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An evaluation by laser Doppler anemometry of the correction algorithm based on Kaimal co-spectra for high frequency losses of EC flux measurements of CH_4 and N_2O

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ABSTRACT

Eddy covariance (EC) technique is often used to determine greenhouse gas exchange at the earth's surface. In general, the instruments involved have a limited high frequency response which reduces the ability to detect the contribution to the flux of small eddies and in addition sensor separation gives high frequency losses. These missing contributions cause an EC flux underestimation which increases for higher values of the stability parameter *z/L*. Corrections can be performed based on the (empirical) Kaimal co-spectra; however, these were derived using instruments with a limited frequency response. In this study, the validity of the Kaimal spectrum during stable atmospheric conditions is assessed using laser Doppler anemometry (LDA) measurements of the vertical wind velocity at 1 m height during several stable nights at Cabauw in the Netherlands. LDA provides a means to determine the entire turbulent energy spectrum, i.e., from the production scale down to the dissipation scale. Since the measured spectra are found to be in good agreement with the Kaimal spectra, we assume that the Kaimal co-spectra are valid as well. Next, the effect of high frequency correction based on Kaimal co-spectra is assessed using 1 month of EC flux data of CH_4 and N_2O measured by quantum cascade laser (QCL) spectrometry at Reeuwijk in the Netherlands. After correction, the cumulative emissions increased about 15% for both gases. This underlines the importance of correcting for high frequency losses.

1. Introduction

During the last decade, climate change has become an important societal issue. Accurate measurements of trace gas fluxes and energy fluxes are very important for the study of environmental, biological and climatological controls of net surface exchange between ecosystem and atmosphere. EC flux measurements are often used to estimate the integrated emission on a hectare scale with a continuous coverage in time (e.g., Fowler et al., 1995; Laville et al., 1999; Veenendaal et al., 2007; Hendriks et al., 2008). For temperature and moisture, the EC technique can be evaluated independently using the energy balance closure. It has been shown that this balance is not always closed and fractional imbalances are larger at night than during daytime (e.g., Wilson et al., 2002; Kroon, 2004). This result indicates that scalar fluxes might be underestimated systematically. Therefore, all possible causes of the non-closure should be explored in more detail. Possible reasons are, among others, the assumption of no advection, high frequency losses due to damping in the tube, sensor separation and limited response time.

Many researchers apply a high frequency correction to turbulent fluxes to account for the effect of missing eddies. An Ogive based algorithm, described by, e.g., Aubinet et al. (2000) and Ammann et al. (2006) is often used for correcting these high frequency losses. This method is based on a comparison of the co-spectrum of temperature flux with the co-spectrum of CH_4 flux or N_2O flux. Kroon et al. (2007) showed that the high frequency losses are almost negligible up to the 2 Hz cut-off frequency of the quantum cascade laser (QCL) spectrometer using this Ogive algorithm. Therefore, no corrections were applied for the high frequency losses. However, these analyses were restricted to just a few cases in neutral atmospheric conditions and the losses were not evaluated for frequencies in the range between 2 Hz and the Kolmogorov scale.

Several other studies have reported on correction algorithms for high frequency losses using the empirical Kaimal co-spectra (Kaimal et al., 1972), e.g., Kristensen and Fitzjarrald (1984), Moore (1986), Bosveld (1999) and Aubinet et al. (2000). However, it is not

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certain whether the spectral shape of the Kaimal co-spectra is correct down to the dissipation scale since these spectra were derived using sonic anemometry with which not all small-scale contributions could be detected. The uncertainty in the spectral shape from production scale down to dissipation scale is larger for stable atmospheric conditions than for unstable conditions since the turbulent length-scale decreases (e.g., Van der Wiel et al., 2008) making the high frequency spectral contributions more prominent. In addition, during stable to very stable conditions buoyancy can affect isotropy (promoting 'pancake' eddies) and therefore possibly modify the spectral shape. Since the relative effect of non-detected eddies on the flux is supposed to be larger during stable conditions than during unstable conditions, it is important to validate the Kaimal co-spectra during stable conditions.

Because of that, the first goal of this study is to check the validity of the spectral shape of Kaimal spectra in the high frequency range during stable atmospheric conditions. The present evaluation is however limited to the vertical wind velocity (w) spectrum since our measurement technique is limited to one wind-component and techniques are not capable of sampling, e.g., CH_4 and N_2O down to the dissipation scale. However, the validity of the vertical wind velocity spectrum is the most critical check since the vertical velocity is most directly influenced by buoyancy effects; in other words, if thermal stratification is to have an influence on (co)-spectra, this must be most clearly visible in the vertical velocity spectrum. For a tracer gas (passive scalar) the effect will be less pronounced than in the w-spectrum. Therefore, if the Kaimal vertical velocity spectra are found to be in good agreement with the measured w-spectra, it will be reasonable to assume that the Kaimal co-spectra are valid as well.

Several measurement techniques are available for measuring the vertical wind velocity spectrum. The sonic anemometer is commonly used for EC flux measurements. This instrument is very reliable and robust. However, the smallest scale that can be detected is about the path length (usually 0.15 m). Hot-wire anemometry (HWA) is a technique that can detect smaller scales than sonic anemometry, even to the Taylor scale (Gulitski et al., 2007). However, it is not easy to carry out HWA measurements in the atmosphere since the wires are very fragile and there is a serious drift requiring multiple calibrations. In this study, the vertical wind velocity fluctuations are determined using both laser Doppler anemometry (LDA) and sonic anemometry. LDA works well under laboratory conditions (e.g., Snyder and Castro, 1998; Tummers et al., 2007). The technique is ideally suited for turbulence measurements, since LDA provides a non-intrusive means to determine the entire turbulent energy spectrum, i.e., from the production scale down to the dissipation scale. Drawbacks of LDA are the complexity of the system, the costs and the technical aspects of bringing seeding particles in the measurement area. We have developed an LDA system that is capable of operating under atmospheric conditions and have performed measurements with it at a grassland site at Cabauw in the Netherlands during several nights in 2008. We determine the variance spectrum of the vertical wind velocity at a height of 1 m using both LDA and sonic anemometry and compare these with the Kaimal spectra. Next, we focus on the correction algorithm based on Kaimal co-spectra and we assess its effect using 1 month of CH_4 and N_2O EC flux data measured at Reeuwijk in the Netherlands.

2. Experimental site and climatic conditions

The measurements have been conducted at a grassland site located near the village Cabauw, in the Netherlands (51°58′12.73″N, 4°55′34.98″E). To avoid flow obstruction, all instrumentation was placed at a distance of about 250 m from the main building. The measurement field consists of meadows and narrow ditches which are on average 40 m apart. The water level in the ditches is kept at about 0.40 m below the surface (Beljaars and Bosveld, 1997). The grass height ranges from 0.03 to 0.30 m. We have carried out the LDA measurements during five nights in the period from February to July 2008. Table 1 summarizes the periods and their atmospheric conditions. The stability is characterized by z/L with z the measurement height and L the Monin–Obukhov length scale. The stability was determined using both profile measurements and EC flux measurements, but the resulting stability parameters differ significantly in both methods, probably owing to the strong stability. The Monin–Obukhov length scale varied between $z/L = -0.01$ and 0.41 at 13 February 2008 and 17 June 2008, respectively, using the profile method. In addition, we use the difference between downward and upward long wave radiation LW for a characterization of the cooling of the nocturnal boundary-layer where values below $-50\ \mathrm{W\,m^{-2}}$ indicate cloudless conditions. Radiation measurements were performed at a height of 1.5 m. It was cloudy during 8 February and 7 April 2008. The micrometeorological measurements were made available by the KNMI.

In addition, we have performed EC flux measurements of CH_4 and N_2O at an intensively managed dairy farm in 2007. This farm is located at Oukoop near the town of Reeuwijk in the Netherlands (52°02′11.22″N, 4°46′49.53″E). The terrain around the measurement tower was flat and free of obstruction for at least 600 m in all directions, except for the container in which the QCL was placed (20 m North-East from the tower). Manure and fertilizer are applied about five times a year from February to September. In addition, there are about four harvest events. Cow manure and artificial fertilizer application were about $55\ \mathrm{m^3\,ha^{-1}}$ ($253\ \mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$) and $370\ \mathrm{kg\,ha^{-1}}$ ($100\ \mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$) in 2006. In this study, we assess the effect of high frequency losses using 1 month data from 14 September 2007 to 12 October 2007. The average temperature and the average weekly precipitation were about 11.6 °C and 14 mm, respectively. Cow manure was applied on 15 September 2007 with an amount of $46\ \mathrm{kg\,N\,ha^{-1}}$. More information about the measurement site can be found in Veenendaal et al. (2007).

Table 1
Description of the atmospheric conditions during the measurement nights at Cabauw in the Netherlands in 2008. Shown are wind speed U, air temperature T_{air}, net long wave radiation LW and stability parameter z/L where z denotes the measurement height and L the Monin–Obukhov length scale. The measurement heights are indicated in the subscripts.

	8 February	13 February	7 April	17 June	18 June
Start time (UTC)	08-02 19:10	13-02 20:40	07-04 21:30	17-06 22:40	19-6 00:30
End time (UTC)	08-02 22:40	13-02 23:30	07-04 22:40	18-06 01:30	19-6 02:40
U_{10m} ($\mathrm{m\,s^{-1}}$)	3.6	2.5	2.7	2.3	2.6
$T_{air.10m}$ (°C)	6.8	1.5	3.6	13.4	15.1
$LW_{1.5m}$ ($\mathrm{W\,m^{-2}}$)	−47	6	−45	−30	−15
z/L_{10m}[a] (−)	0.04	−0.01	0.23	0.41	0.07
z/L_{3m}[b] (−)	0.11	0.00	0.81	1.14	0.19

[a] Measured by the profile method using 2 and 10 m data.
[b] Measured by the EC flux method at 3 m height.