Biogeosciences Discuss., 10, 5149–5173, 2013
www.biogeosciences-discuss.net/10/5149/2013/
doi:10.5194/bgd-10-5149-2013

Biogeosciences Discussions
Open Access

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

On the impact of atmospheric waves on fluxes and turbulence statistics during nighttime conditions: a case study

D. J. Durden[1], C. J. Nappo[2], M. Y. Leclerc[1], H. F. Duarte[1], G. Zhang[1], L. B. M. Pires[1], M. J. Parker[3], and R. J. Kurzeja[3]

[1]The University of Georgia, Griffin, GA 30223, USA
[2]CJN Research Meteorology, Knoxville, TN 37919, USA
[3]Savannah River National Laboratory, Aiken, SC 29802, USA

Received: 7 December 2012 – Accepted: 28 January 2013 – Published: 14 March 2013

Correspondence to: M. Y. Leclerc (mleclerc@uga.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc

Printer-friendly Version
Interactive Discussion

Abstract

The interpretation of flux measurements in the nocturnal stable boundary layer is typically fraught with difficulties. This paper reports on how the presence of waves in a time series leads to an overestimation of turbulence statistics and errors in turbulent flux 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 and errors in turbulent flux calculations. 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 turbulence statistics more than 50 %. The presence of the wave modulates the calculated turbulent 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 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 found to depend on the choice of the variables. This is a product of the width of the averaging window in relation to the wave cycle and dealt with the phase relationship of the variables being analyzed; hence, these errors are primarily introduced through our processing methods. These results provide a novel insight into errors introduced in turbulent fluxes. By contributing more accurate inputs of both turbulent kinetic energy and u_*, these results could be invaluable in improving modeling efforts applied to nocturnal exchange.

BGD
10, 5149–5173, 2013

1 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; Newsom and Banta, 2003; 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

BGD
10, 5149–5173, 2013

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 et al., 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). When 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 turbulent flux calculations and better understanding of ecosystem exchange during periods of intermittent turbulence during nocturnal stable conditions. Furthermore, van Gorsel et al. (2011) found that the presence of gravity waves could influence the storage term calculations; thus, the potential impact of waves on net ecosystem exchange should be examined in forthcoming studies. This would lead to a better understanding of different ecosystems sources/sinks 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. The prevalence of waves in the nocturnal stable boundary layer accentuates the importance of accounting for wave activity in measurement campaigns seeking "true" turbulence and turbulent flux calculations.

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 turbulent flux calculations (hereafter any reference to fluxes refers to turbulent fluxes) 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.

2 Measurements

2.1 Site description

Turbulence and eddy-covariance data were obtained from instruments located at 34, 68, and 329 m a.g.l. on a tower located near Beech Island, SC (33° 24′ 21″ N, 81° 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.

2.2 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

BGD
10, 5149–5173, 2013

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 $q(zt)$ is performed as follows:

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

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:

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

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
BGD
10, 5149–5173, 2013
Impact of atmospheric waves on turbulence and fluxes
D. J. Durden

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

$$\overline{w'q'}^{\text{corrected}} = \overline{\left(w - \overline{w} - \tilde{w}\right)\left(q - \overline{q} - \tilde{q}\right)} \quad (3)$$

where Eq. (3) is the turbulent 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.

2.3 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 22 April to 9 June 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

BGD
10, 5149–5173, 2013

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 min, 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, 23 April 2009 and 3 December 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.

3 Results and discussion

3.1 Detection of wave events

The morning hours (00:00 to 06:00 Eastern Standard Time (EST)) of 23 April 2009 and 3 December 2009 exhibited well-defined wave episodes as shown in Fig. 2. Between 02:30 and 04:30 on 23 April 2009, one wave disturbance occurred with an approximate period of 7 min and another with an approximate period of 4 min. On 3 December 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 23 April 2009 and 10 min from 03:30 to 05:30 on 3 December 2009.

BGD
10, 5149–5173, 2013

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. 23 April 2009 was a calm quiescent night with an average Ri_B of 2.64 and friction velocities (u_*) less than 0.2 $m\,s^{-1}$ 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).

3 December 2009 presents a different set of atmospheric conditions. During that night, the average Ri_B was 0.13 and u_* exceeded 0.25 $m\,s^{-1}$ 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 23 April 2009. This is in part due to the larger amount of turbulence present simultaneously with the wave: the degree of error is inversely 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.

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 23 April 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° on both 23 April 2009 and 3 December 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.

3.2 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 23 April at 34 m (Fig. 5a–d) and 329 m (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

BGD
10, 5149–5173, 2013

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.

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:

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

where the overbar represents averaging over the duration of the wave event The averaged turbulence kinetic energy ($\langle \mathrm{TKE} \rangle$), friction velocity ($\langle u* \rangle$), and CO_2 flux ($\langle F_c \rangle$) are presented in Figs. 6a–f and 7a–f, for the 34 and 329 m levels on the nights of 23 April and 3 December 2009, respectively.

The turbulence kinetic energy is overestimated on both nights for all averaging periods, but the percent error is far greater on 23 April 2009, 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 329 m level on 23 April 2009 and 5 min average on 3 December 2009. The inflation observed at the 329 m level when shorter averages were used led to u_* exceeding the 0.25 $\mathrm{m\,s^{-1}}$ 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 23 April 2009. 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, 3 December is only

BGD
10, 5149–5173, 2013

marginally impacted due to large contributions from high frequencies and the mildly stable conditions.

On 3 December 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). 23 April 2009 presents a somewhat special case as the sensible heat flux at the 34 m level is positive (not shown) and the CO_2 flux is negative, in contrast with typical night-time 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). 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 3 December 2009 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 23 April 2009 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 3 December 2009. 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

BGD
10, 5149–5173, 2013

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 impacted by waves of various periods and amplitudes.

4 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 overestimation 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_*($\sim 0.5\,\mathrm{m\,s^{-1}}$) 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 $0.25\,\mathrm{m\,s^{-1}}$, 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

BGD
10, 5149–5173, 2013

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 of 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 turbulent 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. 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

BGD
10, 5149–5173, 2013

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.

Acknowledgements. We wish to extend our thanks to David Cotton for his useful comments on the manuscript. The present study was conducted thanks to a grant from the US Dept. of Energy, Office of Science, Terrestrial Carbon Processes grant no. ER64321.

References

Aubinet, M.: Eddy covariance CO_2 flux measurements in nocturnal conditions: an analysis of the problem, Ecol. Appl., 18, 1368–1378, 2008.

Aubinet, M.: Direct CO_2 advection measurements and the night flux problem, Agr. Forest Meteorol., 150, 651–654, 2010.

Balsley B., Fritts, D., Frehlich, R., Jones, R. M., Vadas, S., and Coulter, R.: Up-gully flow in the great plains region: a mechanism for perturbing the nighttime lower atmosphere?, Geophys. Res. Lett., 29, 1931, doi:10.1029/2002GL015435, 2002.

Banta, R. M., Pichugina, Y. L., and Newsom, R. K.: Relationship between low-level jet properties and turbulence kinetic energy in the nocturnal stable boundary layer, J. Atmos. Sci., 60, 2549–2555, 2003.

Blumen, W., Banta, R. M., Burns, S. P., Fritts, D. C., Newsom, R. K., Poulos, G. S., and Sun, J.: Turbulence statistics of a Kelvin-Helmholtz billow event observed in the nighttime boundary layer during the CASES-99 field program, Dynam. Atmos. Oceans, 34, 189–204, 2001.

Chimonas, G.: Surface drag instabilities in the atmospheric boundary-layer, J. Atmos. Sci., 50, 1914–1924, 1993.

Chimonas, G.: Steps, waves and turbulence in the stably stratified planetary boundary layer, Bound.-Lay. Meteorol., 90, 397–421, 1999.

Coleman, T. A. and Knupp, K. R.: Radiometer and profiler analysis of the effects of a bore and a solitary wave on the stability of the nocturnal boundary layer, Mon. Wea. Rev., 139, 211–223, 2011.

Cooper, D. I., Leclerc, M. Y., Archuleta, J., Coulter, R., Eichinger, E. W., Kao, C. Y. J., and Nappo, C. J.: Mass exchange in the stable boundary layer by coherent structures, Agr. Forest Meteorol., 136, 114–131, 2006.

BGD
10, 5149–5173, 2013

Darby, L. S., Banta, R. M., Brewer, W. A., Neff, W. D., Marchbanks, R. D., McCarty, B. J., Senff, C. J., White, A. B., Angevine, W. M., and Williams, E. J.: Vertical variations in O_3 concentrations before and after a gust front passage, J. Geophys. Res., 107, 4176, doi:10.1029/2001JD000996, 2002.

Einaudi, F. and Finnigan, J. J.: The interaction between an internal gravity wave and the planetary boundary Layer – Part I: The linear analysis, Q. J. Roy. Meteor. Soc., 107, 793–806, 1981.

Einaudi, F. and Finnigan, J. J.: Wave-turbulence dynamics in the stably stratified boundary layer, J. Atmos. Sci., 50, 1841–1864, 1993.

Einaudi, F., Finnigan, J. J., and Fua, D.: Gravity wave turbulence interaction in the presence of a critical level, J. Atmos. Sci., 41, 661–667, 1984.

Emmanuel, C. B.: Richardson number profiles through shear instability wave regions observed in the lower planetary boundary layer, Bound.-Lay. Meteorol., 5, 19–27, 1973.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., and Dolman, H.: Gap filling strategies for long term energy flux data sets, Agr. Forest Meteorol., 107, 71–77, 2001.

Finnigan, J. J.: Kinetic energy transfer between internal gravity waves and turbulence, J. Atmos. Sci., 45, 486–505, 1988.

Finnigan, J. J.: A note on wave-turbulence interaction and the possibility of scaling the very stable boundary layer, Bound.-Lay. Meteorol., 90, 529–539, 1999.

Finnigan, J. J. and Einaudi, F.: The interactions between an internal gravity wave and the planetary boundary layer – Part II: Effect of the wave on the turbulence structure, Q. J. Roy. Meteor. Soc., 107, 807–832, 1981.

Fritts, D. C., Nappo, C., Riggin, D. M., Balsley, B. B., Eichinger, W. E., and Newsom, R. K.: Analysis of ducted motions in the stable nocturnal boundary layer during CASES-99, J. Atmos. Sci., 60, 2450–2472, 2003.

Gedzelman, S. D.: Short-period atmospheric gravity-waves – a study of their statistical properties and source mechanisms, Mon. Wea. Rev., 111, 1293–1299, 1983.

Gossard, E. E. and Hooke, W. H.: Waves in the Atmosphere, Elsevier Scientific Publishing, New York, 1975.

Goulden, M. L., Munger, J. W., Fan, S.-M., Daube, B. C., and Wofsy, S. C.: Measurements of carbon sequestration by long-term eddy covariance: method and a critical evaluation of accuracy, Glob. Change Biol., 2, 169–182, 1996.

BGD
10, 5149–5173, 2013

Impact of atmospheric waves on turbulence and fluxes

D. J. Durden

Grivet-Talocia, S., Einaudi, F., Clark, W. L., Dennett, R. D., Nastrom, G. D., and VanZandt, T. E.: A 4-yr climatology of pressure disturbances using a barometer network in central Illinois, Mon. Wea. Rev., 127, 1613–1629, 1999.
Hauf, T., Finke, U., Neisser, J., Bull, G., and Stangenberg, J.-G.: A ground-based network for atmospheric pressure fluctuations, J. Atmos. Ocean. Tech., 13, 1001–1023, 1996.
Hooke, W., Hall, F., and Gossard, E.: Observed generation of an atmospheric gravity wave by shear instability in the mean flow of the planetary boundary layer, Bound.-Lay. Meteorol., 5, 29–41, 1973.
Karipot, A., Leclerc, M. Y., Zhang, G., Lewin, K. F., Nagy, J., Hendrey, G. R., and Starr, G.: Influence of nocturnal low-level jet on turbulence structure and CO_2 flux measurements over a forest canopy, J. Geophys. Res.-Atmos., 113, D10102, doi:10.1029/2007JD009149, 2008.
Mahrt, L.: Stratified atmospheric boundary layers, Bound.-Lay. Meteorol., 90, 375–396, 1999.
Mahrt, L.: Characteristics of submeso winds in the stable boundary layer, Bound.-Lay. Meteorol., 130, 1–14, 2009.
Mahrt, L.: Common microfronts and other solitary events in the nocturnal boundary layer, Q. J. Roy. Meteor. Soc., 136, 1712–1722, 2010.
Mahrt, L. and Vickers, D.: Contrasting vertical structures of nocturnal boundary layers, Bound.-Lay. Meteorol., 105, 351–363, 2002.
Mathieu, N., Strachan, I. B., Leclerc, M. Y., Karipot, A., and Pattey, E.: Role of low-level jets and boundary-layer properties on the NBL budget technique, Agr. Forest Meteorol., 135, 35–43, 2005.
Nappo, C. J.: Sporadic breakdowns of stability in the PBL over simple and complex terrain, Bound.-Lay. Meteorol., 54, 69–87, 1991.
Nappo, C. J.: An Introduction to Atmospheric Gravity Waves, Academic Press, New York, 2002.
Nappo, C. J., Miller, D. R., and Hiscox, A. L.: Wave-modified flux and plume dispersion in the stable boundary layer, Bound.-Lay. Meteorol., 129, 211–223, 2008.
Newsom, R. K. and Banta, R. M.: Shear-flow instability in the stable nocturnal boundary layer as observed by Doppler lidar during CASES-99, J. Atmos. Sci., 30, 16–33, 2003.
Rees, J. M. and Mobbs, S. D.: Studies of internal gravity waves at Halley Base, Antarctica, using wind observations, Q. J. Roy. Meteor. Soc., 114, 939–966, 1988.
Rees, J. M., Denholm-Price, J. C. W., King, J. C., and Anderson, P. S.: A climatological study of internal gravity waves in the atmospheric boundary layer, J. Atmos. Sci., 57, 511–526, 2000.

BGD
10, 5149–5173, 2013

Impact of atmospheric waves on turbulence and fluxes

D. J. Durden

Sun, J., Burns, S. P., Lenschow, D. H., Banta, R. M., Newsom, R. K., Coulter, R., Frasier, S., Ince, T., Nappo, C., Cuxart, J., Blumen, W., Lee, X. and Hu, X. Z.: Intermittent turbulence associated with a density current passage in the stable boundary layer, Bound.-Lay. Meteorol., 105, 199–219, 2002.

Sun, J., Lenschow, D. H., Burns, S. P., Banta, R. M., Newsom, R. K., Coulter, R., Frasier, S., Ince, T., Nappo, C., Balsley, B. B., Jensen, M., Mahrt, L., Miller, D., and Skelly, B.: Atmospheric disturbances that generate intermittent turbulence in nocturnal boundary layers, Bound.-Lay. Meteorol., 110, 255–279, 2004.

Torrence, C. and Compo, G. P.: A practical guide to wavelet analysis, B. Am. Meteorol. Soc., 79, 61–78, 1998.

van Gorsel, E., Harman, I. N., Finnigan, J. J., and Leuning, R.: Decoupling of air flow above and in plant canopies and gravity waves affect micrometeorological estimates of net scalar exchange, Agr. Forest Meteorol., 151, 927–933, 2011.

Viana, S., Yagüe, C., and Maqueda, G.: Propagation and effects of a mesoscale gravity wave over a weakly-stratified nocturnal boundary layer during the SABLES2006 field campaign, Bound.-Lay. Meteorol., 133, 165–188, 2009.

Webb, E. K., Pearman, G. I., and Leuning, R.: Correction of flux measurements for density effects due to heat and water vapour transfer, Q. J. Roy. Meteor. Soc., 106, 85–100, 1980.

Zeri, M. and Sa, L. D. A.: Horizontal and vertical turbulent fluxes forced by a gravity wave event in the nocturnal atmospheric surface layer over the Amazon forest, Bound.-Lay. Meteorol., 138, 413–431, 2011.

BGD
10, 5149–5173, 2013

Fig. 1. (a) A microbarograph station and **(b)** the tall tower with flux measurement levels at 34, 68, and 329 m

BGD
10, 5149–5173, 2013

Impact of atmospheric waves on turbulence and fluxes

D. J. Durden

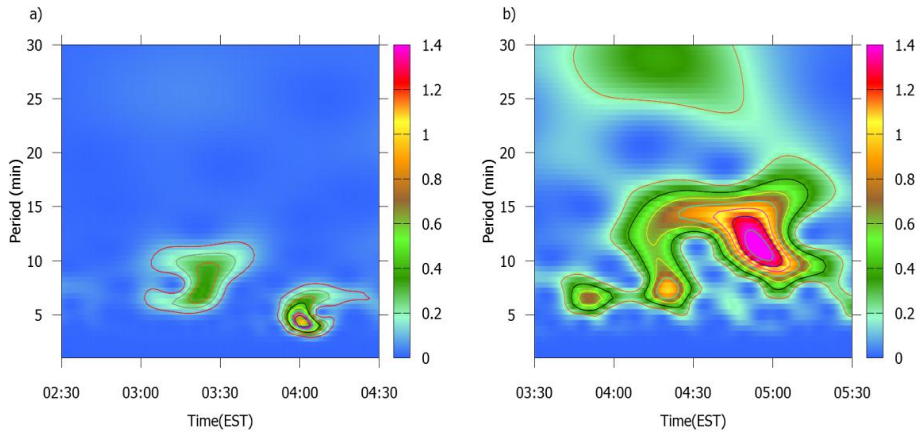

Fig. 2. Wavelet analysis of surface static pressure data from the microbarograph sensor for **(a)** 23 April 2009 and **(b)** 3 December 2009. Increases in wavelet energy density during periods of wave-like activity are used to identify wave period and duration.

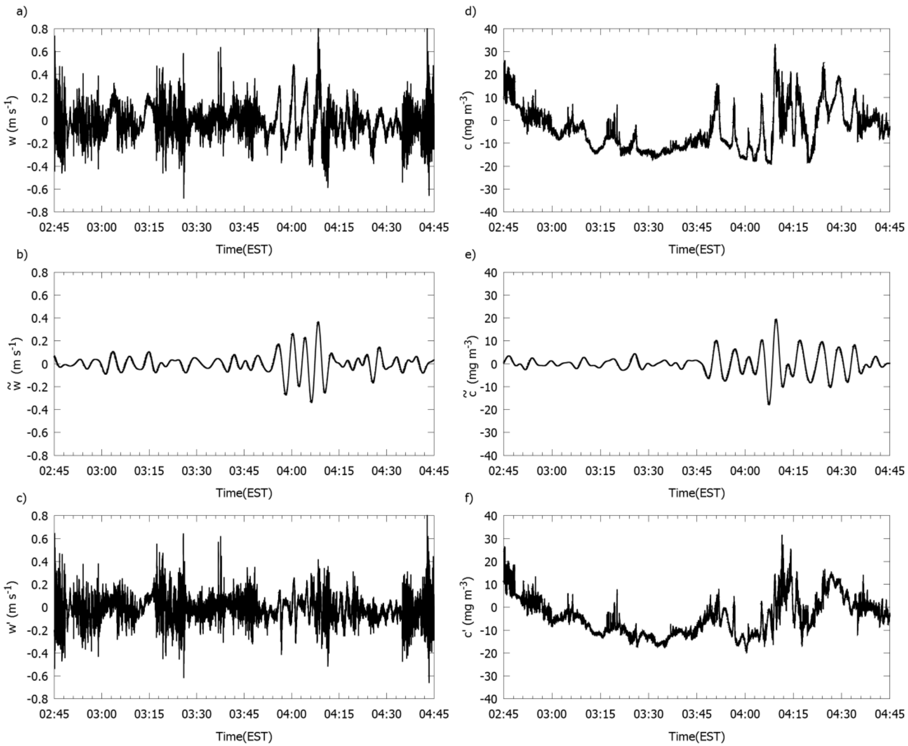

Fig. 3. Triple decomposition of variables w and c are represented as detrended signals **(a)** w and **(d)** c, wave signals **(b)** $\tilde{w}$ and **(e)** $\tilde{c}$, and turbulence signals **(c)** w' and **(f)** c' at the 34 m level on the tall tower on the night of 23 April 2009. Bottom figures represent the "corrected" turbulence signal.

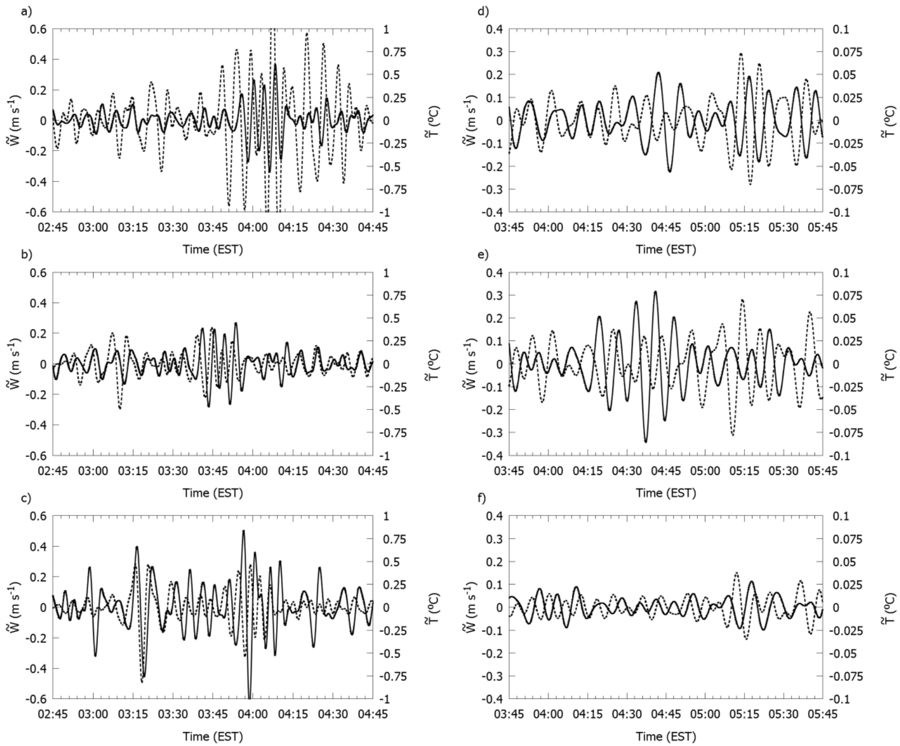

Fig. 4. $\tilde{w}$ (solid) and $\tilde{T}$ (dashed) at 34, 68, and 329 m for 23 April 2009 (**a**, **b**, and **c**) and 3 December 2009 (**d**, **e**, and **f**). The phase relationship between $\tilde{w}$ and $\tilde{T}$ is observed to be $\sim 90^{\circ}$ out of phase during the wave activity, except during the large amplitude event occurring around 05:15 on 3 December 2009 where $\tilde{w}$ and $\tilde{T}$ appear to be 180° out of phase.

BGD
10, 5149–5173, 2013

Impact of atmospheric waves on turbulence and fluxes

D. J. Durden

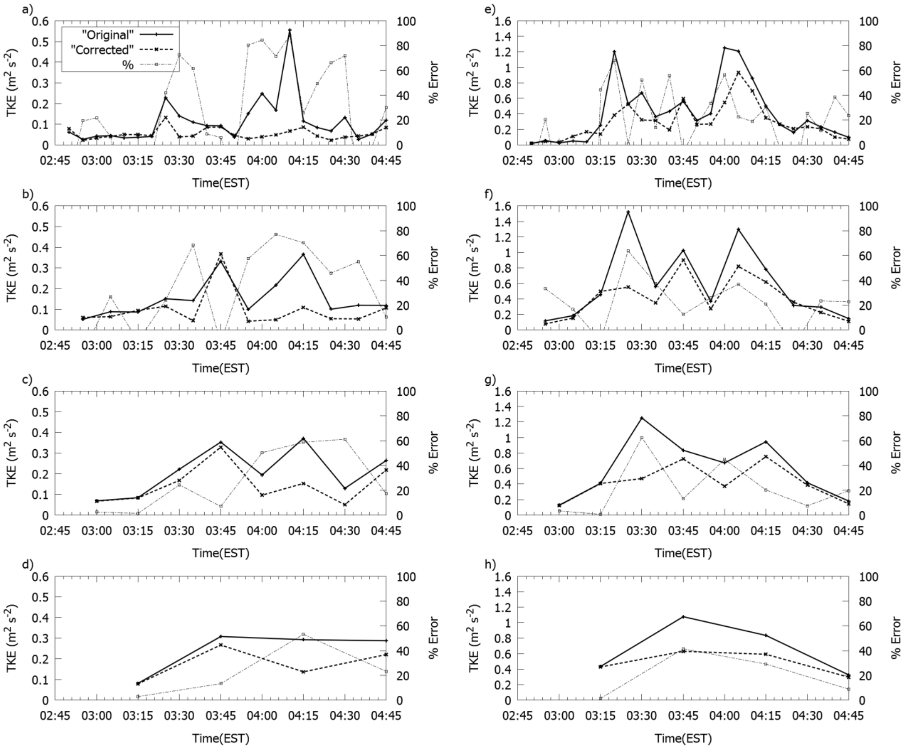

Fig. 5. Turbulent kinetic energy calculations using the original signal ("original") and the corrected signal after wave removal ("corrected") from the time series at 34 (**a**, **b**, **c**, and **d**) and 329 m (**e**, **f**, **g**, and **h**) levels on the tall tower using different averaging periods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

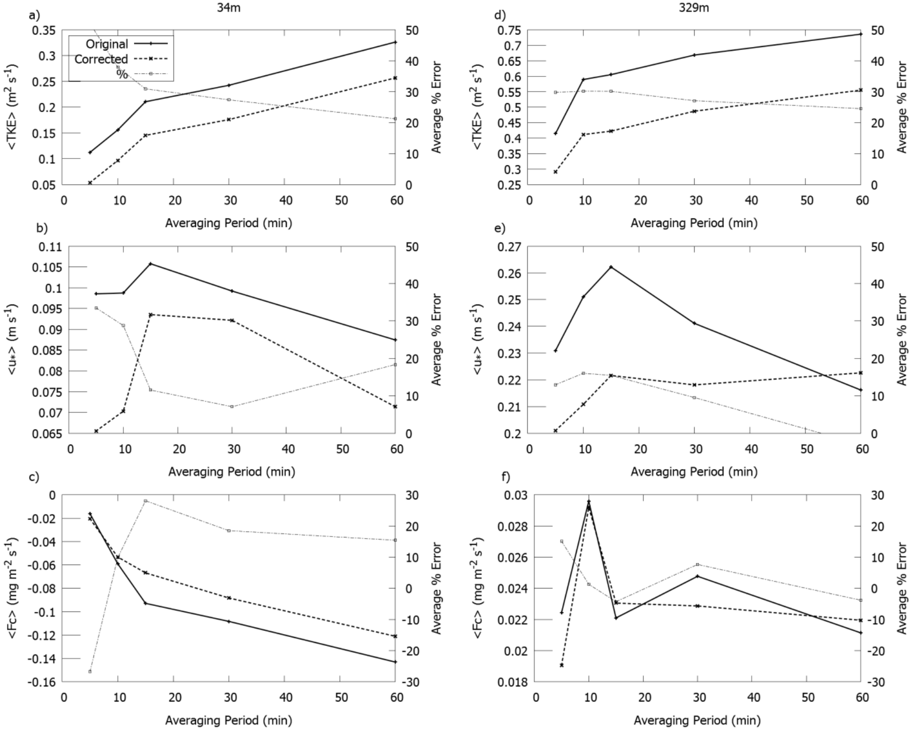

Fig. 6. Average turbulent kinetic energy (⟨TKE⟩), u_* (⟨$u*$⟩), and CO_2 flux (⟨F_c⟩) in the "original" and "corrected" time series during the wave event on 23 April 2009 at the 34 (**a**, **b**, and **c**) and 329 m (**d**, **e**, and **f**) levels on the tall tower are depicted using different averaging periods. The average percent error introduced by the absence of such corrections is also displayed.

BGD
10, 5149–5173, 2013

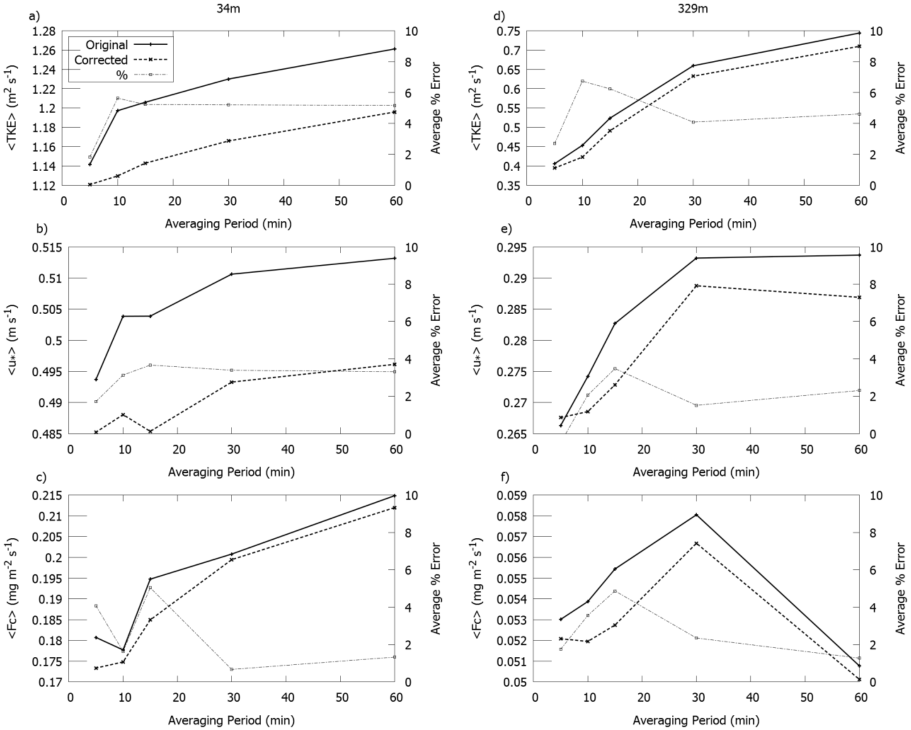

Fig. 7. Average turbulent kinetic energy (⟨TKE⟩), u_* (⟨$u*$⟩), and CO_2 flux (⟨F_c⟩) for the "original" and "corrected" time series during the wave event on 3 December 2009 at the 34 (**a**, **b**, and **c**) and 329 m (**d**, **e**, and **f**) levels on the tall tower are depicted using different averaging periods. The average percent error introduced by the absence of such corrections is also displayed.

BGD
10, 5149–5173, 2013