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

Andrea Lammert[1] and Felix Ament[1]

[1]Meteorological Institute, University of Hamburg, Bundesstr. 55, 20146 Hamburg, Germany

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

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 to investigte this assumption. The results are based on an one-and-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 confirmed 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 about 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 have been installed on research vessels, buoys, and platforms to measure the near-surface CO_2 fluxes above 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), Prytherch et al. (2010b), Weiss et al. (2007), Kondo and Tsukamoto (2007)). This lower layer of the atmosphere, the Prandl-layer, is approximated 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 bases 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 Section 5. 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 & 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 additional sensors in June 2008. A combination of 3-component sonic anemometers (USA1) and open-path infrared gas 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. Fig. 2 shows the boom with the instrumentation and the alignment of the sonic and the LICOR which is identical at both heights. The sonic is installed overarm, the LICOR instrument below the sonic. This setting was chosen to minimize the distance of the measuring volumes of both instruments (the distance is 20 cm) and to enable an as large as possible sector without flow distortion. For the same reason the instruments at the different heights are installed at different sides of the boom, so the horizontal distance of the installations is nearly one meter.
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.

In this paper continuous measurements over one and a half years, June 2008 to December 2009, are analysed and the fluxes at both heights are compared to each other.

3 Data prozessing

Both instrument types, the sonic anemometer as the LICOR, yield measurements with a temporal resolution of 10 Hz. The high frequency data were filtered due to spikes and rain. The FINO platform itself has an influence on the measurement in the case of northern wind directions. Therefore the data are filtered due to wind directions between 285 to 35° to exclude not only possible flow distortion but also an influence of the platform generator on the CO_2 measurements. On the basis of 10 min mean values we have used a so called sectorwise tilt correction as alignment correction. This procedure is similar to a planar fit correction, but applied for 10° sectors instead of the whole plane.

The comparison of the high frequency measurements 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.

4 Measurement quanities

The time series at 13.8 m height of vertical wind speed (w), horizontal wind speed (ff), air temperature (T), absolute humidity (AH), and the CO_2 density (CO_2) are plotted as daily means in Figure 3. 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 months, 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.

5 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:

$$F_m = -\rho_a \overline{u'w'} \quad (1)$$

$$H = \rho_a c_p \overline{T'w'} \quad (2)$$

$$LE = L_e \overline{\rho_v' w'} \quad (3)$$

$$F_{CO_2} = \overline{w' \rho_c'} \quad (4)$$

where ρ_a is the density of dry air, ρ_c of CO_2 and ρ_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 have 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 Webb, the sensible heat flux according 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 temporally 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. 4 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 o bserved 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.

Fig. 5 shows the comparison of the turbulent fluxes with 30 min resolution in 13.8 m 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. 6 the distribution functions 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. 6 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 m and 13.8 m height in 35 % of time.

6 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 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 mea-

surement height. Although this paper can not provide an explanation for vertical CO_2 flux gradients, it is worthwhile to document this effect, since 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. The mean difference for the year 2009 between both height is 0.018 mg/(m^2s), with a mean CO_2 flux of -0.019 mg/(m^2s) for the lower and -0.036 mg/(m^2s) for the upper height level. So, the mean difference is in the same magnitude as the flux itself.

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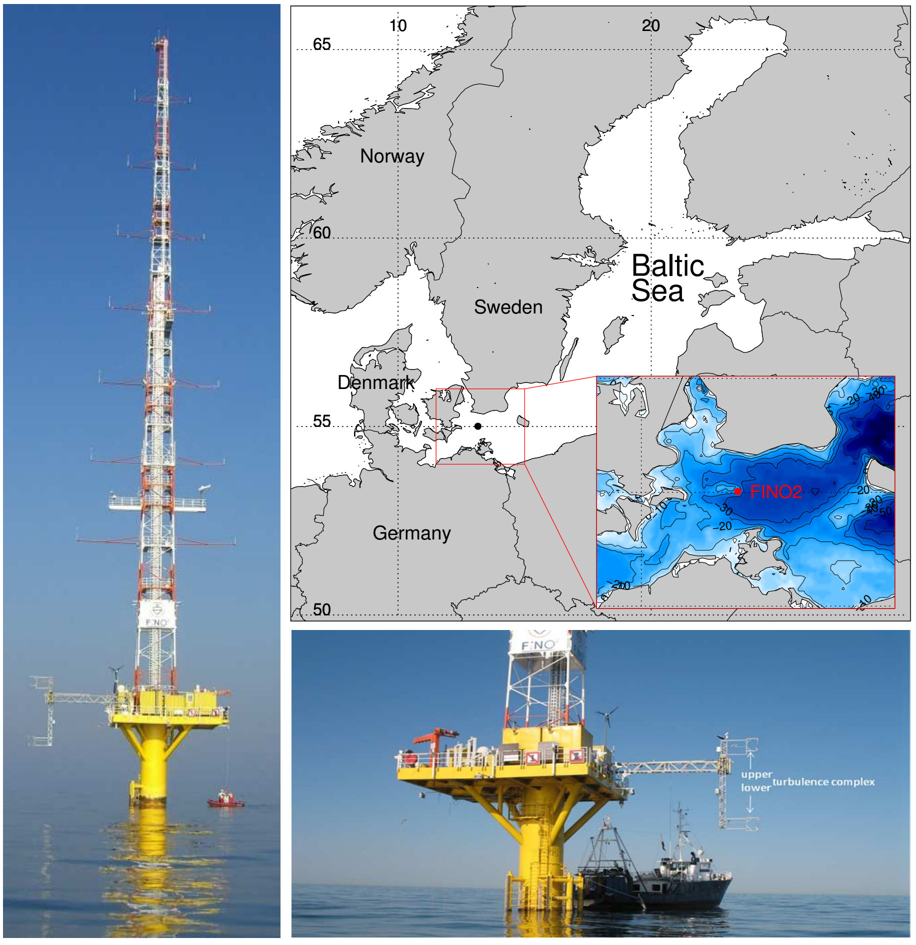

Figure 1. FINO2: position in the Baltic Sea (top, right), the whole mast (left), and the platform with the boom and instrument installation at 6.8 m and 13.8 m height above sea surface (bottom).

Figure 2. Instrument boom at FINO2 with the turbulence sensors at both heights and instrument installation in more detail (small picture).

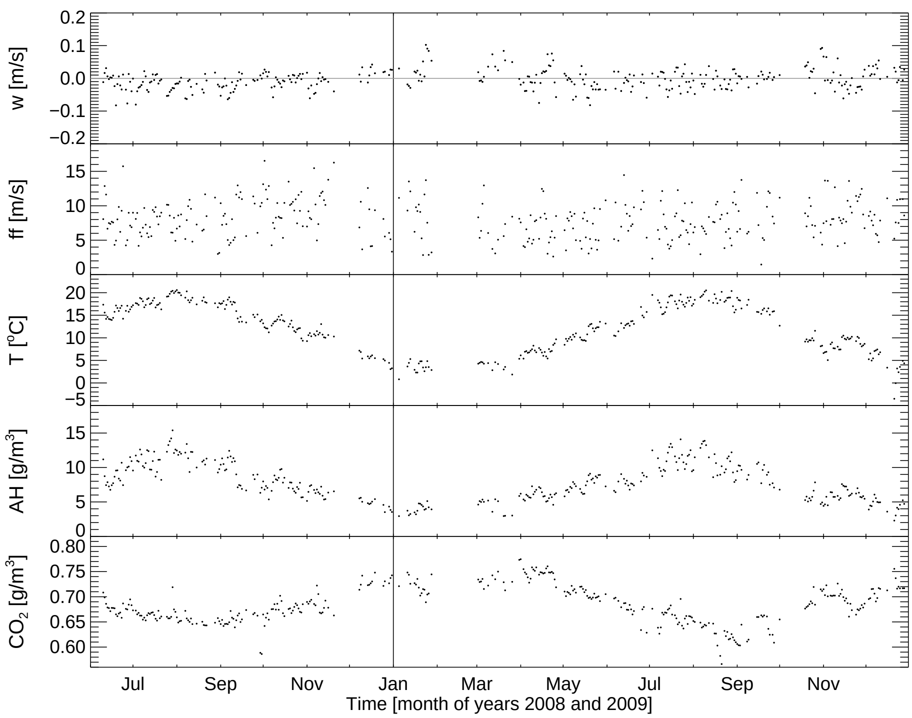

Figure 3. Daily means of measured quantities at 13.8 m height above sea surface: vertical wind speed w, horizontal wind speed ff, ait temperature T, absolute humidity AH, and CO_2 density from June 2008 to December 2009.

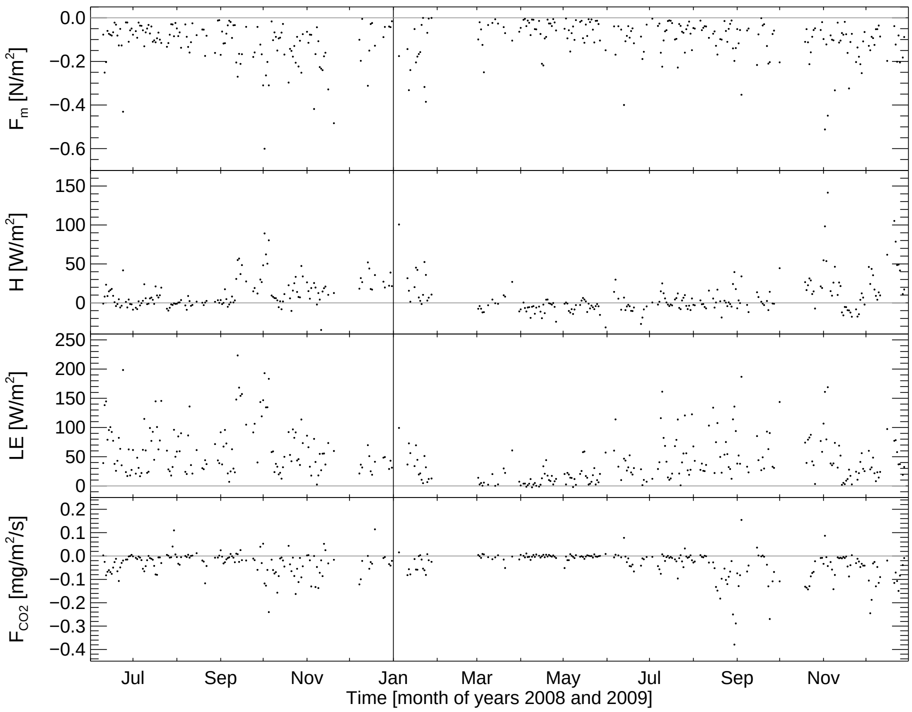

Figure 4. Daily means of momentum flux F_M, sensible and latent heat flux, H and LE, and CO2 flux in 13.8 m height, from June 2008 to December 2009.

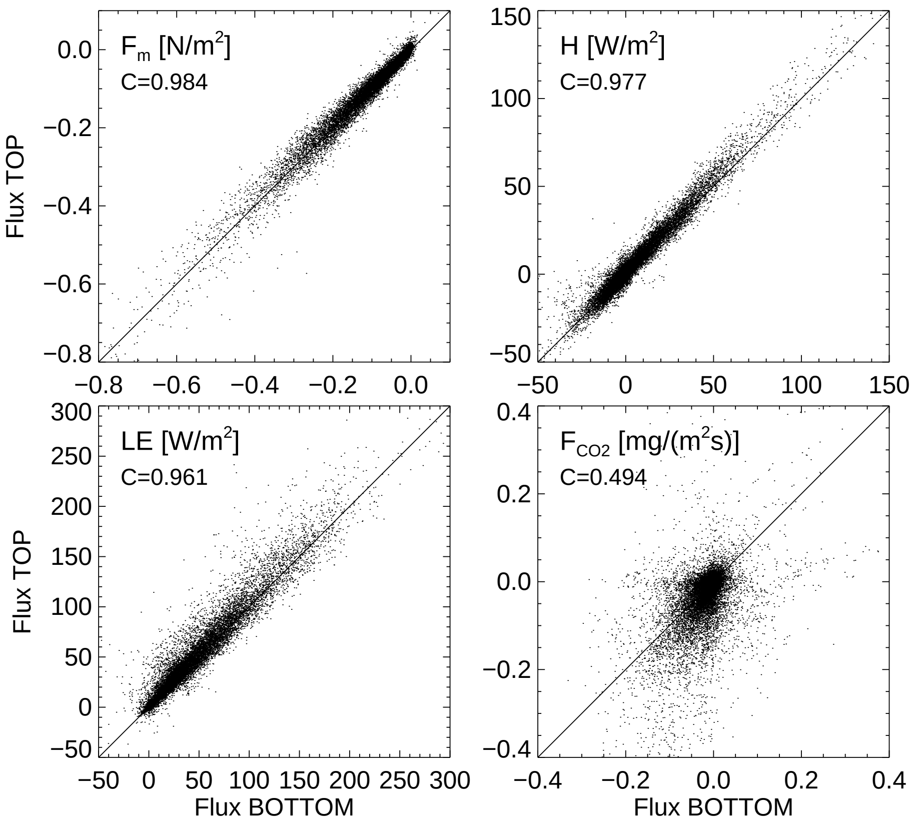

Figure 5. Comparison of turbulent fluxes at two different heights, TOP (13.8 m) vs. BOTTOM (6.8 m). The temporal resolution is 30 min. Top: momentum flux F_m (left) and sensible heat flux H (right), bottom: latent heat flux LE (left) and CO_2 fluxes (right). C gives the correlation coefficient.

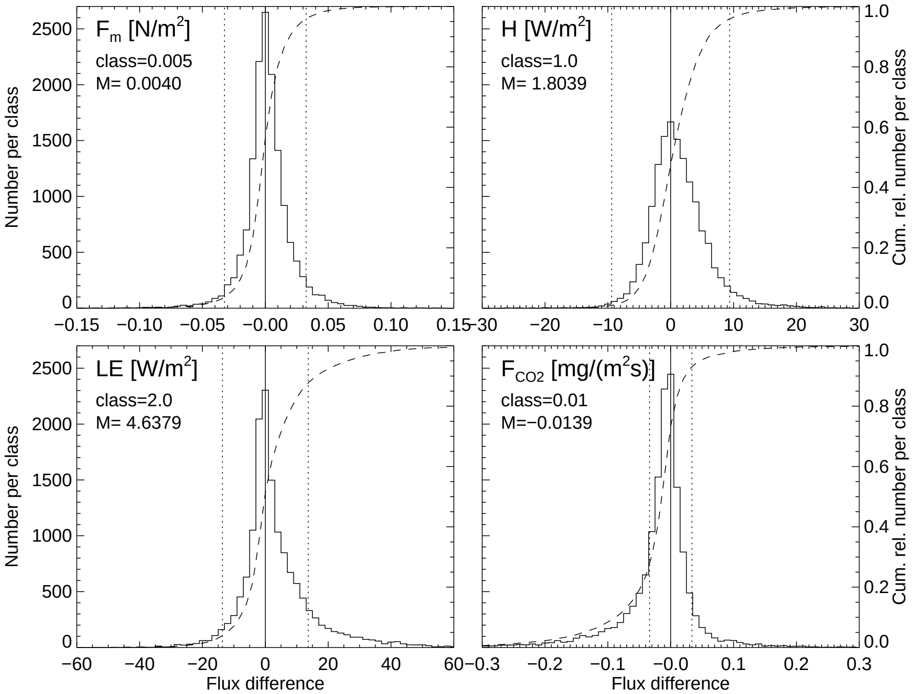

Figure 6. Distribution of flux differences (TOP-BOTTOM) for momentum (F_m), sensible (H) and latent heat (LE), and CO_2 flux (CO_2), based on 30 min values for 1,5 years. M gives the mean difference each, class stands for the width of class for each flux difference. The dotted lines give the measurements uncertainties, derived from the RMSE each.