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# A Study of the Performance of Open- and Closed-Path Fast Infrared Sensors for Humidity and $CO_2$ Fluctuations

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**December 1999**

**Abstract** In order to investigate the reliability of some of the instruments most used to measure humidity and $CO_2$ concentration fluctuations in field campaigns, two identically equipped meteorological measuring stations were operated for 30 days in the autumn 1995. Each mast was equipped with three different types of fast infrared sensors to measure fluctuations of humidity and $CO_2$. Moreover the masts were equipped with standard instrumentation to measure wind speed, wind direction, temperature, humidity, pressure and solar radiation and with a Gill sonic anemometer/thermometer to measure turbulent fluctuations of temperature and wind components. Turbulent data were recorded with an effective sampling rate of 10 Hz. Thirty-minute averaged statistics of the atmospheric turbulence were derived. In this paper we analyse two periods of three days each and present some results of the comparisons among the absolute values of concentrations measured by fast and slow instruments. Moreover the inter comparison of fluxes estimated by different types of instruments obtained by the eddy correlation method is presented.

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# Contents

# Preface

The correct estimation of turbulent surface fluxes of scalars such as temperature, humidity and gaseous compounds of the atmosphere is very important for many fields in Geophysics like air-sea and land-atmosphere exchange processes, climatology and meteorological modelling, remote sensing, air pollution etc. Scalars can be defined to be passive or active. Passive scalars are defined as those whose variations do not significantly affect the buoyancy of a parcel of air whereas buoyancy is affected by variation in active scalars. Research over the past two decades has determined that the scalars T and q can be described to be active or passive depending on the stability conditions while the other atmospheric compounds are always classified as passive.

Since scalars are transported by turbulence, they are supposed to be correlated but in some studies on temperature T and moisture q they have been found to be unrelated. This could be explained by interaction between local scales and large scales. Significant deviations could be attributed to non-ideal conditions (local advection, extreme stability). However sometimes instrumental limitations play a role in the explanation of the lack of correlation. For this reason special regard should be given to the performance of the instruments used to measure turbulent fluctuations of scalars. The fluctuating part of a scalar measuring signal is needed to calculate turbulent fluxes in the atmosphere together with fluctuations of wind speed components by the eddy correlation method. For temperature a vast literature about the sonic thermometer/anemometer can be found, (see e.g.. Schotanus et al., 1973 and Kaimal, 1979). To measure fluxes of other scalars besides q, $CO_2$ and T, methods like the eddy accumulation techniques are being developed. Here we focus on measurements of humidity and $CO_2$.

In order to measure concentration and fluctuations of $CO_2$ and/or water vapour, fast infrared gas analysers are used based on the characteristic absorption band in the infrared of the two gases. Two different types of instruments have been developed namely the open- path and closed-path. In a closed-path instrument air is sucked through a tube from the measuring point to the gas analyser cell. Open-path instruments measure the concentration of a gas directly at the sampling point.

In the past decade technological advance, theoretical studies (Kristensen 1997) and experimental work (Leuning and Moncrief, 1990; Lenschow and Raupach, 1991; Lee et al. 1994; Leuning and Judd, 1996) have addressed the performance of the most used devices to measure fluctuations of humidity and $CO_2$ and the use of the eddy correlation method to calculate fluxes. The performance of both closed and open-path instruments and their advantages and disadvantages have also been described.

Webb et. al. (1980) reported that to have a precise measurement of the turbulent flux of the density of a minor constituents of the atmosphere, the constituent density variation caused by the turbulent fluctuations in temperature and moisture must be taken in account. In case the minor constituent is water vapour (absolute humidity) then only the variation due to the temperature must be taken in account. The correction to be applied is called Webb correction.

Here we address water vapour and $CO_2$ fluxes in order to investigate the reliability of three of the most common instruments used in experimental campaign. In this study, measurements from a two identically equipped masts have been analysed and compared. Moreover we discuss the application of the Webb's correction.

# 1 Experimental Set-Up

Two meteorological measuring stations were operated from October the 13th 1995 to November the 14th on a site located in the Risoe area in Denmark. Two 10-m high masts were placed at a distance of ten metres from each other, in the NW-SE ($135^o$-$315^o$) direction. This set-up guarantee that turbulence measurements for wind directions in the $180^o$-$270^o$ sector remain not perturbed by the instruments and the mast.

The masts, were identically equipped with fast instruments to measure turbulent fluctuations of wind velocity, temperature, humidity and $CO_2$. At 6 m height the open-path instruments were placed up-side down wise above the sonic anemometer. The tube of the closed-path instrument was joined at the sonic anemometer while the body of the closed-path analyser was located at the bottom of the mast. Furthermore standard meteorological instrumentation to measure profiles of wind-speed, direction, temperature, humidity, pressure and solar radiation were also available. In order to sample and process the data the RISOE-DAQ data acquisition and processing program has been applied. The data were recorded with a sampling rate of 20-Hz and block-averaged corresponding to an effective sampling rate of 10-Hz. Based on the 10-Hz data the 30-minute average statistics of the atmospheric turbulence were derived. In addition all raw data (10 Hz) were stored with the purpose of making a detailed re-analysis of the measurements possible at a later stage.

## 1.1 Infrared Gas Analysers

Common instruments to measure concentrations and fluctuations of $CO_2$ and/or water vapour are based on infrared light absorption. Two types of instruments are found on the market, open- and closed-path sensors. Open-path instruments measure the concentration of the gas directly at the sampling point. In closed-path instruments air is sucked through a tube from the measuring point to the gas analyser cell.

Three types of fast infrared gas analysers were used in this investigation. A closed-path Li-Cor 6262 ($H_2O$ and $CO_2$), LICOR, Inc. Lincon, Nebraska, USA, an open-path Advanet E009A ($H_2O$ and $CO_2$), Advanced System Inc., Okayama, Japan and an OPHIR IR-2000 ($H_2O$), OPHIR, Lackewood Inc., CO. All instruments were in duplicate, (a set on each mast).

All infrared instrument measurements can show a $H_2O$ and $CO_2$ cross-correlation caused by the absorption bands overlapping of the two gases, (Leuning and Judd, 1996).

**The Ophir (Ir-2000) Hygrometer**

The OPHIR hygrometer is an open-path instrument. It measures absolute humidity (water vapour density, $gm^{-3}$) by using a dual wavelength differential absorption technique. The instrument measures transmissions of infrared radiation within the 2 μm water-vapour absorption band and compares the transmission measurement to the transmission within a nearby band in which water vapour absorption is negligible.

**Advanet E009a**

The ADVANET E009A hygrometer is an infrared open-path instrument operating on the same principle as the OPHIR. The advantage of this instrument is that it measures both absolute humidity and $CO_2$ concentration by using a dual wavelength differential absorption technique. The instrument measures transmissions of infrared radiation within the water-vapour and $CO_2$ absorption bands.

**Li-Cor (6262)**

The LI-6262 is a closed-path infrared gas analyser. The measurements of the concentration of $H_2O$ and $CO_2$ are performed by evaluating the difference in absorption of the infrared radiation passing through two gas sampling cells. The absorption in the sampling cell is compared to the absorption in the reference cell filled with NO and the output of the analyser is proportional to the difference of the absorption between the two cells.

To control the absolute value of humidity and $CO_2$ concentrations slow response reference sensors have been used: a Th. Friedrichs Electric Psycrometer for $H_2O$ and an ADC-7000 for $CO_2$. Advantages and disadvantages for an open- and closed-path instruments are summarised below:

**OPEN-PATH INSTRUMENTS**

- OPHIR ( $H_2O$)
- ADVANET E009A (OHTAKI) ($H_2O$ and $CO_2$)

*Table 2a. Advantages and disadvantages for an open-path instrument.*

| ADVANTAGES | DISADVANTAGES |
|---|---|
| • **Direct estimate of fluxes by the eddy correlation method.** | • **Create distortion of the flow** |
| | • **Need of Webb correction if they measure concentration** |

**CLOSED-PATH INSTRUMENTS**

- LI-COR 6262 ($H_2O$ and $CO_2$)

*Table 2b. Advantages and disadvantages for a closed-path instrument.*

| ADVANTAGES | DISADVANTAGES |
|---|---|
| • **No flow distortion and** | • **Time lag ,** |
| • **No Webb correction** | • **Damping of high frequencies and** |
| | • **Various corrections** |

## 1.2 The Flow Distortion

The flow distortion can be induced by various sources like the instrument body that perturbs the flow field, the supporting structures of the mast or by the boom on which the instrument is located. The flow distortion can be minimised in different ways as for instance by placing the instruments such that their bodies do not influence the flow in the direction of interest. As mentioned above, in our set-up the flow is not perturbed when it comes from our sector of interest (180°-270°). The problem does not exist for closed-path instruments because their main body is located at the bottom of the mast at a certain distance from the sonic anemometer. On the other hand a closed-path instrument suffers from other features: its signal is time lagged with respect to the sonic signal and the flow undergoes a dumping of high-frequency concentration fluctuations in the tube. The latter can lead to flux underestimation but it can be minimised if the flow is maintained turbulent in the tube (Lenschow and Raupach, 1991).

## 1.3 Webb Correction

Webb et. al. (1980) reported that to have a precise measurement of the turbulent flux of the density of a minor constituents in the atmosphere, the constituent density variation caused by the fluxes of heat and moisture must be taken into account. If the minor constituent is water vapour (absolute humidity), then only the variation caused by the heat flux needs to be taken into account. The results of the application of this correction will be discussed later in the report.

# 2 Results and Discussions

In this report we concentrate on two periods of three days each where the flow comes from ideal directions and most of the instruments were operative. During both periods surface stability conditions were neutral to stable. Since both periods were showing the same peculiarity we are going to show results from one of them, namely from Julian date 296.6 to 299.0

## 2.1 Comparison of Absolute Values

Figures 1 shows time series of absolute humidity for the three instruments.

Figure 2 shows the time series of concentration values of $CO_2$ for the two E009 and the two LI-COR instruments.

From these figures and from previous studies, (i.e. Sempreviva and Gryning 1996) we can conclude in general that fast infrared sensors are not very good at measuring values of gas density. However a bias in the absolute value does not influence the fluctuations, but a gain must be applied to correct the fluctuations if there is a drift in the instrument response. A good solution is to operate a slow but precise reference sensor for calibration along with the flux instrument. In our campaign the absolute values of concentrations of $H_2O$ and $CO_2$ from the fast sensors have been compared with the values measured by relatively slow reference instrument. Since the instruments were drifting slowly compared to the our average period, the gain has been calculated for each instrument by a fitting procedure using the scatter plots of the fast versus the slow sensor and it has applied to the fluctuation values.

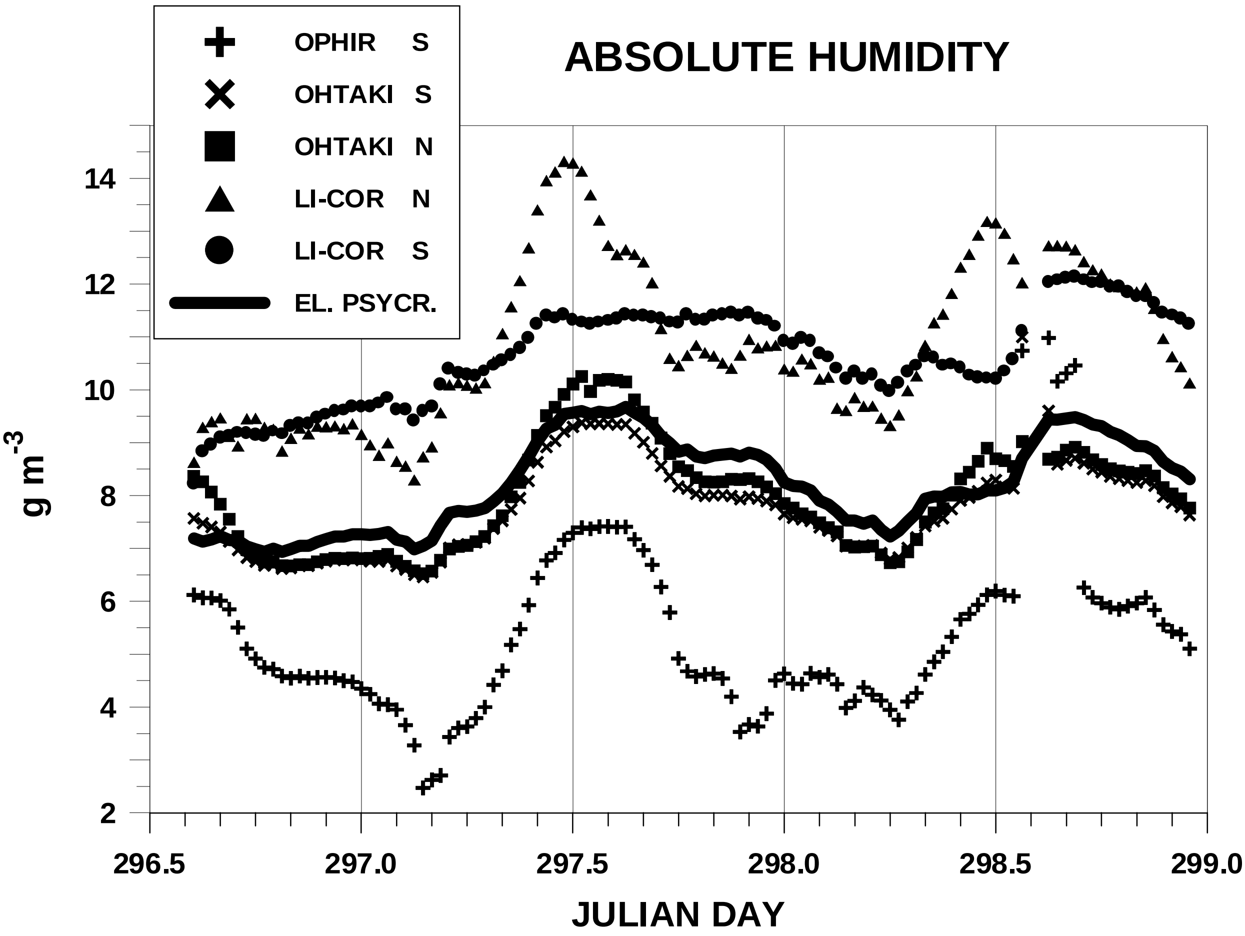


*Figure 1. Comparison between time series of the absolute humidity measured by the fast sensors and the absolute humidity measured by the reference sensor*

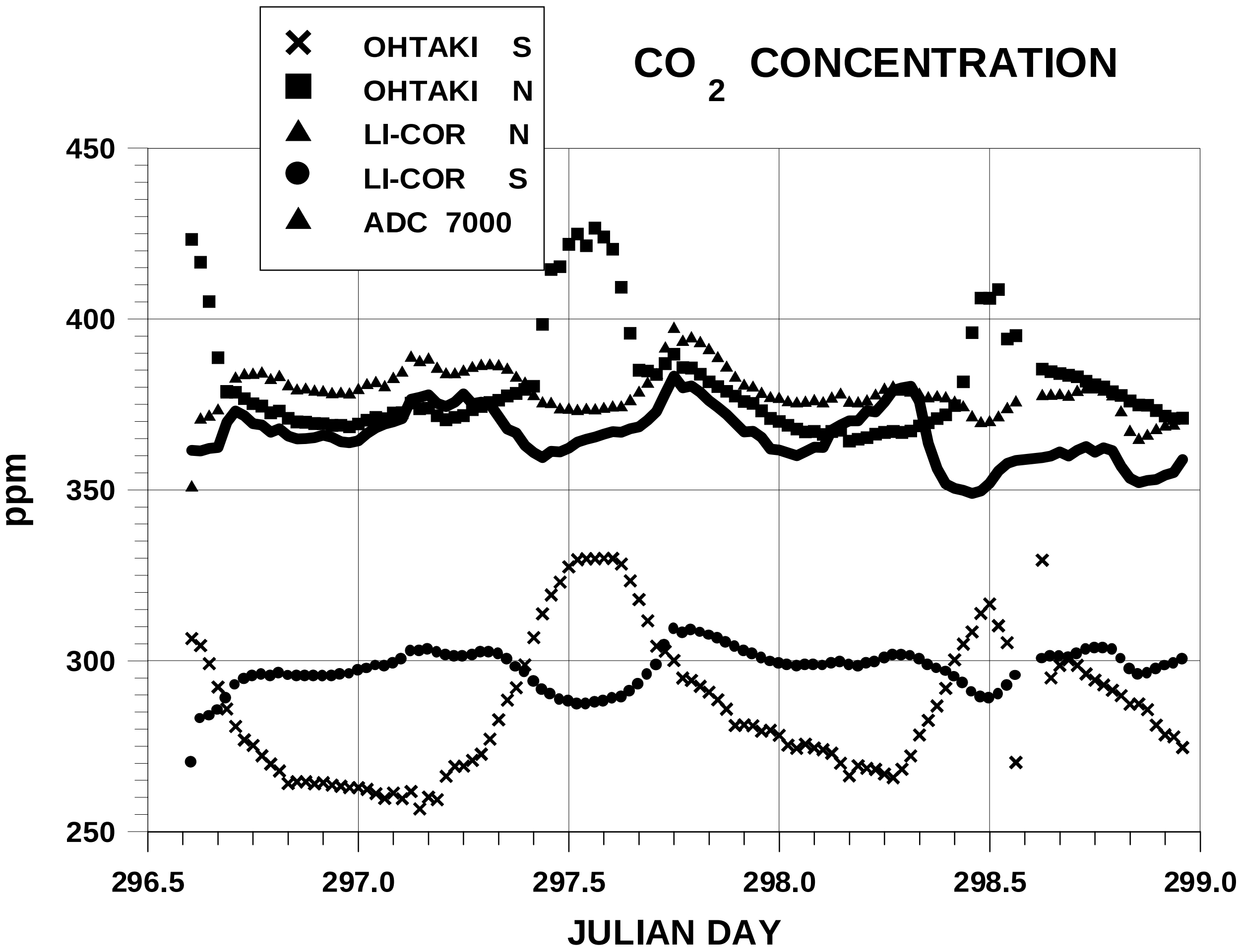


*Figure 2. Comparison between time series of the $CO_2$ concentration measured by the fast sensors and the absolute humidity measured by the reference sensor*

## 2.2 Flux Inter-Comparison

### Water Vapour Fluxes

Fluxes were calculated applying the eddy correlation method. Figure 3 shows the inter comparison between the fluxes of $H_2O$ obtained by each instrument for the second period. All instruments were operative except the OPHIR at the South mast. Furthermore the LI-COR North was not comparing well with the other instruments probably because of condensed water in the sampling tube.

We have calculated the mean flux and the standard deviation $\sigma$ from the instruments. In figure 4 the time series of mean flux and standard deviation from all instruments is shown.

### $CO_2$ fluxes

To compare the performance of the LI-COR with that of the Advanet E009 instruments, data from the second period have been considered. In this period, all four instruments were in operation.

Figure 5 shows the inter comparison between the fluxes of $CO_2$. In figure 6 the time series of the mean flux and the related standard deviation is shown.

### Discussion

We note a satisfactory agreement among fluxes from the various instruments. To estimate the uncertainty that we could expect when measuring with a fast infrared instrument, the percentage ratio R between the standard deviation and the mean value of the fluxes has been calculated.

$$R = \frac{\sigma}{\overline{wq}} * 100$$

Figure 7 shows the value of the ratio R for water vapour for the two periods versus the mean flux.

For small fluxes the value of R is greater than for large fluxes. R is decreasing to approximately 25% with increasing value of the flux.

Concerning $CO_2$ the R ratio is shown in figure 8 as a function of the mean flux value. As for water vapour the ratio is greater for small fluxes than for large fluxes. Again it becomes approximately 25% as the values of the flux increases.

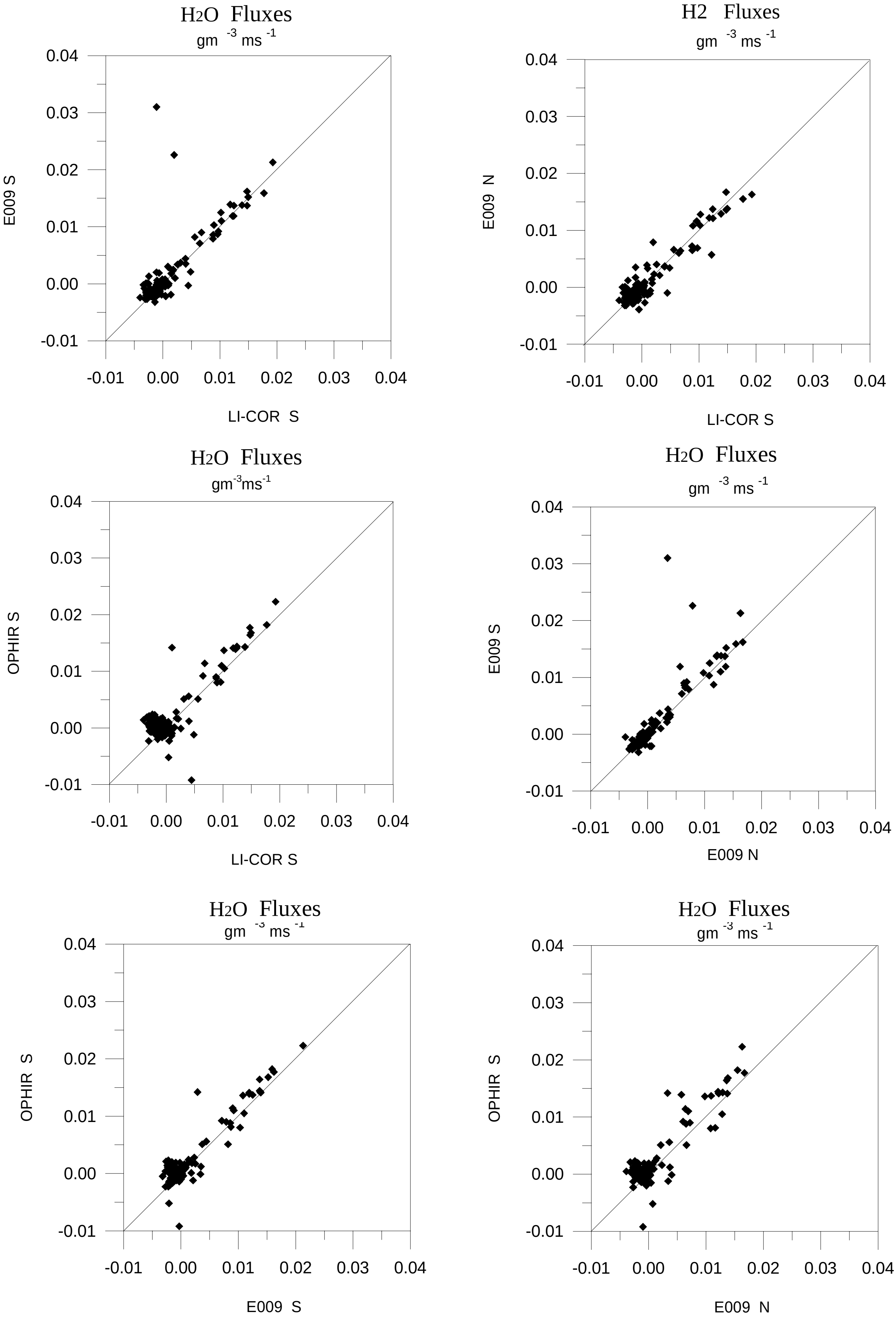


*Figure 3. Comparison of $CO_2$ fluxes estimated by different instruments at the two masts. With N we indicate the northern mast and with S we indicate the southern mast.*

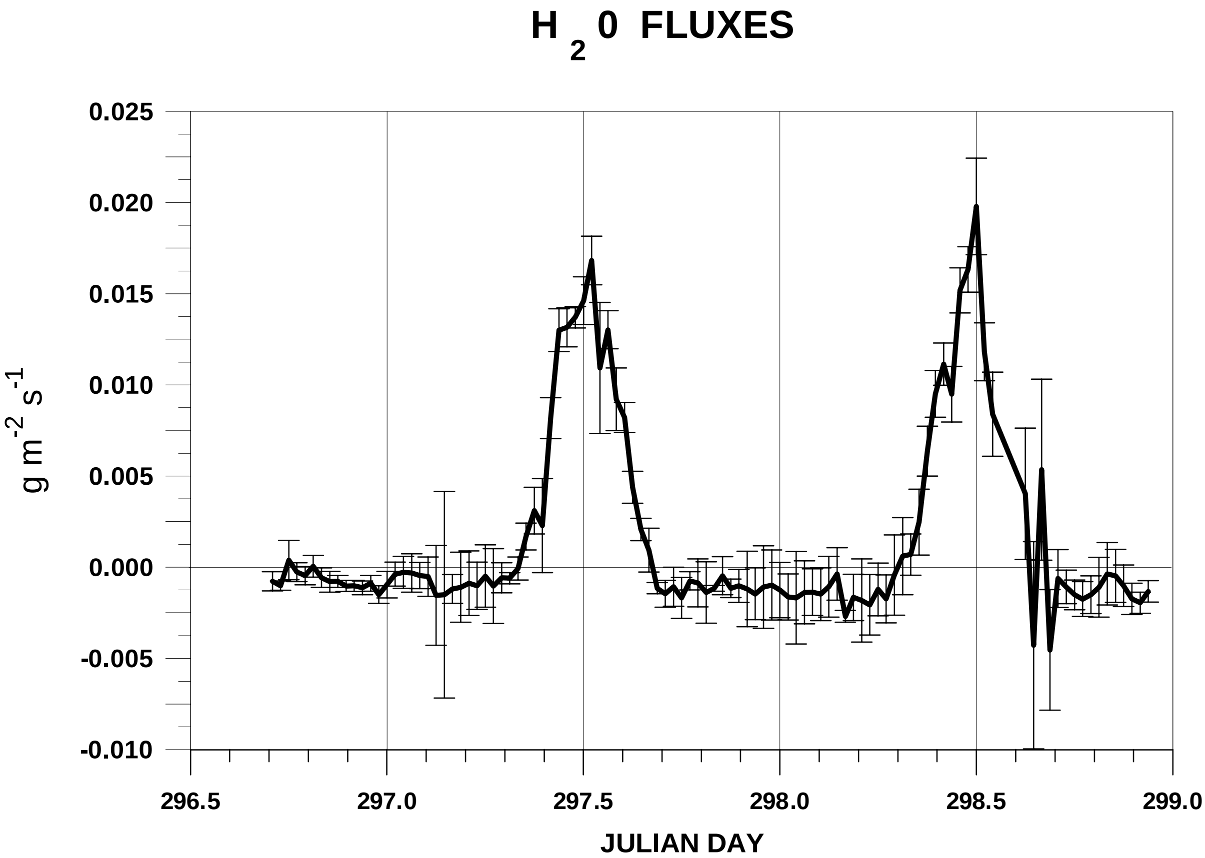


*Figure 4. Time series of mean $H_2O$ flux, calculated by averaging the fluxes obtained from each instrument, and the resulting standard deviation.*

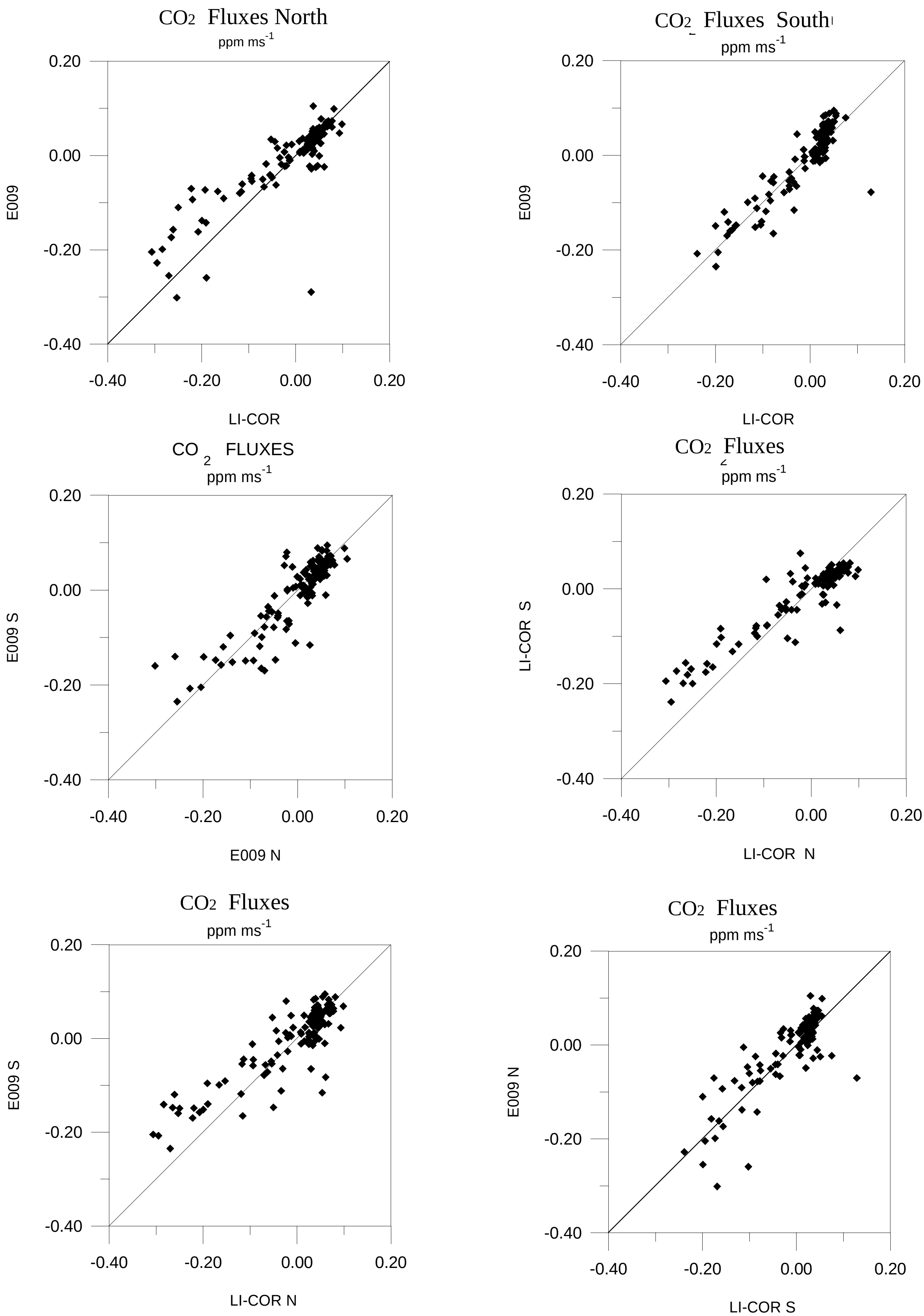


*Figure 5. Comparison of $CO_2$ fluxes estimated by different instruments at the two masts. With N we indicate the northern mast and with S we indicate the southern mast.*

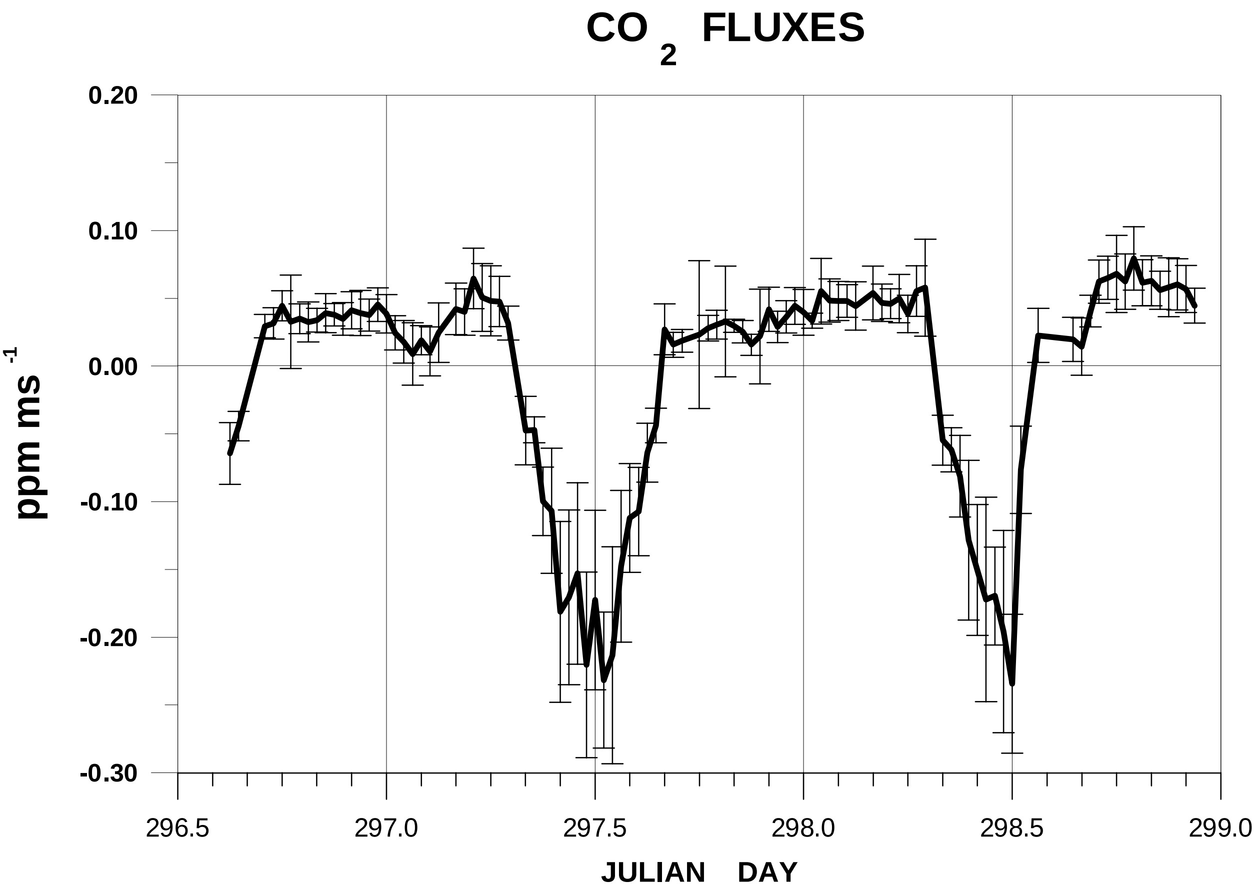


*Figure 6. Time series of mean $CO_2$ flux calculated by averaging the fluxes from each instrument and the resulting standard deviation.*

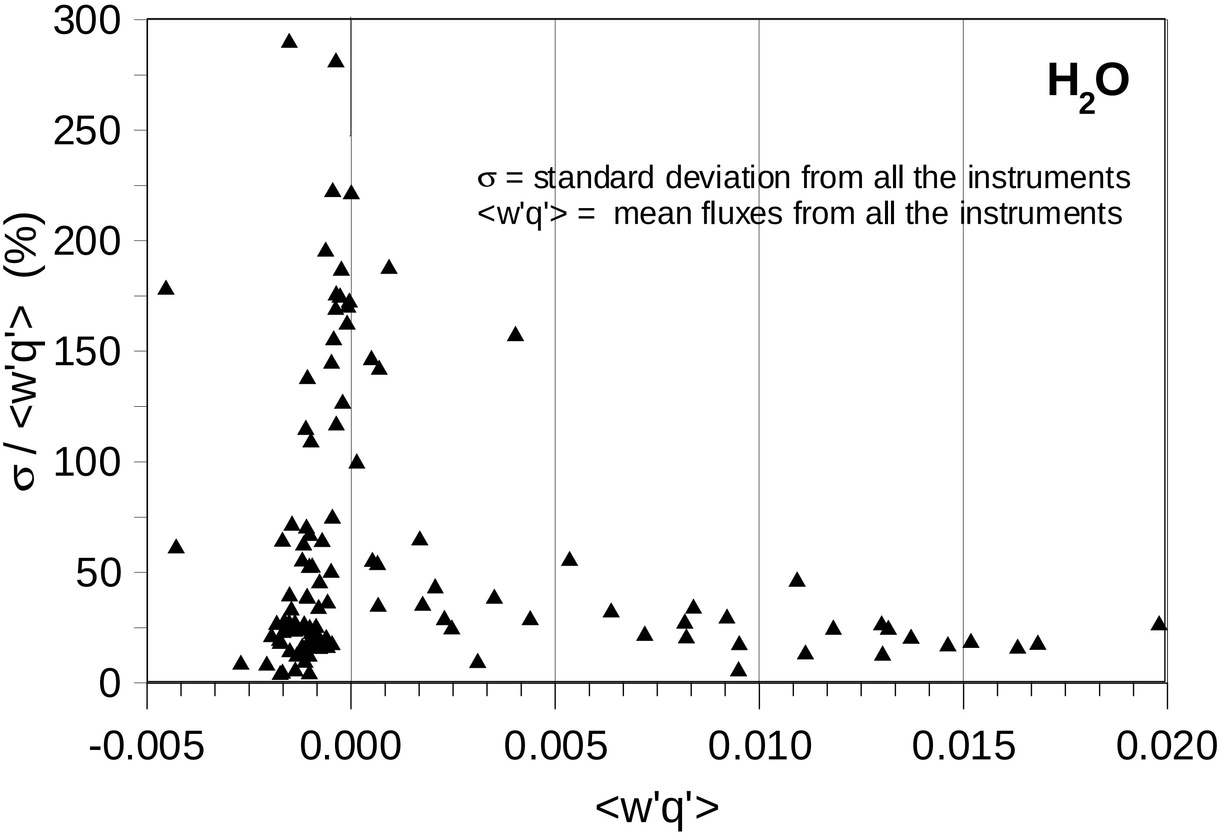


*Figure 7. Ratio R between the standard deviation and the mean $H_2O$ flux estimated by the fluxes from all instruments. This ratio is shown versus the values of the mean flux. It gives an estimate of the uncertainty that we could expect when measuring with a fast infrared instrument.*

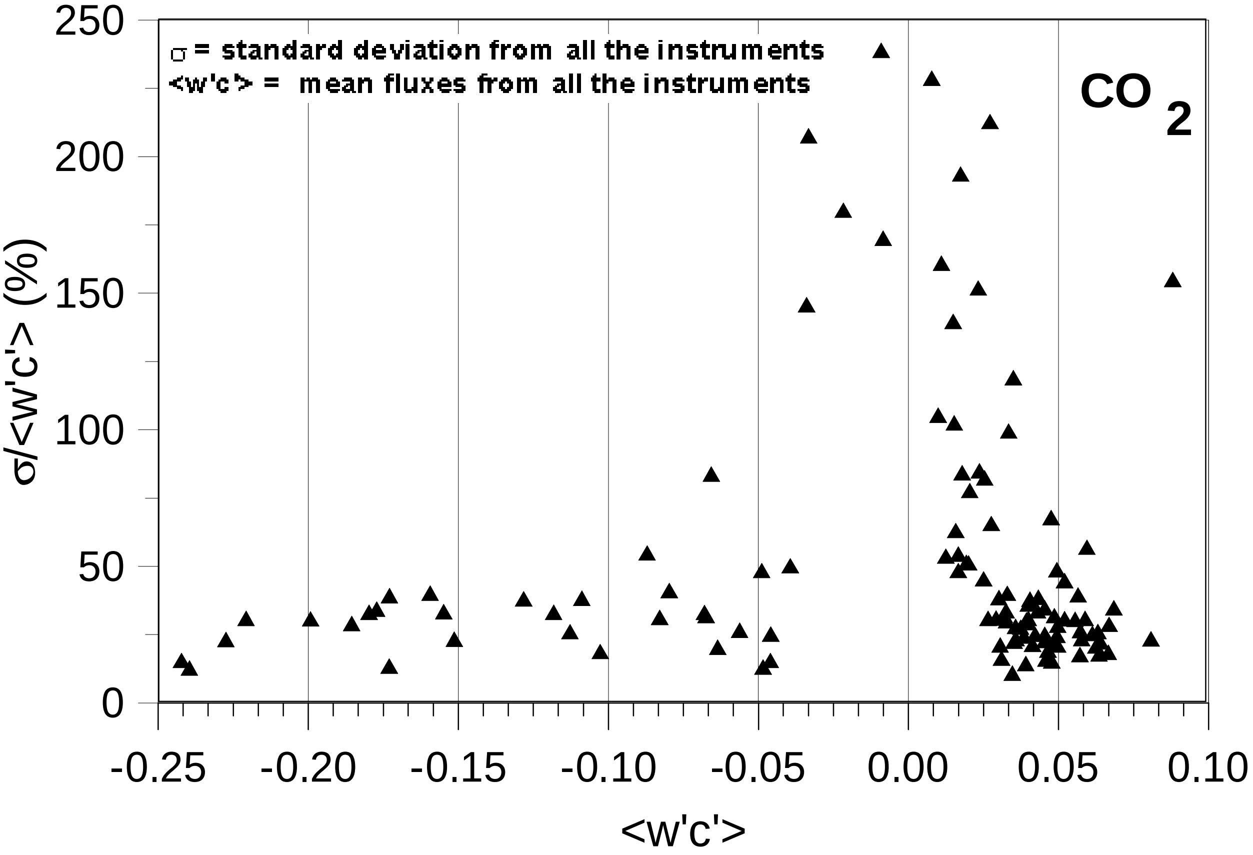


*Figure 8. Ratio R between the standard deviation and the mean $CO_2$ flux estimated by the fluxes from all instruments. This ratio is shown versus the values of the mean flux. It gives an estimate of the uncertainty that we could expect when measuring with a fast infrared instrument.*

# 3 Webb Correction

As mentioned above Webb et al. (1980) and other authors reported that to have a precise measurement of the turbulent flux of a minor atmospheric constituent, the constituent density variation caused by the turbulent fluxes of heat and moisture must be taken in account. If the minor constituent is the water vapour (absolute humidity) then only the variation caused by the heat flux must be taken in account. Since the instruments used in this study measure the moisture density $\rho_v$ the fluxes must be corrected.

If $E_{raw}$ and $F_{raw}$ are respectively the uncorrected fluxes of the moisture and $CO_2$, $\mu = (\overline{m_a} / \overline{m_v})$ is the ratio between molecular masses for dry and wet air, $\lambda = (\overline{\rho_v} / \overline{\rho_a})$ is the mixing ratio between water vapor and dry air density respectively.

Then the corrected water vapour flux is given by (Webb et al. 1980)

$$E = (1 + \mu\lambda)\{E_{raw} + (\overline{\rho_v} / \overline{\rho})(H / c_p)\overline{T}$$

Corrected minor species flux

$$F = F_{raw} + (\overline{\rho c} / \overline{\rho a})\{\mu /(1 + \mu\sigma)\} E + (\overline{\rho_c} / \overline{\rho})(H / c_p)\overline{T}$$

Leuning et. al. (1982) found typical correction values of 50% or larger. Webb et. al. (1980) show that the value of the correction could also destroy the flux values.

Closed-path instruments do not usually need these correction because the flow is brought to the sensor chamber through a tube where heat transfer through the tube wall ensures dumping of temperature fluctuations.

Here we have addressed the Webb correction for the $CO_2$ fluxes only because it is usually quite significant. Figures 9 and 10 show the time series of the mean flux with its standard deviation and the ratio R in function of the fluxes respectively. Also in this case the correction reduces the magnitude of the fluxes. During the night this reduction might lead to negative flux while we expect the fluxes to be positive due to the plants photosyntesis activity.

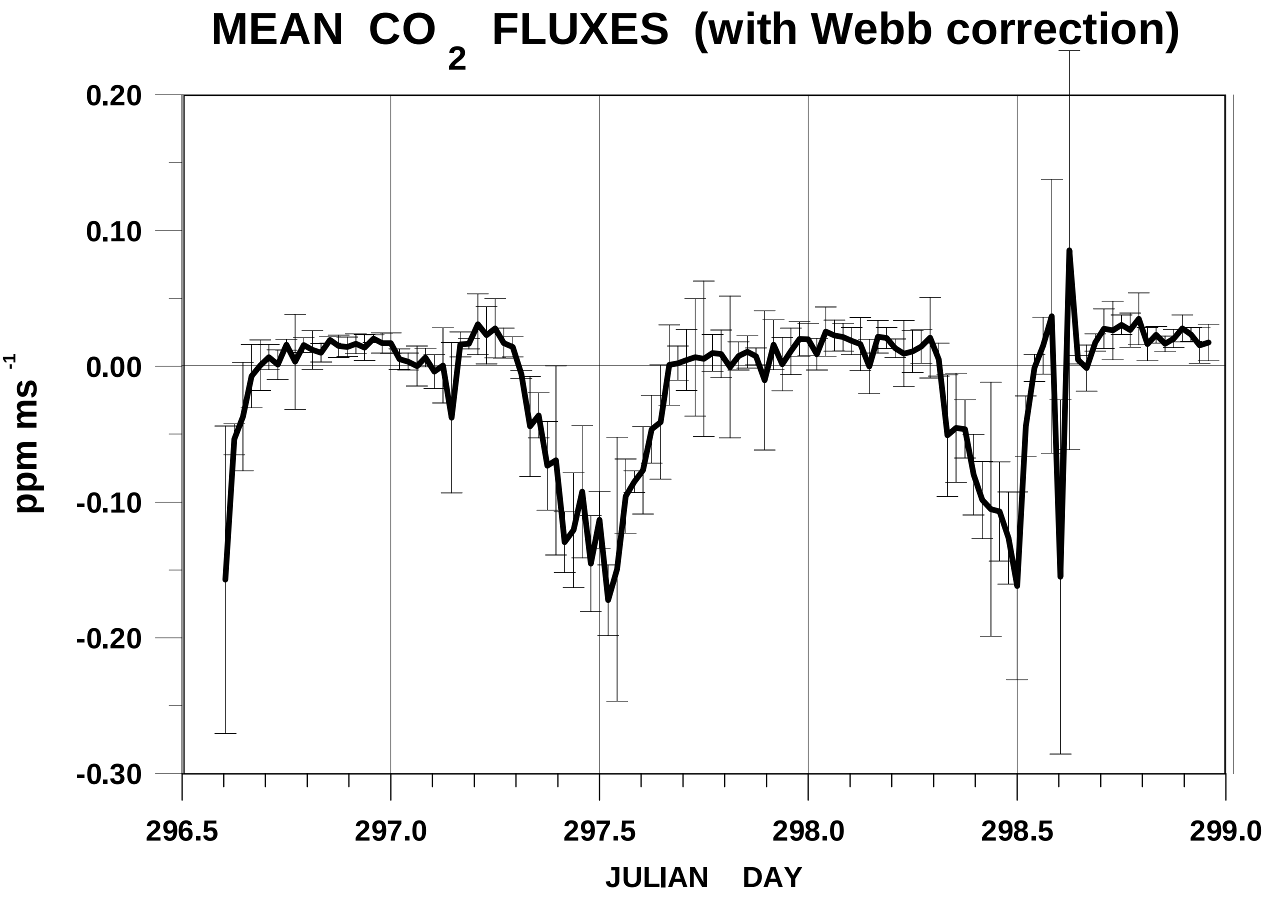


*Figure 9. As in figure 7 but in this case the Webb correction has been applied to the $CO_2$ fluxes obtained by the Advanet E009 data. From the comparison with figure 7 we note that the corrected fluxes are smaller than the one without correction*

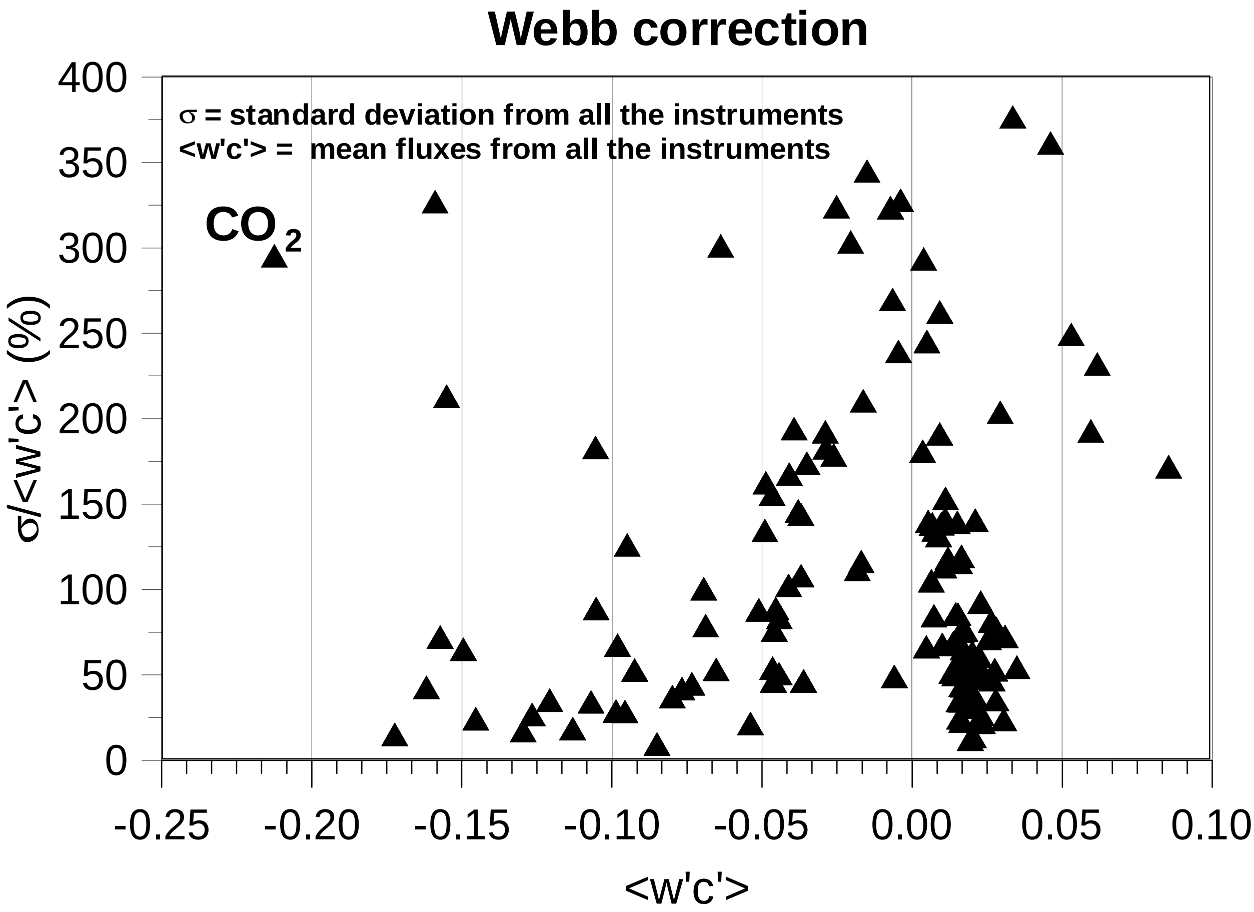


*Figure 10. As in figure 8. In this case the Webb correction has been applied to the $CO_2$ flux obtained by the Advanet E009 instrument.The Webb correction reduce the fluxes and increases the uncertainty.*

# 4 Time Lag

When estimating fluxes by the eddy-correlation method, the problem of time lag is often encountered. There are two main reasons for a time lag to occur, separation between sampling points and delay of the scalar analysis because of tubing.

When measuring fluxes by using a sonic anemometer and a device for measurements of concentration fluctuation values, the time lag is zero if the instruments are co-located at the same mast or if the flow is perpendicular to a line between the instruments. In case of a flow that is not perpendicular to the line, the time lag decrease with increasing wind speed.

In a closed-path instrument there is always a time lag caused by the transport of the flow in the tube. and we consider two methods: the flow rate method and the eddy correlation method.

### Flow rate method

The time lag caused by the displacement between the measuring point and the gas analyser can be estimated by using the length *l* and internal diameter *d* of the tubes and the inflow rate value *Fl*. The inflow value has been recorded during all measuring period.

We denote the north sensor and the south sensor by subscript N and S respectively. In our case $l_N$ = 15m, $l_S$ = 9 m , $Fl_N$ = 24-31 *l /min* , $Fl_S$ = 8-15 *l /min*, $d_N$ = 8mm and $d_S$ = 3 mm.

This results in values for the time lag of $t_N$= 7.5 - 5.8 s and $t_S$ = 3-1s for the South and North instrument respectively.

### Cross-correlation method

The cross-correlation method is based on the knowledge that the correlation between scalar and vertical velocity results in fluxes. On this basis we consider different time lags around the expected one and take the time lag which gives the maximum correlation between w and the scalar. Figure 11 shows the time lag estimated by this method for high values of the fluxes for both LI-CORs. On the other hand, with small and statistically more indeterminate fluxes, figure 12, more than one maximum of the correlation between the w and the scalar signal can be found, leading to a wrong time lag value. This is clear in figure 13 where the characteristic time lag value for each LI-COR, estimated by the cross-correlation method, is shown as a function of the flux value. The time lags approach the flow rate time lag for high values of the flux. We can conclude that the time lags, estimated by using the inflow method, is a more reliable estimate in all conditions.

On the other hand the advantage of the cross-correlation method is to estimate a time lag which is including the other possible case of time lag described above.

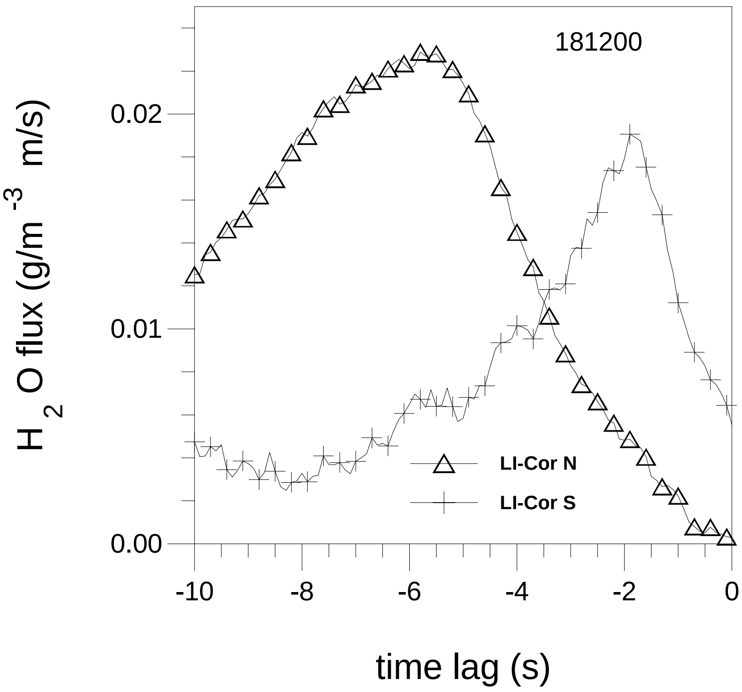


*Figure 11. Flux of water vapour calculated for different time lags. The time lag corresponding to the maximum flux is chosen.*

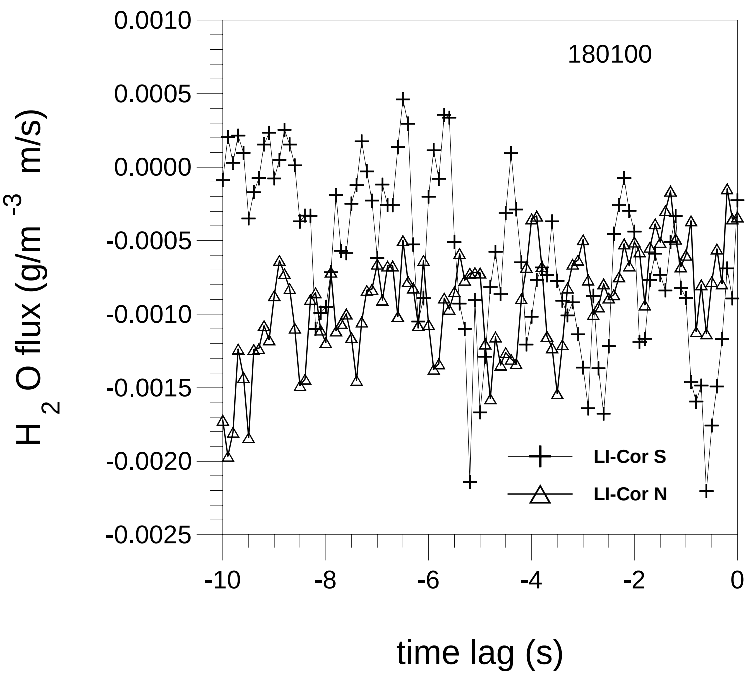


*Figure 12. Time lags calculated by the cross-correlation method. When fluxes are small, this method can be misleading. More than one maximum can occur because of statistically undetermined fluxes.*

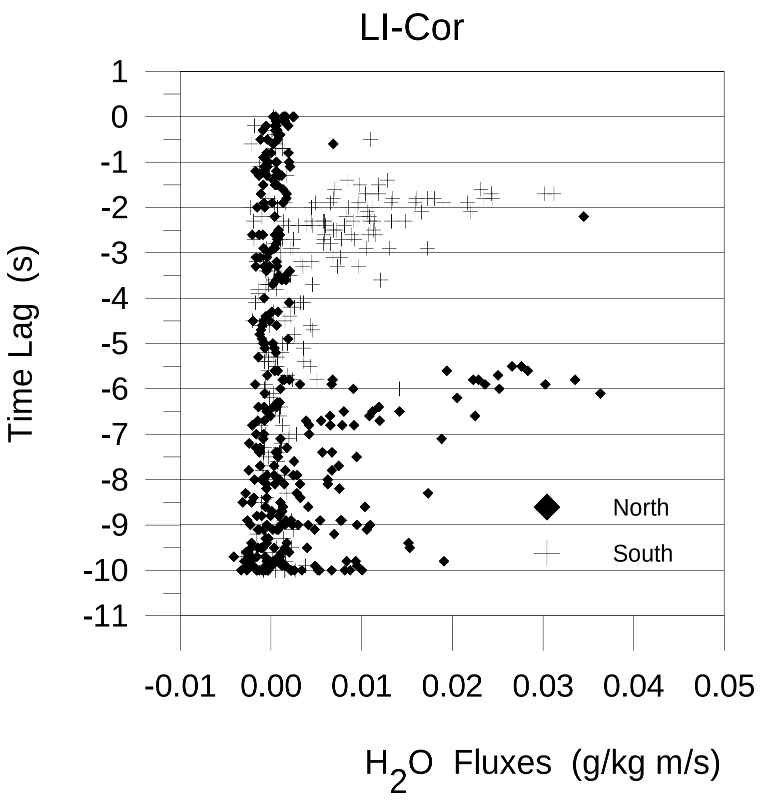


*Figure 13. Time lags for the two instruments versus values of the flux calculated by the cross- correlation method.*

# 5 Conclusions

In this inter-comparison of various instruments to measure water vapour and $CO_2$ fluctuations, we have come to the following conclusions.

- A slow reference instrument measuring the relevant concentrations should be available in order to be able to correct the fluctuations of the fast instrument from possible drifts in its calibration.
- For a good experimental campaign more than one instrument to measure a given flux should in operation in order to be able to make consistent checks.
- An uncertainty within 25% for both $CO_2$ and $H_2O$ can be expected if the measurements are performed with only an instrument.
- Time lag caused by sampling tubes can be calculated with a good approximation by means of the flow rate of the instrument. This practical method avoids error due to the cross correlation method with respect to low fluxes values.
- Application of the Webb correction reduces the magnitude of the fluxes of $CO_2$. During the night this reduction might lead to negative flux while we expect the fluxes to be positive due to the plants photosyntesis activity.

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Abstract (max. 2000 characters)

In order to investigate the reliability of some of the instruments most used to measure humidity and $CO_2$ concentration fluctuations in field campaigns, two identically equipped meteorological measuring stations were operated for 30 days in the autumn 1995. Each mast was equipped with three different types of fast infrared sensors to measure fluctuations of humidity and $CO_2$. Moreover the masts were equipped with standard instrumentation to measure wind speed, wind direction, temperature, humidity, pressure and solar radiation and with a Gill sonic anemometer/thermometer to measure turbulent fluctuations of temperature and wind components. Turbulent data were recorded with an effective sampling rate of 10 Hz. Thirty-minute averaged statistics of the atmospheric turbulence were derived. In this paper we analyse two periods of three days each and present some results of the comparisons among the absolute values of concentrations measured by fast and slow instruments. Moreover the inter comparison of fluxes estimated by different types of instruments obtained by the eddy correlation method is presented.

Descriptors INIS/EDB

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