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# $CO_2$-flux measurements above the Baltic Sea at two heights: flux gradients in the surface layer

**A. Lammert and F. Ament**

Meteorological Institute, University of Hamburg, Bundesstr. 55, 20146 Hamburg, Germany

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Correspondence to: A. Lammert (andrea.lammert@uni-hamburg.de)

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## Abstract

The estimation of $CO_2$ exchange between the ocean and the atmosphere is essential to understand the global carbon cycle. The eddy-covariance technique offers a very direct approach to observe these fluxes. The turbulent $CO_2$ flux is measured as well as the sensible and latent heat flux and the momentum flux, a few meters above the ocean in the atmosphere. Assuming a constant-flux layer in the near surface part of the atmospheric boundary, this flux equals the exchange flux between ocean and atmosphere. The goal of this paper is the comparison of long-term flux measurements at two different heights above the Baltic Sea due to this assumption. The results are based on an one-and-a-half year record of quality controlled eddy covariance measurements. Concerning the flux of momentum and of sensible and latent heat, the constant-flux layer theory can be validated because flux gradients between the two heights are more than 95 % of the time insignificantly small. In contrast, significant gradients, which are larger than the measurement error, occur for the $CO_2$ flux in nearly 35 % of the time. Data, used for this paper are published at http://doi.pangaea.de/10.1594/PANGAEA.808714.

## 1 Introduction

The chemical composition of the atmosphere is influenced in a very high amount by the exchange of gases between the ocean and the atmosphere. Particularly the exchange of carbon dioxide ($CO_2$) is of interest due to the climate relevant effects of $CO_2$ and the role of the ocean as a major sink for anthropogenic produced $CO_2$ (Denman et al., 2007). A frequently used and very direct method to measure turbulent fluxes of momentum, heat and trace gases (e.g. $CO_2$) is the eddy-covariance technique. The technique itself has been proved and enhanced since more than 30 years (e.g. Webb et al., 1980; Fuehrer and Friehe, 2002). Eddy-covariance systems were and are installed on research vessels, buoys, and platforms to measure the near-surface $CO_2$ fluxes above





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the oceans, mostly on a short time scale of a few weeks (e.g. Huang et al., 2012; Else et al., 2011; Prytherch et al., 2010a, b; Weiss et al., 2007; Kondo and Tsukamoto, 2007). This lower layer of the atmosphere, the Prandl-layer, is characterized by height-constant turbulent flux. With the assumption of the constant-flux layer it is possible to obtain the $CO_2$ flux at the boundary between water and atmosphere from a flux measurement in several meters height. Measurements in one height are also above land a common practice for the determination of $CO_2$ fluxes and further the estimation of the carbon net ecosystem exchange (e.g., Knohl et al., 2003; Hollinger and Richardson, 2005; Grünwald and Bernhofer, 2007). To test the assumption of the constant flux layer, two eddy-covariance systems at different heights (i.e. 6.8 and 13.8 m above the sea surface) were installed in 2008 at the research platform FINO2 in the Baltic sea. Each system consisted of a fast sonic anemometer and an open-path infrared gas analyzers for $CO_2$ and $H_2O$. This publication has the goal to test the constant-flux theory with respect to the $CO_2$ flux on the basis of long-term measurements of turbulent fluxes and $CO_2$ over 1.5 years. Therefore the $CO_2$ flux will be estimated and compared in both heights with standard eddy-covariance technique in combination with the standard correction terms, see Sect. 4. To highlight the special characteristics of the $CO_2$ flux, the latent and sensible heat flux as well as the momentum flux will be analysed additionally to serve as a reference. The data, described in this paper are published in the PANGAEA system (Data Publisher for Earth and Environmental Science), Lammert et al. (2013).

## 2 FINO2 – site and instrumentation

Since 2007 the FINO2 platform is situated in the South-west of the Baltic Sea, in the tri-border region between Germany, Denmark, and Sweden, see Fig. 1. The platform collects meteorological (between 30 and 101 m height), oceanographic and biological data. In the frame of the research project SOPRAN (Surface Ocean Processes in the Anthropocene, see(http://sopran.pangaea.de), the platform was equipped with





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additional sensors in June 2008. A combination of 3-component sonic anemometers (USA1) and open-path infrared gar analyzers for $CO_2$ and $H_2O$ (LICOR 7500) were installed at a 9 m long boom south of the platform in two heights, at 6.8 and 13.8 m above sea surface. Additionally slow temperature and humidity sensors were installed at each height. The gas analyser systems were calibrated before the installation and worked permanently without any calibration during the whole measurement period of one and half years. The comparison with the measurements of the slow sensors showed for both instruments no significant long-term drift in temperature and $H_2O$. Drifts on smaller time scales (in the order of days) due to the contamination with sea salt, were cleaned naturally by rain. The drift of both quantities had no influence on the fluctuation at the eddy-timescale, which, in contrast to the mean values, are important for the flux estimation. All data were filtered due to spikes, rain, and the influence of the mast. In this paper continuous measurements over one and a half years, June 2008 to December 2009, are analysed and the fluxes are compared in both heights.

## 3 Time series

The directly measured quantities at 13.8 m height, vertical wind speed ($w$), horizontal wind speed (ff), air temperature ($T$), absolute humidity (AH), and the $CO_2$ density ($CO_2$) are plotted in Fig. 2. Over the time interval of one and a half years an annual cycle, typical for the Baltic Sea, is recognizable for temperature and humidity (for comparison see Weiss et al., 2007). The maximum temperature, around 20 °C, is observed in August, the minimum, around 0 °C, in winter. The absolute humidity is in the range between 3 and 13 g m$^{-3}$. In contrast the $CO_2$ density shows the maximum, near 0.8 g m$^{-3}$, in the winter month, and the minimum, 0.6 g m$^{-3}$, in summer. Neither the vertical nor the horizontal wind speed show a clear annual cycle. The time period from June to December is comparable for all variables in both years, 2008 and 2009.





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## 4 Turbulent fluxes and flux gradients

The estimation of fluxes, like momentum or $CO_2$, based on the correlation of high resolved fluctuations of the vertical wind speed with quantities like horizontal wind fluctuations or $CO_2$ fluctuations. The raw eddy-covariance fluxes of the momentum $F_m$, sensible and latent heat $H$ and LE, and $CO_2$ were calculated over 30 min intervals from the fast sensors as given by:

$$F_m = -\rho_a \overline{u'w'} \tag{1}$$

$$H = \rho_a c_p \overline{T'w'} \tag{2}$$

$$\mathrm{LE} = L_e \overline{\rho_v' w'} \tag{3}$$

$$F_{CO_2} = \overline{w'\rho_c'} \tag{4}$$

where $\rho_a$ is the density of dry air, $\rho_c$ of $CO_2$ and $\rho_v$ of water vapor. $L_e$ is the latent heat of vaporization, $c_p$ the specific heat, and $T$ the air temperature. Over-bars denote temporal means and dashes the fluctuations with respect to these means. It is necessary to correct the raw fluxes due to correlated density effects, e.g. for the $CO_2$ flux, therefore the latent and sensible heat flux has to be taken into account. A common used correction was given by Webb et al. (1980):

$$F_{CO_2} = \overline{w'\rho_c'} + \mu \frac{\rho_c}{\rho_a} \overline{w'\rho_v'} + (1 + \mu\sigma)\overline{\rho}_c \frac{\overline{w'T'}}{\overline{T}}$$

with the ratio of molecular masses $\mu = m_a/m_v$ and of densities of air constituents $\sigma = \overline{\rho_v}/\overline{\rho_a}$. The subscript v stands for water vapor. The latent heat fluxes are corrected according to Webb, the sensible heat flux according to Schotanus. For a detailed description of the eddy-covariance method and its correction terms please see, a.o. Webb et al. (1980), Fuehrer and Friehe (2002).

The determination of the measurement error for turbulent fluxes with an error propagation is in general very difficult, e.g. due to the correction terms. Assuming temporarily





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uncorrelated measurement errors, the root mean square deviation of preceding 30 min flux estimates provides an upper limit for the root mean square error (RMSE) of the measurements. Similar approaches to determine observation errors, e.g. by extrapolating the auto correlation function towards a zero time-lag are frequently used in data assimilation (e.g. Schlatter, 1975) and known as nugget-effect.

The turbulent fluxes of the whole time period of 1.5 years are shown in Fig. 3 as daily average. The momentum fluxes are in the range of −0.7 to nearly 0.0 $kg\,(ms^{-2})$. The sensible heat flux shows a clear annual signal, with maximum values in autumn and winter. The amplitude and variability of daily latent heat fluxes is higher, compared to the sensible heat. The minimum is in March/April, whereas high values of more then 100 $W\,m^{-2}$ are observed from July till November in both years. The $CO_2$ fluxes show very small variability with values between −0.5 to 0.4 $mg\,(m^{-2}\,s)$. This magnitude is in the same range as observed by other authors, e.g. −0.2 to 0.05 $mg\,(m^{-2}\,s)$ above the Baltic Sea (Weiss et al., 2007), or −0.1 to 0.3 $mg\,(m^{-2}\,s)$ near coast above the Sea of Japan (Iwata et al., 2004). Compared to measurements above land surface, the fluxes of momentum, sensible heat, and $CO_2$ show no significant diurnal (not shown) and a much weaker annual cycle.

Figure 4 shows the comparison of the turbulent fluxes with 30 min resolution in 13.8 vs. 6.8 m height. The scatter plots of the momentum and sensible heat flux show the expected strong dependency of both heights, with a very high correlation coefficient of about 0.98 each. Both fluxes are determined by the analyses of just the sonic anemometers. For the latent heat flux the correlation is a bit lower, with $C = 0.96$. In contrast, the comparison of the $CO_2$ fluxes shows a wide spread around zero, with a very low correlation coefficient of 0.46. For both, the latent heat and the $CO_2$ flux, we have to take into account that an instrument combination of sonic anemometers and the LICOR is used. Nevertheless the relatively low correlation of the $CO_2$ fluxes, compared to the other turbulent fluxes is surprisingly.

For this reason, we calculated the gradient of both fluxes (top height minus bottom height) and analysed the distribution of these gradients. In Fig. 5 the distribution func-





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tions of the gradients are shown, additionally with the cumulative distributions, for all four turbulent fluxes. While the momentum-flux gradients are distributed nearly Gaussian, the heat flux gradient distributions both have a light positive skewness. The $CO_2$-flux gradient distribution shows a clear negative skewness. All distributions show the maximum at zero difference. In order to distinguish between insignificant flux gradients due to random measurement error and real flux gradients, the estimated uncertainties from the RMSE of all fluxes are plotted in Fig. 5 as dotted lines. By means of these limits, it is clearly evident that for the momentum flux just less than 5 % of all gradients are significant. Same is valid for the sensible heat flux. For the latent heat flux applies a positive mean gradient of 4.6 $W m^{-2}$, while 12 plus 3 % of the gradients are significant. So the latent heat flux in the upper height is significantly higher then in the lower height in 12 % of the observed time interval. The $CO_2$-flux, with the negative skewness in the gradient distribution, is significantly higher in 13.8 m than in 6.8 m in just 5 % of all time steps, but in nearly 30 % of all analysed cases, the gradients are significantly negative. In summary, the measurements at the FINO2 platform indicate significant $CO_2$ flux gradients between 6.8 and 13.8 m height in 35 % of time.

## 5 Conclusions

The eddy covariance technique is a well established method to measure turbulent fluxes of trace gases like $CO_2$ in the surface layer. With the assumption of height constant vertical fluxes in this part of the boundary layer, measurements at only one height could be used to characterize the flux at the surface. In this paper we have presented long term measurements of the vertical $CO_2$, momentum, and sensible and latent heat flux above the Baltic Sea at two heights. The flux uncertainties were estimated on the basis of the root mean square deviation between subsequent flux estimates. The validity of the constant flux-layer assumption could be confirmed for the momentum and the sensible heat flux: the differences between the two measurements heights are in nearly 95 % of the time smaller than the measurement uncertainty. Likewise both flux





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measurements are highly correlated with a correlation coefficient of 0.98 each. The latent heat flux, with a correlation of 0.96 between the two heights, differs significantly in 15 % of time.

In contrast, 35 % of all $CO_2$ flux differences are significant, i.e. larger than the measurement error. Consequently the estimated surface flux will depend considerably on the choice of the measurement height. Although this paper can not provide an explanation for vertical $CO_2$ flux gradients, it is worthwhile to document this effect, since it should be taken into account while interpreting eddy-covariance $CO_2$ flux measurements above the ocean. In general, measurements are just performed at a single and arbitrary chosen measurement height. Some discrepancy between various observational studies, like e.g. the large scatter between observed $CO_2$ transfer velocity reported by Weiss et al. (2007), may partly be attributed to vertical $CO_2$ flux gradients in the surface layer. In Peters (2007) the author discusses the theory of horizontal advection differences as reason for differences between one measurement height and the real $CO_2$ flux through the air-water interface. His solution for the estimation of the real flux, without knowledge of the horizontal advection, is the measurement of the $CO_2$ flux at different heights. But it has to be taken into account, that Peters (2007) describes the differences as zero-mean error in the long term, which was not confirmed by the results of this analysis. The mean difference for the year 2009 between both height is 0.018 mg $(m^{-2}\,s)$, with a mean $CO_2$ flux of −0.019 mg $(m^{-2}\,s)$ for the lower and −0.036 mg $(m^{-2}\,s)$ for the upper height level. So, the mean difference is in the same magnitude as the flux itself.

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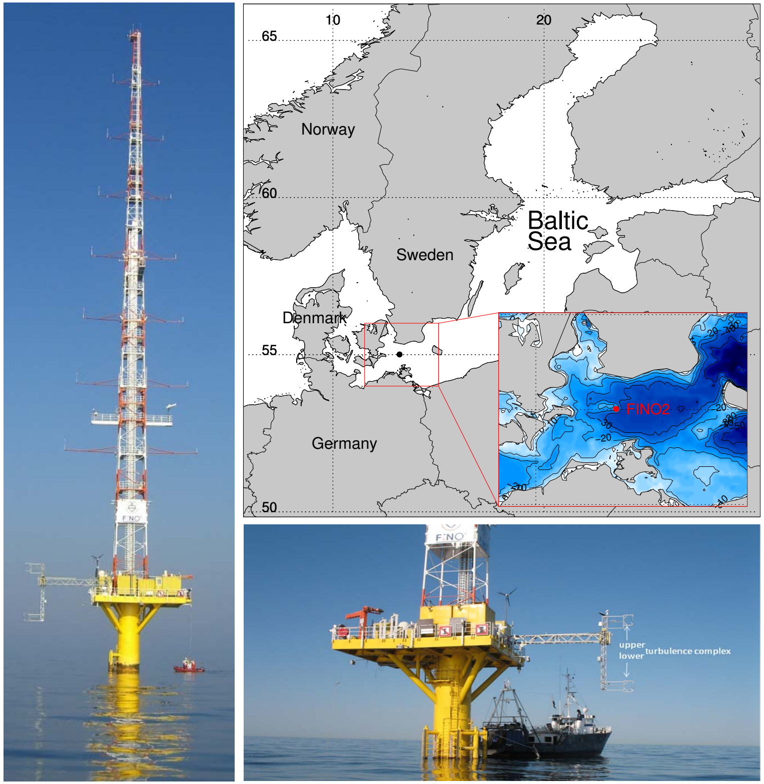


**Figure 1.** FINO2: position in the Baltic Sea (top, right), the measurement mast (left), and the platform with the boom and instrument installation at 6.8 and 13.8 m height above sea surface (bottom).





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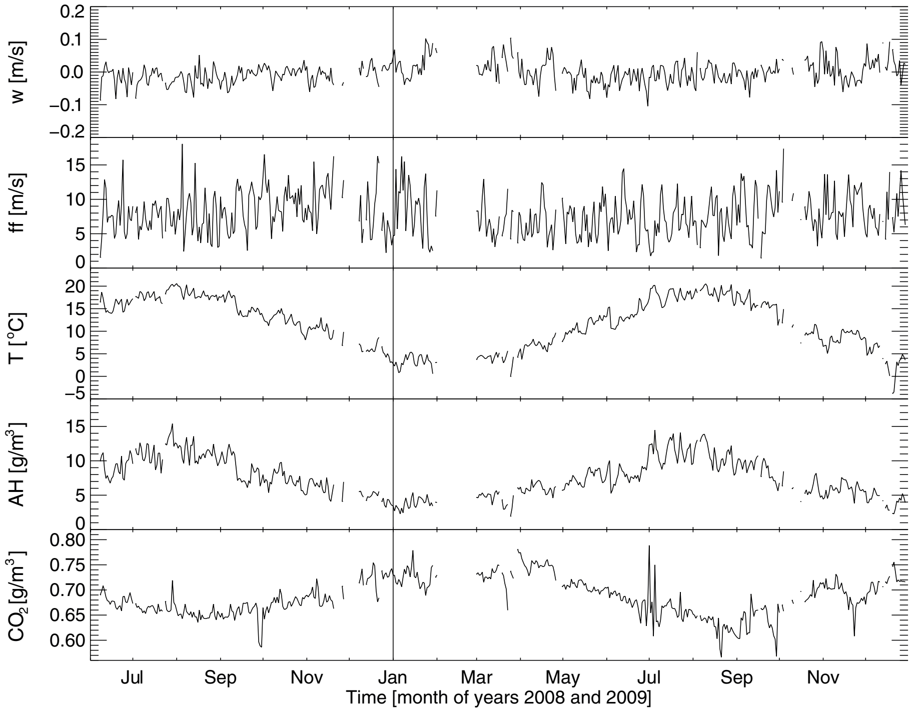


**Figure 2.** Daily means of measured quantities at 13.8 m height above sea surface: vertical wind speed $w$, horizontal wind speed ff, air temperature $T$, absolute humidity AH, and $CO_2$ density from June 2008 to December 2009.





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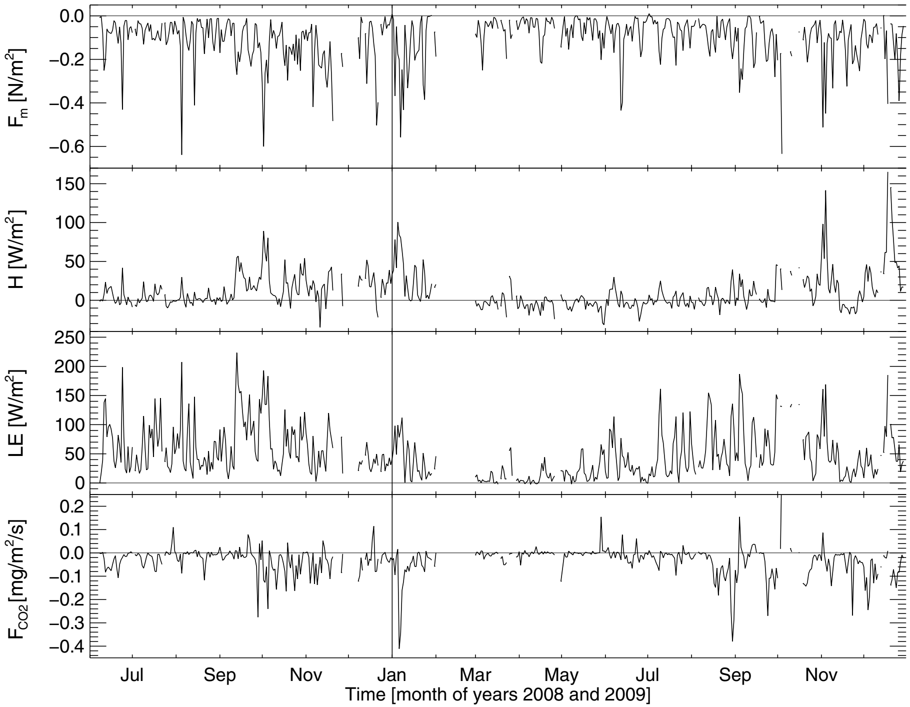


**Figure 3.** Daily means of momentum flux $F_M$, sensible and latent heat flux, $H$ and LE, and $CO_2$ flux in 13.8 m height, from June 2008 to December 2009.





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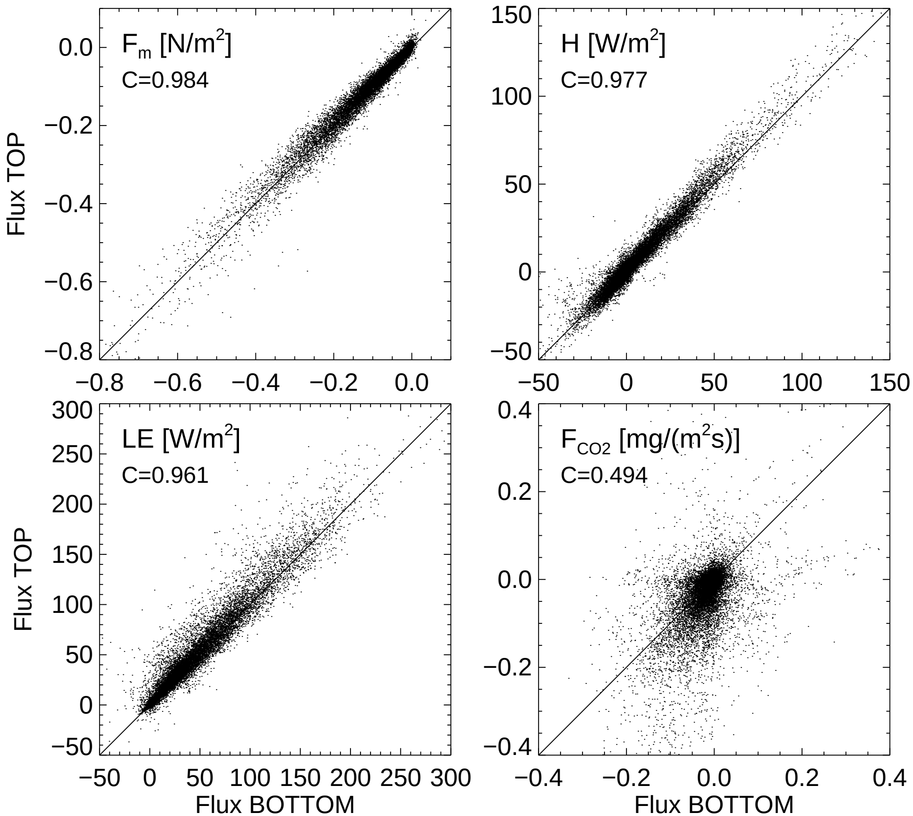


**Figure 4.** Comparison of turbulent fluxes at two different heights, TOP (13.8 m) vs. BOTTOM (6.8 m). The temporal resolution is 30 min. Top: momentum flux $F_m$ (left) and sensible heat flux $H$ (right), bottom: latent heat flux LE (left) and $CO_2$ fluxes (right). C gives the correlation coefficient.





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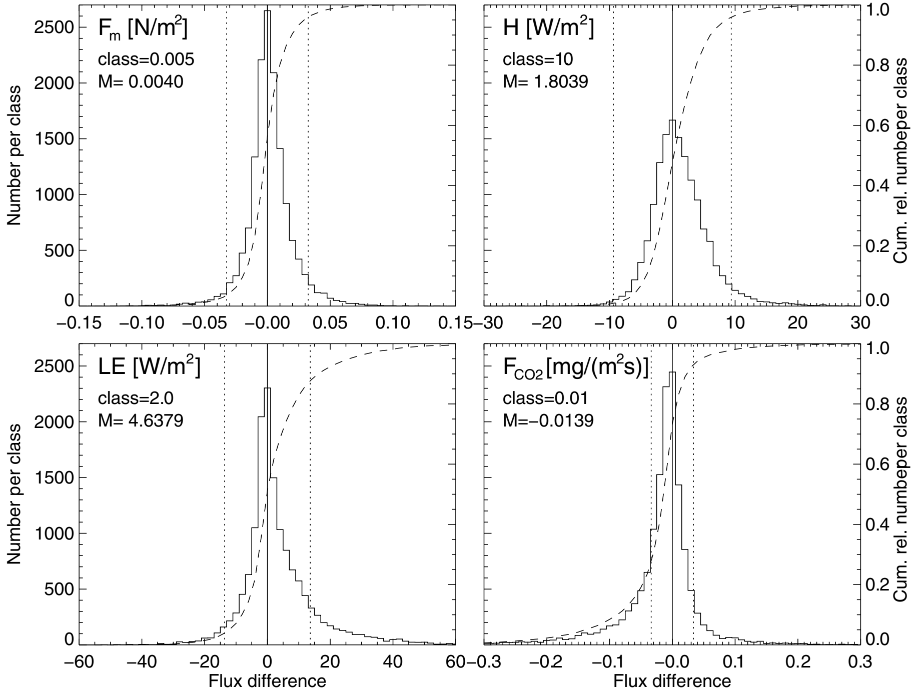


**Figure 5.** Distribution of flux differences (TOP-BOTTOM) for momentum ($F_m$), sensible ($H$) and latent heat (LE), and $CO_2$ flux ($CO_2$), based on 30 min values for 1.5 years. M gives the mean difference, class stands for the width of class for each flux difference. The dotted lines give the measurements uncertainties, derived from the RMSE.





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