studied. The presence of these large amplitude wave events was shown to impact the calculation of both turbulence statistics and fluxes in the nocturnal boundary layer. Without proper filtering, inflated turbulence statistics of up to 50% and erroneous flux calculations may occur on quiescent nights. The presence of the wave also modulates the calculated fluxes of CO_2, resulting in errors in the flux calculations of the order of 10% over the duration of the wave depending on the averaging time used. These errors will persist in varying degrees, regardless of the selected averaging period.

The impact of the wave on turbulence statistics and fluxes varies with height in the stable nocturnal boundary layer due to differences in turbulence and wave propagation properties. The variability in the amount of overestimation of turbulence statistics and errors in flux calculations appears to be relatively consistent with height when considering the percent error. However, when the difference in turbulence statistics and flux values are considered, their differences become magnified. The impact of averaging time on the overestimation turbulence statistics and errors in flux calculations varied with the choice of examined variable. The amount of the wave cycle included in an averaging period varies as we typically tend to calculate data at convenient time intervals, such as the beginning of the hour (i.e. 04:00). These errors are primarily introduced through signal processing. This suggests that waves of different periods would impact the turbulence statistics and flux calculations differently.

These results suggest that it is important to identify wave activity and remove them when calculating turbulence parameters and fluxes. Doing so leads to a higher level of integrity in turbulence statistics and flux calculations. Neglecting to do this is likely to lead to overestimated turbulence statistics and erroneous flux calculations. Thus, the addition of a microbarograph to flux sites is an inexpensive way to provide information leading to better flux calculations in the nocturnal boundary layer a segue to better long term estimation of carbon exchange. Furthermore, a climatological study seeking to determine possible long term consequences of not filtering the wave signal and better determinations of the threshold for large amplitude events is necessary. The present study has found a consistent overestimation of turbulence statistics for averaging times greater than the wave period. Cases where the wave period is greater than the averaging period exhibit errors in the resulting turbulence statistics and fluxes as the results were modulated by the presence of the wave. The possibility of restoring stationarity by removing the wave signal in cases with larger periods is intriguing and worthy of consideration. An examination on the impact of removing waves characterized by longer periods from turbulence and flux calculations appears warranted.

CHAPTER 3

IMPACT OF A LOW-LEVEL JET ON THE MORNING TRANSITION[2]

[2] Durden, D.J., M.Y. Leclerc, H.F. Duarte, G. Zhang, L.B.M. Pires, M.J. Parker, and R.J. Kurzeja. To be submitted to *Agricultural and Forest Meteorology*

Abstract

This study explores the dynamics of the morning transition. Recent studies have shown that much of the heating in the lower boundary layer is initially caused by entrainment from the residual layer. The interpretation of eddy-covariance measurements remains challenging at best during the morning transition. This paper examines the impact of low-level jet decay on the morning transition: it examines its role in modulating the turbulence structure throughout the boundary layer right to the surface. It is found that surface heating weakens stability in the early morning causing the low-level jet decay which then carries air from aloft to the surface. The CO_2 flux was modestly positive throughout the night indicating upward transport, but larger transport is observed during the initial surface heating at the 34 and 68 m levels. Then, as the jet decay occurs the mixing that ensues results in a large burst of CO_2 being transported up past the 329 m level. The jet decay initiates turbulence and transport of heat and CO_2 that would appear to be purely a result of surface heating without further inspection of processes at higher levels in the boundary layer. The implications of these findings on flux measurements of surface-atmosphere exchange are discussed.

Introduction

Low-level jet (LLJ) is a frequent phenomenon present in the nocturnal boundary layer. The term low-level jet was first coined by Means (1952) to describe low-level accelerations in the wind profile. Blackadar (1957) proposed that the flow acceleration was due to decoupling from the surface above the nocturnal inversion, known as the Blackadar mechanism. Often, jets are described as wind maxima with a peak surpassing some threshold (i.e. 2 m s^{-1}), greater than the winds above and below the jet core (Andreas et al., 2000; Karipot et al., 2008). Low-level jets can result from a host of atmospheric phenomena including baroclinicity, fronts, katabatic flows, inertial oscillations, and land-sea breezes (Banta et al., 2002; Buckley and Kurzeja, 1997; Darby et al., 2002; Whiteman et al., 1997). They are important features of the nocturnal stable boundary layer as they can induce turbulence and mixing through enhanced shear (Banta et al., 2002, 2003, 2006; Karipot et al., 2006, 2008; Prabha et al., 2007; 2008) and transport pollutants to locations long distances from their origin (Corsmeier et al., 1997). During a low-level jet, “non-traditional” vertical turbulence structure may occur with turbulence generated aloft and transported to the surface (“upside-down boundary layer”) (Mahrt, 1999; Mahrt and Vickers, 2002; Banta et al., 2006). Corsmeier et al. (1997), Wu and Raman (1998), Beyrich and Klose (1988) and more recently Sogachev and Leclerc (2011) demonstrated the importance of LLJs in transporting scalars and demonstrated the role of jets in entraining scalars to the surface hundreds of kilometers away from their sources. This downward transport of scalars is of particular relevance in the interpretation of surface-atmosphere exchange studies concerned with the analysis of both CO_2 fluxes and air quality measurements.

The decay of low-level jets represents an important facet of the jet dynamics and yet, it has received scant attention. The potential of the jet decay to impact temperature and scalar quantities was first documented by Izumi (1964) followed by Izumi and Brown (1966). These studies documented the changes that occurred in temperature, wind speed, and mixing ratio during the dissipation of a LLJ before the morning transition, though it was noted that jets generally decay during the morning transition at their site.

Izumi (1964) characterized the changes that occurred during the LLJ decay and nocturnal inversion dissipation and suggested that turbulence plays a large role in the breakdown of both. He noted warming at the upper levels before sunrise, with more rapid warming immediately after sunrise at the upper levels, while observing continuous cooling at the intermediate levels, below the inversion and above the surface heating. Izumi and Brown (1966) performed a case study on a jet, where complete dissipation of the LLJ occurred before sunrise. They noted three distinct stages, a period of abrupt and simultaneous warming and drying, followed by steady temperature, mixing ratio, and wind speed, and finally ending with decreasing temperature and wind speed with a marked increase in mixing ratio. In a more recent study, Karipot et al. (2006) linked intermittent turbulence near the surface to the intermittency of the jet activity throughout the night, where weakening of the jet core coincided with enhanced turbulence.

Newsom and Banta (2003) showed that high shear in sufficiently thin layers results in shear-instability waves that interact with and generate turbulence, indicating that jet activity can reduce stability and result in turbulence generation. Other studies have suggested a modulation of the turbulence structure with an enhancement of the larger eddies during jet events (Duarte et al., 2012; Karipot et al., 2008). Banta et al. (2003) developed a jet Richardson number, incorporating the speed to height ratio into the Richardson number equation:

$$Ri_j = \frac{g}{\theta}\frac{\Delta\theta/\Delta z}{(Uj/Zj)^2}, \tag{1}$$

where Uj and Zj are the LLJ speed and height respectively and $\Delta\theta/\Delta z$ represents the gradient of potential temperature. Ri_j demonstrated a significant relationship with production of turbulent kinetic energy for field measurements and those conducted in a climate-controlled wind tunnel (Banta et al., 2003; Ohya et al., 2008).

The morning transition from the stable nocturnal boundary layer to daytime convective conditions has received some attention in recent studies (Angevine et al., 2001; Angevine, 2008; Lapworth, 2006), particularly in modeling efforts to better understand the dynamics during the transitional period (Beare, 2008). Lapworth (2006) showed that it can take several hours for the sensible heat flux to become positive in the morning, and that heating of the surface layer is predominantly due to turbulent diffusion of entrained air from the residual layer. The transition is enabled by surface heating weakening stability while warming of the lower boundary layer is largely driven by shear-induced entrainment (Angevine et al., 2001).

The stable boundary layer (SBL) forms as a result of radiative cooling of the surface. Above the SBL, a neutral residual layer is found. Entrainment of the warmer air from the residual layer is an important process associated with the growth of the convective boundary layer. Angevine (2008) suggests that the process of entrainment during the morning transition is as important as surface heating in determining heat, moisture, and pollution composition of the daytime boundary layer. The presence of a low-level jet during the morning transition is an additional variable that can potentially impact the turbulence structure of the boundary layer during transition and influence fluxes of heat, water vapor, and CO_2.

The goal of the present study is to assess the impact of LLJ decay on the turbulence structure of the boundary layer and to determine the subsequent effects on fluxes of heat, water vapor, and CO_2 during the morning transition. In particular, an emphasis is placed on the physical processes that occur when a low-level jet decays during the morning transition.

Observational Methods

Description of measurements and instrumentation

Measurements were performed at and around the Savannah River Site (SRS). Sodar data were used to identify low-level jets, turbulence structure, and general changes in the atmospheric flow throughout the nights from April 23rd to May 26th, 2009. The high resolution Scintec sodar with a RASS extension (model SFAS, Scintec Corp., Rottenberg, Germany) provides vertical profiles of wind speed and direction, vertical velocity, temperature, turbulence kinetic energy, and shear. The Scintec sodar collected 15-min averaged profiles from 20-300 m above ground level (AGL) with 5 m vertical gate resolution. 15-min averaged temperature profiles from the RASS extension were available several nights with 10 m vertical gate resolution from 40-300 m AGL. The Remtech sodar (model PA2, Remtech SA, Vélizy Cedex, France) provided coarser 20-m vertical gate resolution from 20-1200 m AGL, but was an integral instrument to this study as many jets formed above the 300 m range set for the Scintec sodar. The Remtech sodar was programmed to retrieve 15-min average profiles of the three components of wind velocity and standard deviations.

Turbulence and flux calculations were obtained from three eddy-covariance (EC) systems located at 33.5, 68, and 329 m above ground level on a tall tower located near Beech Island, SC (33^{o}24’21” N, 81^{o}50’02” W) (Fig. 2.1a). The tall tower is positioned on a rural ridge, at an elevation of ~116 m, overlooking a mixture of mixed pine forests and agricultural fields. Each eddy flux system consists of a three-dimensional sonic anemometer (Applied Technologies, Inc., Longmont, CO) and a fast-response open path CO_2/H_2O gas analyzer (Li-Cor Biosciences, Lincoln, NE). Measurements were collected at 10 Hz. Another eddy-covariance system (~2 m), an automated weather station (Campbell Scientific, Logan, UT), and a set of seven microbarographs (model 270, Setra Systems, Boxborough, MA) were deployed at the base of the tall tower. Locations are within an approximate 20 km radius surrounding the Savannah River Site.

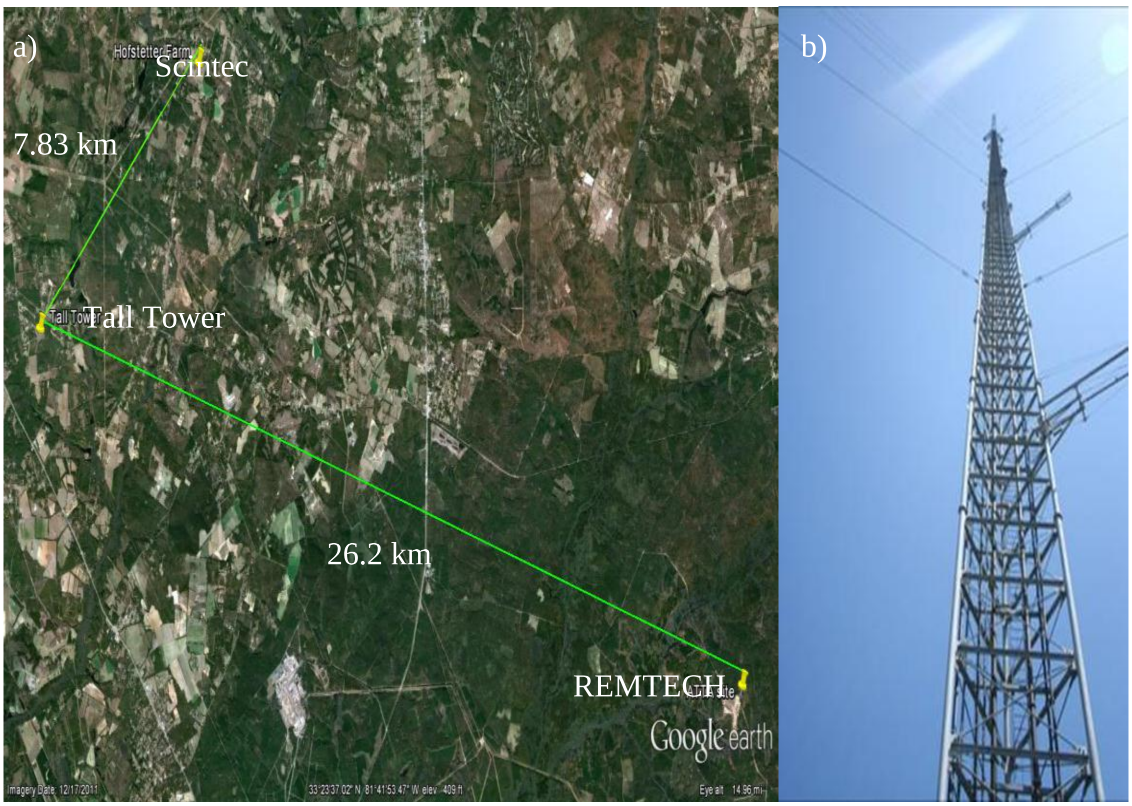

Figure 2.1: (a) Satellite image of the area highlighting the instrumentation locations and distances between the sodars and the tall tower site and (b) a picture of the 450 m tall tower.

Data selection and processing

Gaps in the Remtech sodar measurements were "gap filled" by a cubic spline interpolation routine as a function of height to lend more robust results to the jet detection program. The spline interpolation was allowed to interpolate the 15-min profile output for gaps less than 120 m. This threshold was chosen through a series of tests to assess the impact that gap filling could have on the identification of a jet. The test of this algorithm consisted of selecting a period with no gap in the data and then artificially cutting the jet core from profiles to determine the magnitude of error the spline routine could introduce. It was found that with a 120 m threshold for gaps, the error in the jet height was less than 60 m and the LLJ speed was underestimated by ~ 1.5 m s^{-1} in the most extreme cases. It is noted that gaps in the data typically occur above the jet nose, as the turbulence generated below the jet core results in high reflectivity of the signal up to the jet nose; thus, the impact of the spline interpolation routine has on jet detection is minimal.

Low-level jets were selected using an automated routine that returned the lowest maxima in the wind profile that was more than 2 ms^{-1} greater than the wind speed both above and below the jet nose. The selected jets were then visually inspected to identify cases with a single maximum that lasted throughout the night (i.e. not intermittent in nature) before decaying during the morning transition. These cases were then further evaluated by determining if inertial oscillations were observed through plotting the hodograph of the horizontal wind components, to identify cases where the Blackadar mechanism was at least partially responsible for the formation of the LLJ.

Eddy-covariance fluxes from instrumentation on the tall tower were calculated using 10 Hz time series of u, v, w, temperature, CO_2, and water vapor. A three-dimensional rotation, forcing the vertical and lateral wind components to zero, was performed on the entire time series (i.e. four hour block). The CO_2 fluxes were corrected for variations in air density due to fluctuations in water vapor density and temperature following Webb et al. (1980). All data were checked for quality control and run through a despiking routine (Vickers and Mahrt, 1996).

Results and Discussion

At our site under specific conditions, the decay of a low-level jet sparked a change that impacted the atmospheric dynamics during the morning transition. The morning transition time is still poorly understood, the opposing buoyant and shear forces create an environment in the atmosphere where measurements become hard to interpret. Often the data collected is rejected and due to uncertainties replaced by data collected in different, generally windier, conditions (Goulden, 1996; Baldocchi et al., 2003). In order to study the impact of LLJ decay on the turbulence structure of the boundary layer and the subsequent effects on fluxes of heat, water vapor, and CO_2, we selected two cases, one characterized by a steady, single jet growing to a maximum and then decaying and another lacking the presence of a jet.

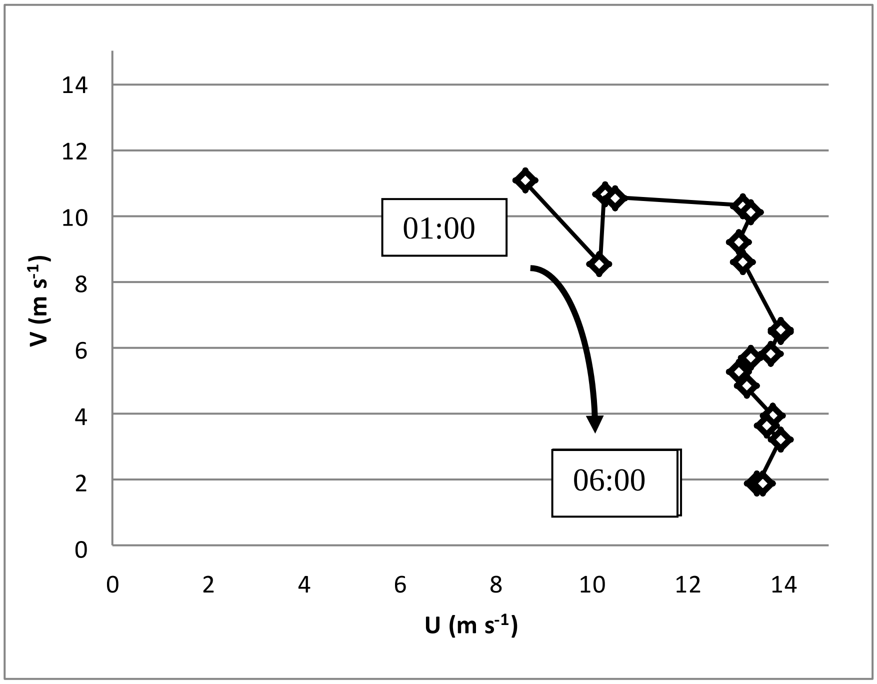

Figure 2.2: Hodograph from May 9th, 2009 demonstrating the presence of an inertial oscillation from 01:00 to 06:00 Eastern Standard Time.

Seven nights during May 2009, where the low-level jets were associated with inertial oscillations, were considered night's representative of our study in contrast to nights without the presence of a jet. The presence of inertial oscillations arises from frictional decoupling, allowing the jet to grow with speed and for CO_2 to accumulate beneath the jet core in the lower boundary layer (Mathieu et al., 2005). There were only two nights in May 2009 without a pronounced jet present; however, the other nights exhibiting jet behavior did not demonstrate frictional decoupling and often were intermittent in nature. Due to added uncertainties, intermittent jets were not considered for this study though their presence undoubtedly impacts the turbulence structure of the lower boundary layer. A sample hodograph from May 9th, 2009 is presented in Fig. 2.2, where the clockwise rotation of the wind vector throughout the night indicates the presence of an inertial oscillation. The presence of the inertial oscillation is taken to indicate frictional decoupling of the flow from the surface.

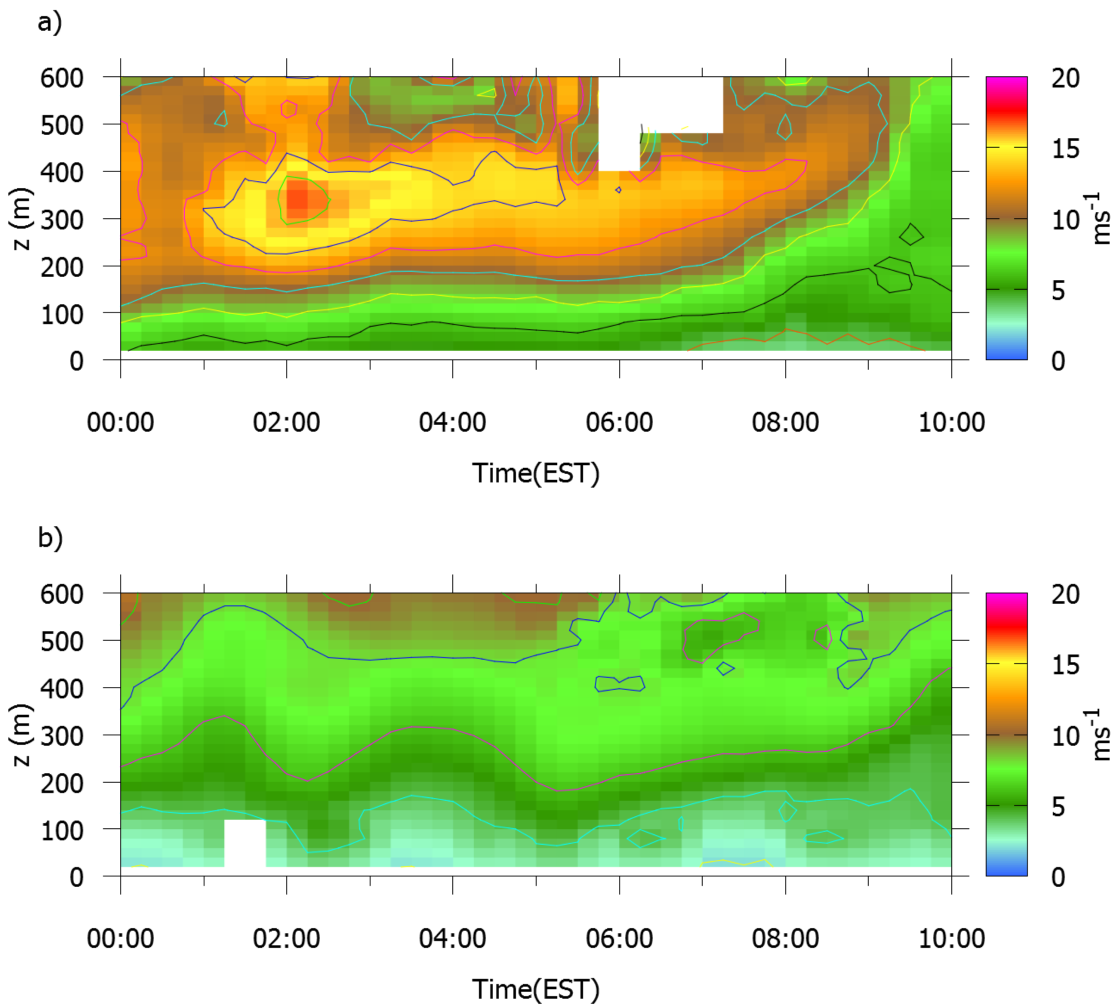

Figure 2.3: Contour plot of 15 min average horizontal wind speed displaying the LLJ on (a) May 9th, 2009 and the wind profile on the contrasting night (b) May 12th, 2009 from the REMTECH sodar.

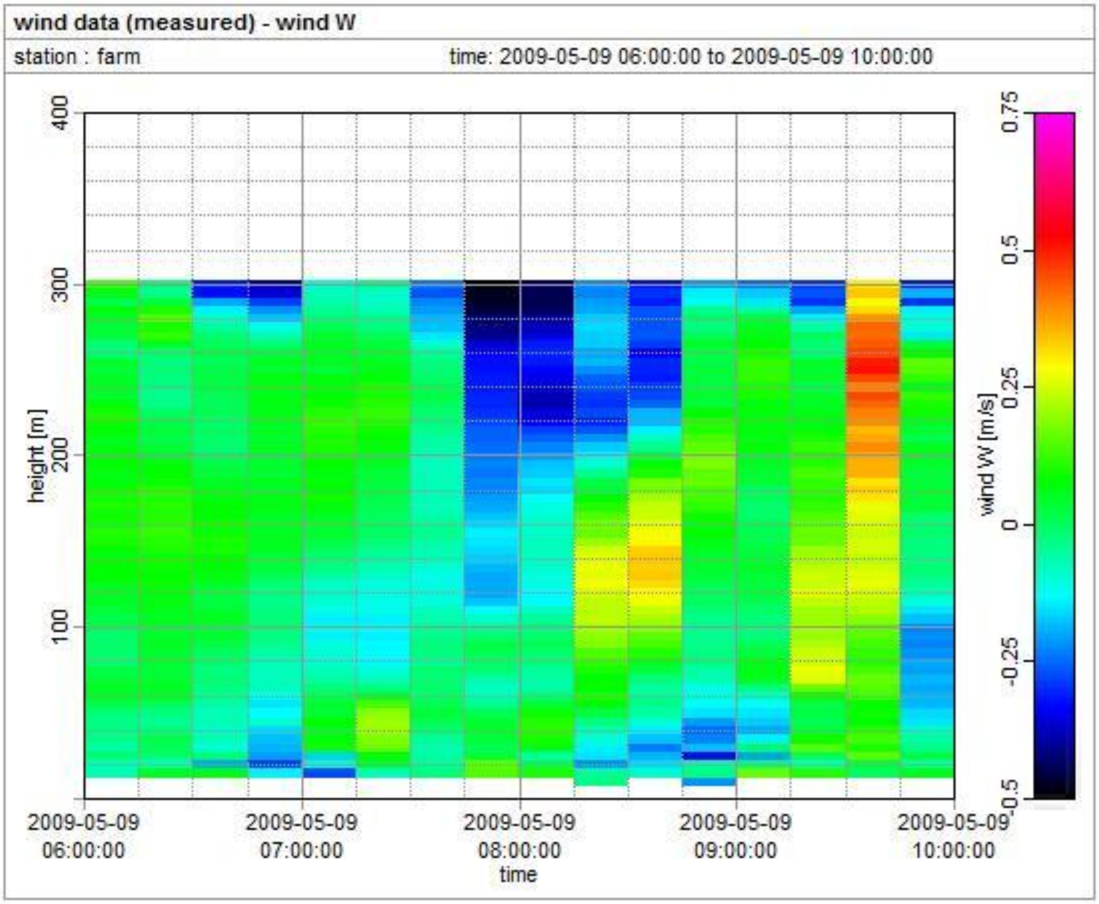

Figure 2.4: Vertical velocity plot from May 9th, 2009 using the Scintec sodar.

May 9th, 2009 is presented as the exemplary case of an LLJ decaying during the morning transition and catalyzing transport of heat and CO_2. This decay generates downward motions of air with properties of CO_2, heat, and moisture that are related to those of the source of origin, which may be hundreds of kilometers away according to Sogachev and Leclerc (2011). These downward motions also result in a flushing of accumulated CO2 and water vapor through the resulting convective mixing initiated by the warmer air being transported down. The night is characterized by a LLJ that forms approximately at 00:00 Eastern Standard Time (hereafter referred to as EST) and persists until ~ 08:00 EST before beginning to decay (Fig. 2.3a). As the jet decays, a downward vertical velocity is observed from 100- 300 m by the high resolution sodar beginning at

07:45 EST (Fig. 2.4). This is quickly followed by an upward burst originating at around 100 m, suggesting that transport of warmer air aloft to the surface initiated convective mixing. This is later followed by larger upward vertical velocities associated with the full convection. The contrasting night May 12th, 2009 was characterized by comparatively weak winds as observed by the sodar (Fig. 2.3b).

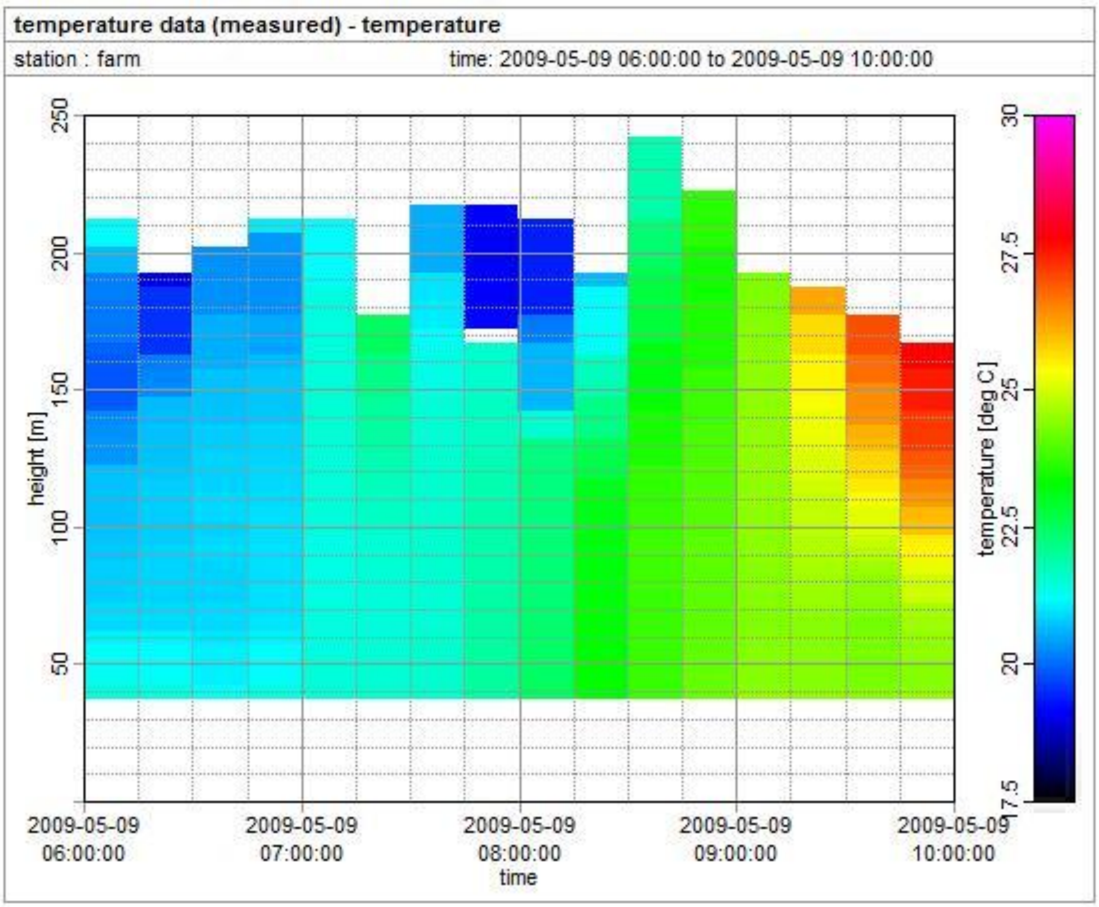

Figure 2.5: Temperature profiles from the RASS on May 9th, 2009.

It can be seen that at 150 m the air aloft is warmer than the air below 100 m briefly before the jet decay. The air aloft (> 150 m) then becomes much cooler as the air at the lower levels warm. Finally as the jet decays at approximately 08:30 EST, it can be seen that the profile becomes homogenized as the mixing occurs (Fig. 2.5). It is clear that the 15-min averaging time is too coarse to detect the mechanisms of transport during that transition and the profile height is not great enough to distinguish the temperature of the air above the jet core. Yet, it is clearly observed that heat was transported during the LLJ decay as mixing ensued.

It is recognized that calculations of turbulence kinetic energy (hereafter referred to as TKE) from sodar data are best used as indicators of the state of the atmosphere rather than robust absolute quantitative tool as demonstrated from previous studies (Banta et al., 2006; Lokoshchenko, 2002); therefore, the results are taken to be qualitatively correct depicting the location of enhanced turbulence in the vertical. Figure 2.6 shows that TKE is generated aloft by jet during the night, then as the sun begins to heat the surface the TKE increases close to the surface indicating weakening of the stability. Then, the jet decay ensues at 08:30 EST generating large amounts of turbulence throughout the profile up to 300 m.

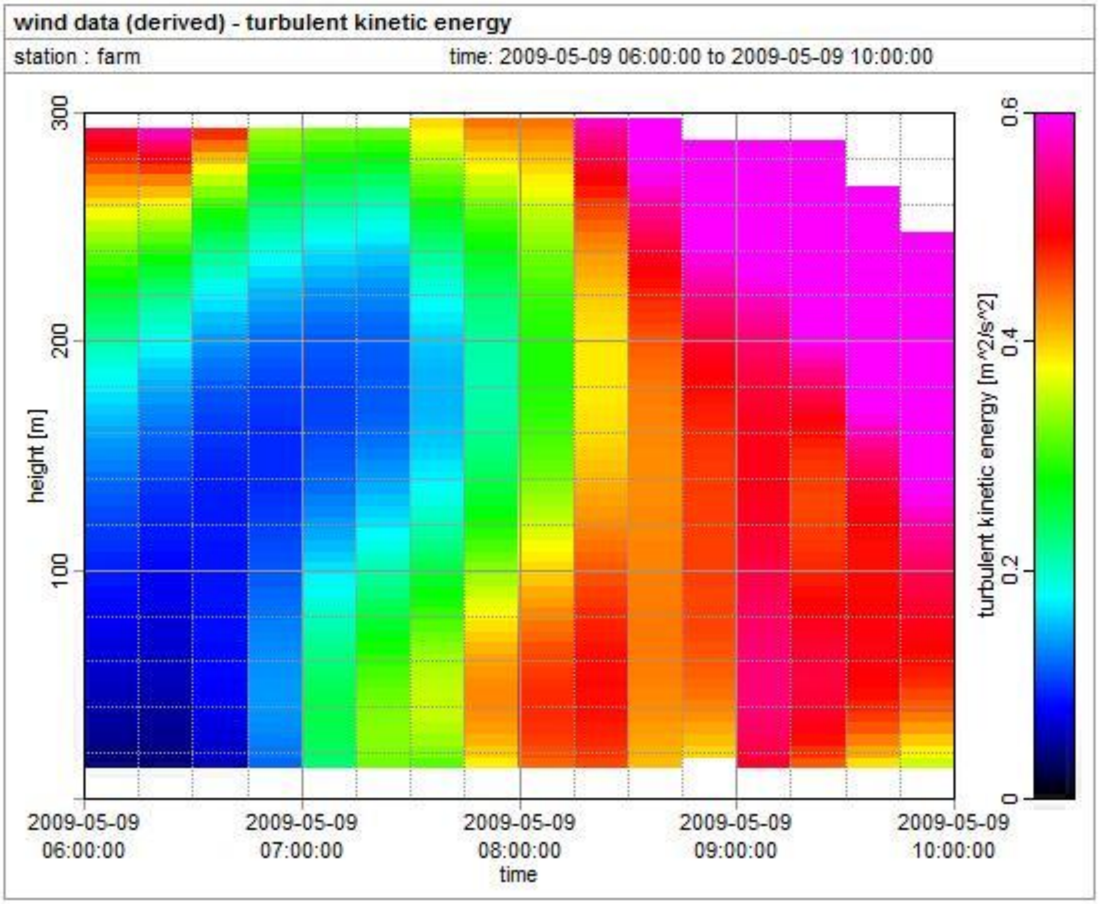

Figure 2.6: 15 min average TKE from the Scintec sodar on May 9th, 2009.

The tall tower data was examined during the night and morning transition to determine the impact the jet had throughout the night and during its decay on May 9th, 2012. May 12th, 2009 is plotted to provide a comparison of the morning transition without the presence of an LLJ. The two cases were chosen due to their close proximity to each other only separated by three days meaning sunrise is approximately the same time, 05:31 EST on May 9th and 05:28 EST on May 12th, and the incoming solar radiation was similar both days (Fig. 2.7) thus, providing truly comparable contrasting cases.

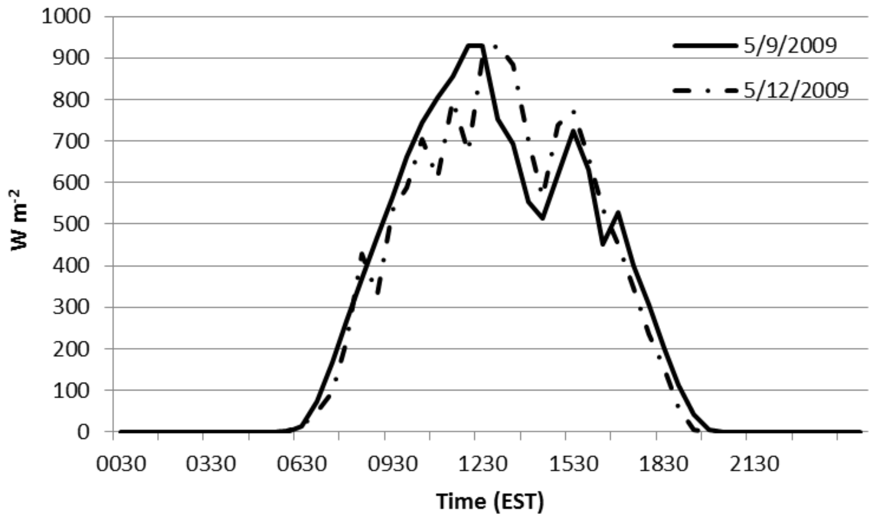

Figure 2.7: Incoming shortwave radiation the mornings of May 9th, 2009 and May 12th, 2009.

Figure 2.8 shows the average wind speed, temperature, and CO_2 concentration from the 34, 68, and 329 m levels on the tall tower for May 9th and 12th, 2009. The LLJ nose is close to the 329 m level and the increase in wind speed is clearly detectable (Figure 2.8a). The temperature at the 329 m level on the tall tower is higher than that at the lower levels during most of the night on May 9th, 2012, but as the jet decays, the temperature at the 329 m level quickly drops as the temperature at the two lower levels increases significantly at 08:00 EST (Fig. 2.8b). Simultaneously, the CO_2 concentration at the 34 and 68 m levels drop drastically and a spike in concentration occurs at the 329 m level (Fig. 2.8c). This suggests a flushing of the CO_2 that accumulated during the night. Whereas, the 329 m temperature never exceeds the 34 and 68 m levels on May 12th, 2009 (Fig. 2.8e), and the CO_2 concentration does not change as drastically at any of the measurement levels (Fig. 2.8f).

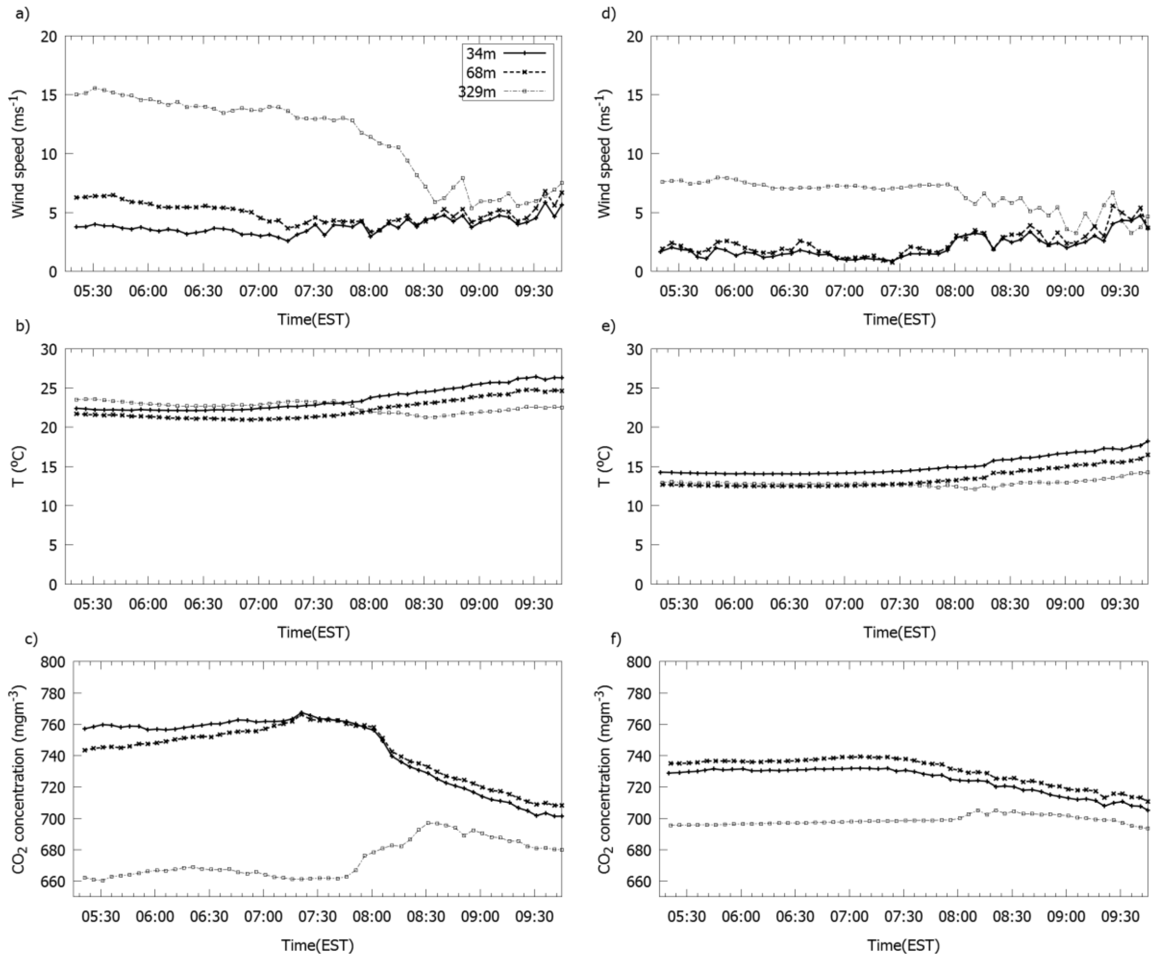

Figure 2.4: (a) Average wind speed, (b) temperature, and (c) CO_2 concentration from the 34, 68, and 329 m levels on tall tower from May 9th, 2009 and May 12th, 2009 (e, f, and g).

The tall tower data corroborate the general increase in TKE observed by the sodar at approximately the same time on May 9th, 2012, though the values are not similar in magnitude as expected (Fig. 2.9a). Figure 2.9b shows that the increased turbulence coinciding with the jet decay resulted in warmer air from aloft being transported down, as the sensible heat flux (H) from the 329 m level was negative during that period. The CO_2 flux was modestly positive throughout the night indicating upward transport, but larger transport is observed during the initial surface heating at the 34 and 68 m levels, but as the jet decay occurs the mixing that ensued results in a large burst of CO_2 being transported up past the 329 m level (Fig 2.9c). Further evidence of the enhanced mixing coinciding with the jet decay during the morning transition is observed as the w'rho$_v$' flux is enhanced as well (Fig 2.9d).

The contrasting night May 12th, 2009 shows that without the presence of a jet during the morning transition, the TKE measured is limited in comparison (Fig. 2.9e). The sensible heat flux at the 329 m level is still negative, suggesting entrainment of warmer air from aloft still plays a role in surface heating, but the large flux as seen in the case with the LLJ is not discernible (Fig 2.9f). Thus, only weak CO_2 fluxes occurred during the morning transition in the absence of a jet (Fig. 2.9g).

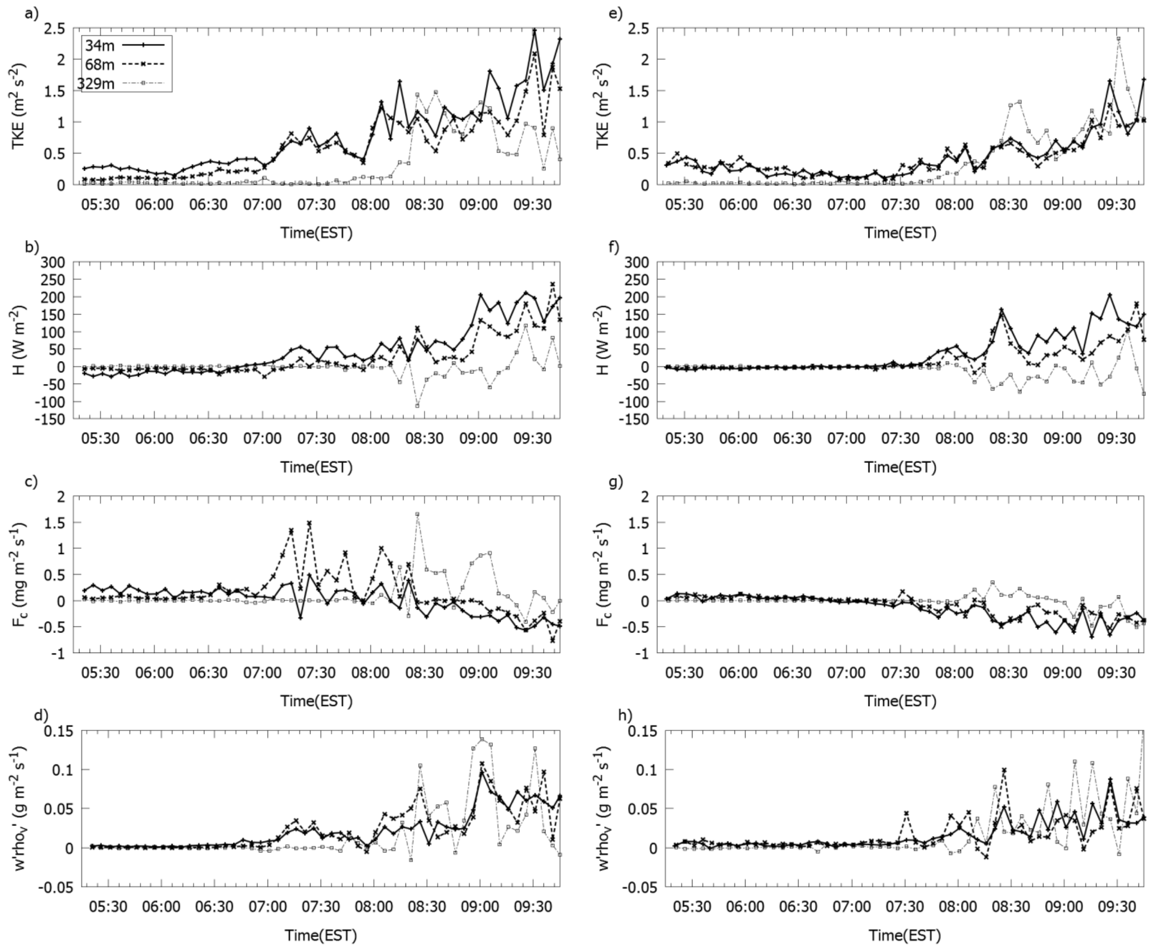

Figure 2.5: (a) TKE, (b) Sensible heat flux (H), (c) CO_2 flux (F_c), and (d) w'rho$_v$' calculated for the 34, 68, and 329m levels of the tall tower for May 9th, 2009 and May 12th, 2009 (e, f, g, and h).

These results suggest that the decay of a traditional LLJ that was formed as a result of frictional decoupling during the morning transition lead to large fluxes of scalars. It is believed that LLJs caused by other phenomena may influence morning transition differently due to different interactions with the surface throughout the night, presumably as a result of different stabilities. This release of CO_2 is common during the morning transition, but the combination of light winds, lack of turbulence and non-stationary conditions, makes quantifying the transport challenging. Yet, the decay of the jet modulating the turbulence structure enhances the vertical CO_2 transport by inducing mixing.

Mathieu et al. (2005) suggested that, in the presence of both an LLJ and thermal inversion, the nocturnal boundary layer technique might be used successfully to capture the large storage of CO_2 typical of those stable boundary layers. This, of course, assumes that other assumptions inherent to the method are fulfilled, i.e. horizontal homogeneity. Given this scenario, the large CO_2 concentrations accumulated throughout the night in such calm nocturnal conditions near the surface are flushed during the morning transition as the jet decays (Figure 2.9bc). This is most evident as the bursts at the 34 and 68 m levels occur briefly before the large flux at the 329 m level, which coincides with the period when the jet decays and the temperature profile returns to normal. These findings may shed light on how a large amount of CO_2 may be transported into the atmosphere that currently is not accounted for in large scale approximations of net ecosystem exchange due to negating measurements made during the morning transition as result of non-stationarity.

Conclusion

This study has examined the impact of a nocturnal low-level jet on turbulence structure and fluxes at different levels during the morning transition using a combination of tall tower and sodar/RASS data. Two contrasting cases, one in the presence of a nocturnal jet and one without, were chosen to elucidate the impact the presence of an LLJ during the morning transition may have on turbulence statistics and flux calculations. Our results indicate that when the transition occurs in the presence of a LLJ, the morning transition is less ambiguous due to the turbulence generated by the LLJ decay. It is often the case that researchers conducting long term net ecosystem exchange studies only include morning transition data into their calculations if the atmosphere is highly turbulent. For instance, Rannik et al. (2006) only included morning transition cases where u_* exceeded 0.3 ms^{-1}; therefore, these cases are quite significant to net ecosystem exchange estimations and understanding their dynamics is important.

Transition time is impacted by the presence of an LLJ through the transport of heat and other scalars as a result of the LLJ decay coinciding with the weakening of stability due to surface heating. The CO_2 flux was modestly positive throughout the night indicating upward transport, but larger transport was observed during the initial surface heating at the 34 and 68 m levels, but as the jet decay occured the mixing that ensued resulted in a large burst of CO_2 being transported up past the 329 m level. Ultimately, the decay of the LLJ during the morning transition resulted in downward transport of heat and a large burst of CO_2 transport into the atmosphere. A comparison with a morning without an LLJ revealed that the flux of CO_2 observed at the 329m level was more than 3 times that of the contrasting night.

Further studies should be conducted using more cases, including jets that do not exhibit frictional decoupling to better understand how LLJs may impact morning transition. Also, a climatological study to quantify the amount of influence the morning transition can have on seasonal and yearly carbon budget is justified. Furthermore, a better understanding of the physical processes could lend better parameterizations for modelers.

CHAPTER 4

CONCLUSIONS

The results of this research extend the findings of the previous research and demonstrate the care that data collected in the nocturnal boundary layer and during transition time must be shown. Without taking into account wave activity, flux calculations may be modulated due to the averaging processes typically used to process eddy-covariance data. The morning transition time must be shown equal care, as a large portion of the nighttime flux can be mixed into atmosphere through a large flushing that occurs during this time. These studies provide another block to the foundation for the flux community to help comprehend fluxes that occur during difficult processing conditions, i.e. stable conditions and morning transition.

The present study has shown that the presence of large amplitude wave-like events occurred on 31% of the nights studied. The presence of these large amplitude wave events was shown to impact the calculation of both turbulence statistics and fluxes in the nocturnal boundary layer. Without proper filtering, inflated turbulence statistics of up to 50% and erroneous flux calculations may occur on quiescent nights. The presence of the wave also modulates the calculated fluxes of CO_2, resulting in errors in the flux calculations up to 10% over the duration of the wave depending on the averaging time used. These errors will persist in different magnitudes, regardless of the selected averaging block. Results on the impact of gravity waves are sensitive to the criteria selected to detect large amplitude pressure fluctuations. A more exhaustive analysis of this, using a larger dataset is indicated. In addition, the results also hinge on different wave frequencies on fluxes and the sum total of each of those frequencies as encountered within the period. For periods larger than the averaging flux period, an effect is also present though the analysis reveals a punctual impact since the full wave cannot be removed.

This study also portrayed the potential importance of the presence of LLJs during the morning transition. It was demonstrated that transition time is impacted by the presence of an LLJ, through the transport of heat and scalars as a result of the LLJ decay coinciding with weakening stability through surface heating. The decay of the LLJ during the morning transition resulted in downward transport of heat and a large burst of CO_2 transport into the atmosphere. The potential for large amounts of CO_2 transport to be overlooked is great during the morning transition, and for accurate calculations of net ecosystem exchange it is imperative that the fluxes during the morning transition be explored in further detail.

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