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

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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 layer, this flux equals the exchange flux between ocean and atmosphere. The purpose of this paper is the comparison of long-term flux measurements at two different heights above the Baltic Sea to investigate this assumption. The results are based on a 1.5-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 differences between the two heights are insignificantly small more than 95 % of the time. In contrast, significant differences, which are larger than the measurement error, occur in the CO_2 flux about 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 to a very great extent 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 of anthropogenically 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 for 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 timescale 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 approximated by a 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 at a height of several meters. Measurements at one height are common practice for the determination of CO_2 fluxes and the estimation of the carbon net ecosystem exchange above land, too (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 (Forschungsplattform in Nord- und Ostsee 2) in the Baltic Sea. Each system consisted of a fast sonic anemometer and an open-path infrared gas analyzer for CO_2 and H_2O. This publication has the goal of testing 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 at both heights with the standard eddy-covariance technique in combination with the standard correction terms (see Sect. 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 analyzed additionally to serve as a reference. The data described in this paper are published in the PANGAEA system

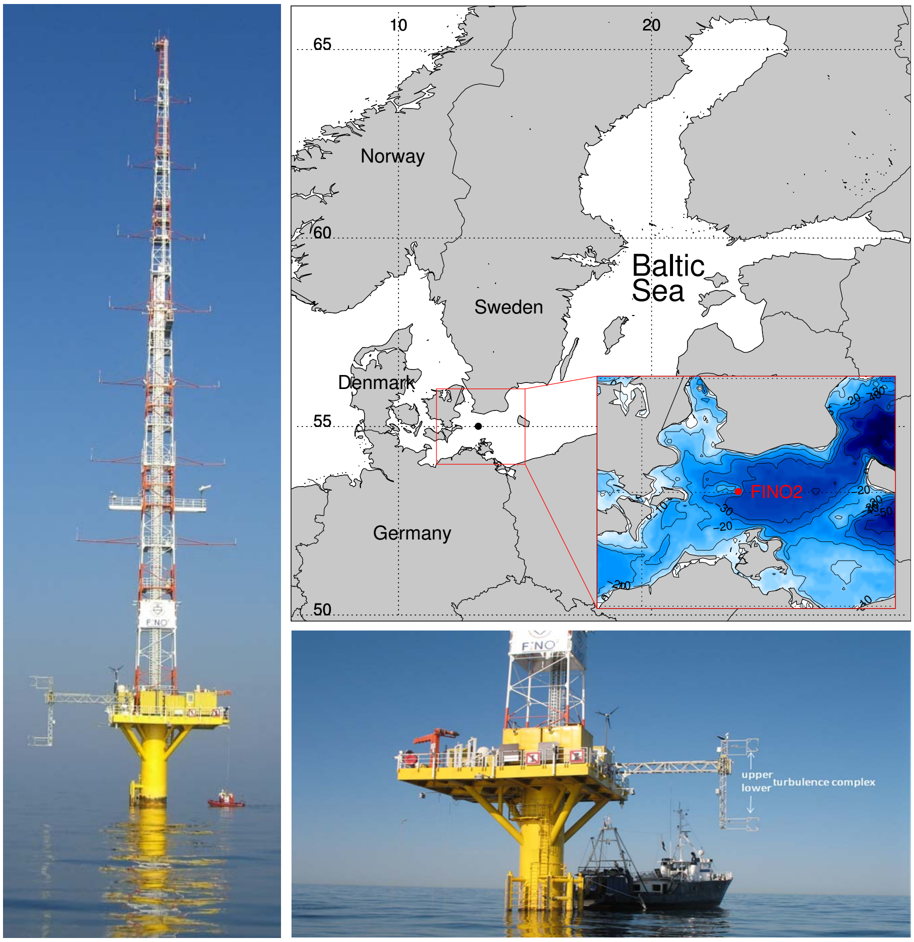

Figure 1. FINO2: position in the Baltic Sea (top, right), the whole mast (left), and the platform with the boom and instrument installation at a height of 6.8 and 13.8 m above sea surface (bottom).

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

(Data Publisher for Earth & Environmental Science; Lammert et al., 2013).

2 FINO2 – site and instrumentation

In 2007 the FINO2 platform was installed in the southwest of the Baltic Sea, in the tri-border region between Germany, Denmark, and Sweden (see Fig. 1). The platform collects meteorological (at several heights of between 30 and 101 m), oceanographic and biological data. In the framework 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 three-component sonic anemometers (USA1) and open-path infrared gas analyzers for CO_2 and H_2O (LI-COR 7500) were installed on a 9 m long boom on the southern side of the platform at two heights, at 6.8 and 13.8 m above sea surface. Figure 2 shows the boom with the instrumentation and the alignment of the sonic anemometer and the LI-COR instrument, which is identical at both heights. The

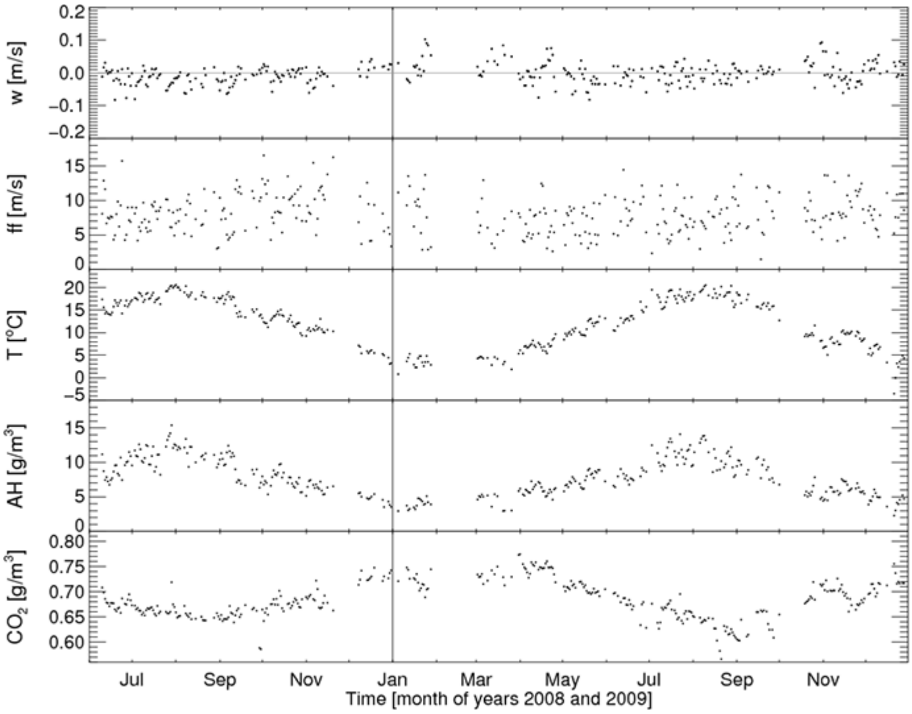

Figure 3. Daily means of measured quantities at a height of 13.8 m above sea surface: vertical wind speed (w), horizontal wind speed (ff), air temperature (T), absolute humidity (AH), and CO_2 density from June 2008 to December 2009.

sonic anemometer is installed overarm and the LI-COR instrument below the sonic anemometer. This setting was chosen to minimize the distance of the measuring volumes of both instruments (the distance is 20 cm) and to create a sector as large as possible without flow distortion. For the same reason the instruments at the different heights are installed on different sides of the boom, so the horizontal distance of the installations is nearly 1 m.

Additionally, slow temperature and humidity sensors were installed at each height. The gas analyzer systems were calibrated before the installation and worked continuously without any calibration during the whole measurement period of 1.5 years.

In this paper continuous measurements over 1.5 years (June 2008 to December 2009) are analyzed and the fluxes at both heights are compared to each other.

3 Data processing

Both instrument types, the sonic anemometer and the LI-COR instrument, 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 northerly winds. Therefore, the data are filtered in the case of wind directions between 285 and 35° to exclude not only possible flow distortion but also influence of the platform generator on the CO_2 measurements. On the basis of 10 min mean values over time periods with steady conditions (e.g., between different maintenance periods), we used a so-called sector-wise tilt correction as alignment correction. This procedure is similar to a planar fit correction but applied to 10° sectors instead of the whole plane.

For both instruments, the comparison of the high-frequency measurements with the measurements of the slow sensors showed no significant long-term drift in temperature and H_2O. Drifts on smaller timescales (on the order of days) due to contamination with sea salt, were cleaned naturally by rain. The drift of both quantities had no influence on the fluctuations on the eddy timescale, which, in contrast to the mean values, are important for the flux estimation.

4 Measurement quantities

The time series at a height of 13.8 m 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 Fig. 3. Over the time interval of 1.5 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 ranges from 3 to 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 an annual cycle.

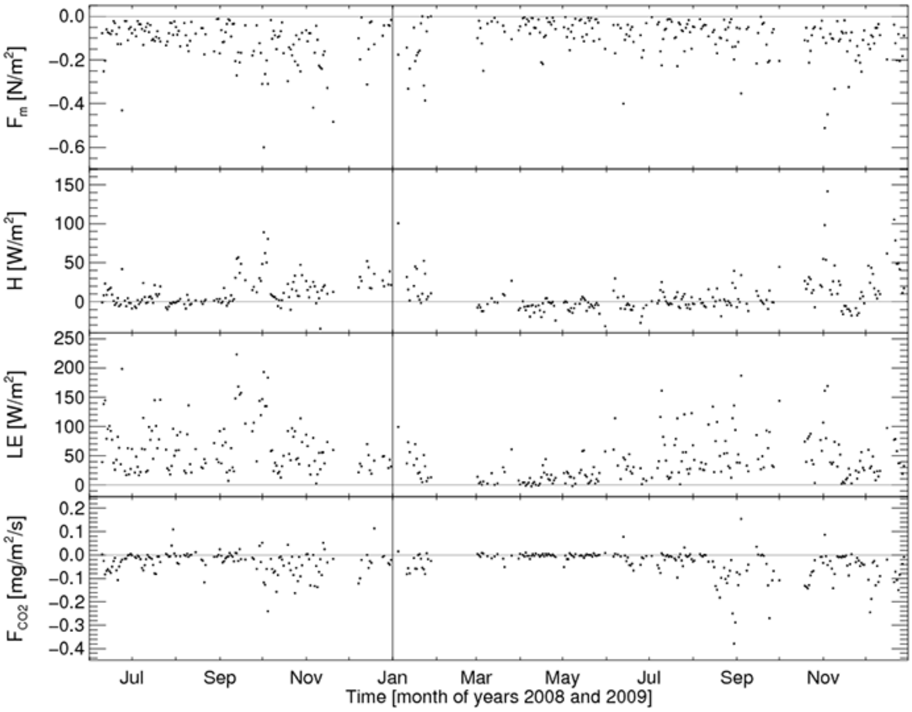

Figure 4. Daily means of momentum flux (F_m), sensible and latent heat flux (H and LE), and CO$_2$ flux at a height of 13.8 m from June 2008 to December 2009.

The daily mean values of the vertical wind velocity fluctuate around 0, ranging from -0.1 to $0.1\,\mathrm{m\,s^{-1}}$. These values are a result of processes such as horizontal convective rolls, large-scale advection or temperature contrasts between water and air. The average over the whole time period is $-0.004\,\mathrm{m\,s^{-1}}$, which is below the measurement uncertainty. The time period from June to December is comparable for all variables in both years, 2008 and 2009.

5 Turbulent fluxes and flux differences

The estimation of fluxes, such as momentum or CO$_2$, are based on the correlation of highly resolved fluctuations of the vertical wind speed with quantities such as 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 and were given by

$$F_\mathrm{m} = -\rho_\mathrm{a}\overline{u'w'} \tag{1}$$

$$H = \rho_\mathrm{a} c_p \overline{T'w'} \tag{2}$$

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

$$F_{\mathrm{CO_2}} = \overline{w'\rho_\mathrm{c}'}, \tag{4}$$

where ρ_a is the density of dry air, ρ_c that of CO$_2$ and ρ_v that 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 commonly used correction was given by Webb et al. (1980):

$$F_{\mathrm{CO_2}} = \overline{w'\rho_\mathrm{c}'} + \mu\frac{\rho_\mathrm{c}}{\rho_\mathrm{a}}\overline{w'\rho_\mathrm{v}'} + (1+\mu\sigma)\overline{\rho}_\mathrm{c}\frac{\overline{w'T'}}{\overline{T}},$$

with the ratio of molecular masses $\mu = m_\mathrm{a}/m_\mathrm{v}$ and of densities of air constituents $\sigma = \overline{\rho_\mathrm{v}}/\overline{\rho_\mathrm{a}}$. 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, amongst others, Webb et al. (1980) and 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 autocorrelation function to a zero time lag, are frequently used in data assimilation (e.g., Schlatter, 1975) and are known as the nugget effect.

The turbulent fluxes of the whole time period of 1.5 years are shown in Fig. 4 as daily averages. The momentum fluxes are in the range of -0.7 to nearly $0.0\,\mathrm{kg/(m\,s^{-2})}$. The

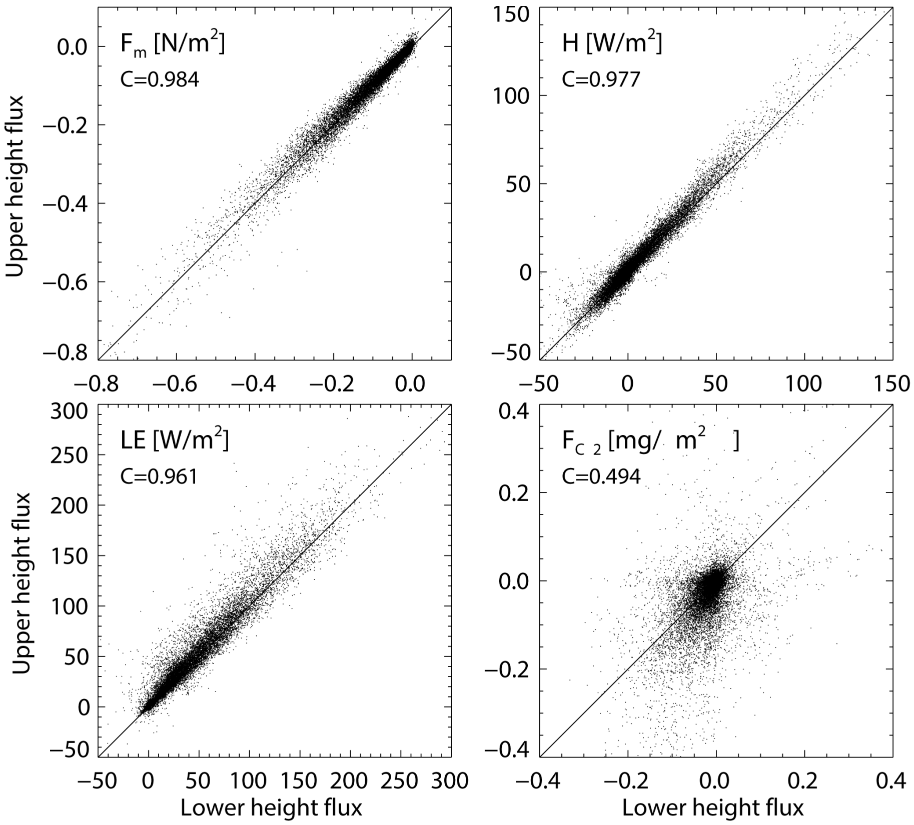

Figure 5. Comparison of turbulent fluxes at two different heights: upper (13.8 m) vs. lower height (6.8 m). The temporal resolution is 30 min. Top: momentum flux F_m (left) and sensible heat flux H (right); bottom: latent heat flux LE (left) and CO$_2$ fluxes (right). C gives the correlation coefficient.

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 or 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 and 0.4 mg (m^2 s)$^{-1}$. This magnitude is in the same range as observed by other authors, e.g., −0.2 to 0.05 mg (m^2 s)$^{-1}$ above the Baltic Sea (Weiss et al., 2007), or −0.1 to 0.3 mg (m^2 s)$^{-1}$ near the 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 5 shows the comparison of the turbulent fluxes with a 30 min resolution at a height of 13.8 m vs. a height of 6.8 m. The scatterplots of the momentum and sensible heat flux show the expected strong association 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 0, 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 LI-COR instrument is used. Nevertheless, the relatively low correlation of the CO$_2$ fluxes, compared to the other turbulent fluxes, is surprising.

For this reason, we calculated the difference in both fluxes (upper height minus lower height) and analyzed the distribution of these differences. In Fig. 6 the distribution functions of the differences are shown, additionally to the cumulative distributions, for all four turbulent fluxes. While the momentum-flux differences are distributed in a nearly Gaussian way, the heat flux difference distributions both have a slight positive skewness. The CO$_2$-flux difference distribution shows a clear negative skewness. All distributions show the maximum at zero difference. In order to distinguish between insignificant flux differences due to random measurement error and real flux differences, 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 differences are significant. The same is valid for the sensible heat flux. A positive mean difference of 4.6 W m^{-2} applies in the case of the latent heat flux, while 12 % positive differences plus 3 %

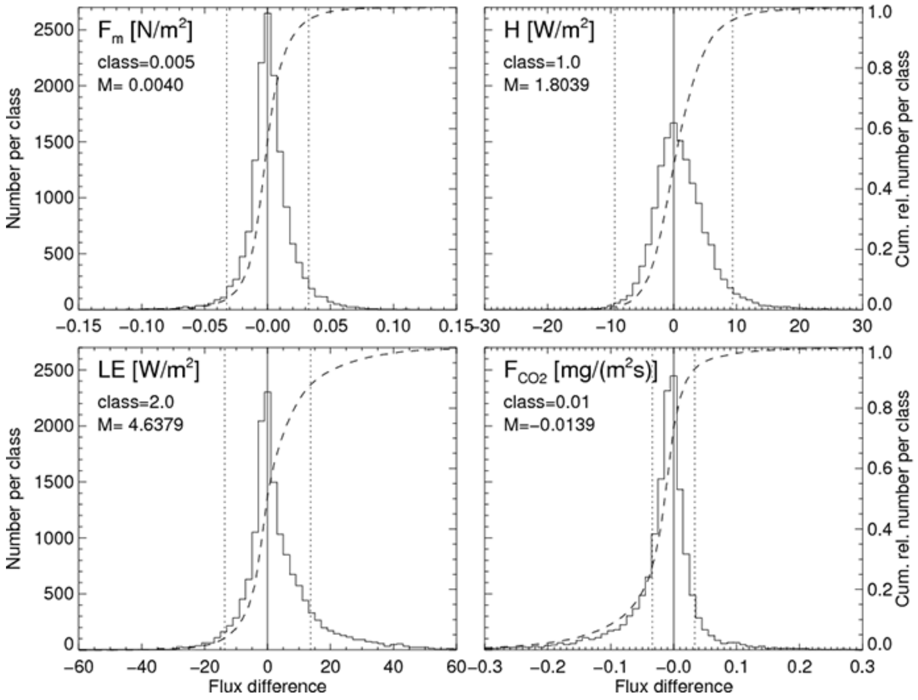

Figure 6. Distribution of flux differences (top to bottom) for momentum (F_m), sensible (H) and latent heat (LE), and CO_2 flux (CO_2), based on 30 min values for 1.5 years. M gives the mean difference for each; class stands for the width of class for each flux difference. The dotted lines give the measurements uncertainties, each derived from the RMSE.

negative differences of all cases are significant. So the latent heat flux at the upper height is significantly higher than at the lower height in 12 % of the observed time interval. The CO_2 flux, with the negative skewness in the difference distribution, is significantly higher at 13.8 m than at 6.8 m in just 5 % of all time steps, but in nearly 30 % of all analyzed cases, the differences are significantly negative. In summary, the measurements at the FINO2 platform indicate significant CO_2 flux differences at heights of 6.8 and 13.8 m in 35 % of the time.

6 Conclusions

The eddy-covariance technique is a well-established method to measure turbulent fluxes of trace gases such as 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: nearly 95 % of the time, the differences between the two measurements heights are 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 15 % of the 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 measurement height. In general, measurements are only performed at a single and arbitrarily chosen measurement height. Some discrepancy between various observational studies, 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 heights is 0.018 mg $(m^2\,s)^{-1}$, with a mean CO_2 flux of -0.019 mg $(m^2\,s)^{-1}$ for the lower and -0.036 mg $(m^2\,s)^{-1}$ for the upper height level. So, the mean difference is of the same magnitude as the flux itself. Although this paper cannot provide an explanation for vertical CO_2 flux differences, 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. A suggestion to bear in mind for future research is that one possible reason for those differences could be a gradient in the originally constant flux layer. An other explanation could be found in the measurement uncertainty of the instruments. It has to be checked whether the resolution of 10 Hz is enough to characterize small eddies, too, and if there are differences in the high-frequency loss at both heights. In this case, the measurement could be used to determine a height-dependent error in the measured CO_2 flux. We have planned a subsequent paper to answer these questions.

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