Water Vapor, CO_2, and Temperature Profiles in and above a Forest—Accuracy Assessment of an Unattended Measurement System

MEELIS MÖLDER

Department of Earth Sciences/Hydrology, Uppsala University, Uppsala, Sweden

ANDERS LINDROTH

Department of Physical Geography, Lund University, Lund, Sweden

SVEN HALLDIN

Department of Earth Sciences/Hydrology, Uppsala University, Uppsala, Sweden

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ABSTRACT

The possibility of a global climate change has increased research interest in the least understood parts of the climate system. One of those parts is the boundary between the land surface of the earth and the lowest part of the planetary boundary layer. The structure of this layer and the exchange processes in it are still incompletely understood for a variety of situations and surfaces, especially in the boreal zone and during the dark parts of the day and the year. Progress in this area requires new data measured continuously and unattended with high accuracy and long-term reliability. A measurement system for profiles of temperature, humidity, and carbon dioxide was designed to meet the above goals. The system used thermocouples and a Li-Cor gas analyzer combined with an array of tubing to suck air from different heights. Turbulent fluctuations of water vapor and carbon dioxide concentrations were smoothed by continuous-flow mixing chambers without moving parts. Half-hourly mean differences in temperature, humidity, and CO_2 were measured to better than 0.03 K, 0.015 g kg^{-1}, and 0.5 μmol mol^{-1}, respectively. These accuracies were confirmed by comparisons with a thermometer-interchange (reversing) system and CO_2 profiles theoretically deduced from eddy-correlation fluxes. Daytime temperature and humidity differences over the full height interval (24.5–87.5 m), as well as over the roughness sublayer part (24.5–58.5 m), commonly exceeded the estimated errors by five times. The CO_2 differences could only be measured reasonably accurately over the entire height interval (24.5–87.5 m) and then only exceeded the error by a factor of 2–3. Temperature and humidity measurements were sufficiently accurate for studies of flux–profile relationships over a forest. The CO_2 profiles were accurate only for rough flux estimates and may be especially useful for nighttime studies.

1. Introduction

The possibility of a global climate change has increased research interest in the least understood parts of the climate system. One of those parts is the boundary between the land surface of the earth and the lowest part of the planetary boundary layer. The structure of this layer and the exchange processes in it are still incompletely understood for a variety of situations and surfaces, especially in the boreal zone and during the dark parts of the day and the year. Rarely occurring situations, like evaporation of intercepted snow or transpiration being reduced because of severe drought, are incompletely understood because of the lack of data. Progress in this area requires new data measured continuously and unattended with high accuracy and long-term reliability. The need for long-term data series for development and verification of many types of hydrological and meteorological models has motivated large-scale international collaboration in projects like Euroflux and Ameriflux.

Studies by Thom et al. (1975), Garratt (1980, 1983), Raupach (1979), and Högström et al. (1989) have revealed that a roughness sublayer with enhanced turbulent exchange and reduced gradients exists over forests, and that ordinary flux–profile relationships do not hold there. Lindroth and Halldin (1990) present data on gradients of temperature and humidity above a coniferous forest in central Sweden. They demonstrate the extent to which typical gradients above a forest are small

Corresponding author address: Dr. Meelis Mölder, Department of Physical Geography, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden.
E-mail: meelis.molder@natgeo.lu.se

compared to those above other vegetation surfaces. Systems to measure profiles above a forest must, therefore, be much more accurate and have a higher resolution than most previously used profile-measurement systems. The authors of this paper are not aware of any published information on frequency distributions for CO_2 gradients, but information about individual profiles (e.g., Denmead and Bradley 1987) makes it clear that also this scalar must be measured with an accuracy close to the limit of modern gas analyzers in order to yield profiles of sufficient accuracy above forests. Lindroth and Halldin (1990) showed especially that measurement of very small gradients requires special evaluation of systematic errors, which can be problematic in traditional fixed-profile systems.

Today it has become common to measure not only carbon dioxide but also the water vapor content with fast-responding gas analyzers. It may seem simple, but it is actually a difficult task to measure gradients of these constituents with high enough accuracy, especially over forests. Profiles of water vapor and carbon dioxide are especially difficult to measure because of their large turbulent fluctuations. Reasonable mean gradients can be obtained by differential measurements and frequent sampling of one difference at time for a long period (Price and Black 1990; Simpson et al. 1998). Another possibility is to smooth out the fluctuations adding some mixing system between the tubing and the analyzer. Price and Black (1990) combined their differential CO_2 measurements with chambers that used fans for adequate mixing. Denmead et al. (1998) used large 35-L single volumes (tubes gave additional 15 L) to dampen the fluctuations of trace gases.

Vermetten et al. (1994) measured CO_2 profiles level by level, sampling for a long time (1.5 plus 4 min) at each level. Recently, Xu et al. (1999) presented a measurement system for CO_2 and also for H_2O (for the first time), where short tubes (7 m) and a minimal volume of the switching and analyzing part of the system allowed switching in 2-s steps and a frequent sampling of six levels.

A measurement system for CO_2 at three levels in a TV tower, having a separate analyzer for each level, has been reported by Bakwin et al. (1995) and Zhao et al. (1997a). High absolute accuracy was achieved by using a regular calibration procedure and a high precision system for checking the calibration gases (Zhao et al. 1997b).

The method, where inside-forest levels have been switched at a low frequency and sampled for a long period, has often been used to estimate the CO_2 storage in the canopy air (Wofsy et al. 1993; Goulden et al. 1996; Baldocchi 1997; Jarvis et al. 1997). These measurements can be quite rough because only the change of total CO_2 content of a canopy-air column over a 30-min or 1-h period is needed.

In some sense, the humidity measurements are more difficult to perform (risk of absorption and condensation in tubes, larger turbulent fluctuations) than CO_2 measurements. No one has reported successful measurements of water vapor where a large number (12) of measurement levels can be averaged reasonably well over 30-min periods.

A program for multiannual, continuous measurements of a large number of hydrological and meteorological variables has been one of the most prioritized parts of NOPEX, a major land surface experiment in the boreal zone of Europe (Halldin et al. 1998). One key element in this program was the measurement of profiles of wind speed, temperature, humidity, and carbon dioxide, which have been carried out at the Central Tower Site (Lundin et al. 1999) in Norunda since June 1994. This site was characterized by a mixed pine–spruce forest extending 1.5–6 km from the measurement tower. The tower was 102 m high and equipped with 12 profile, two radiation, and three eddy-correlation measurement levels.

This paper describes a system for temperature, humidity, and carbon dioxide profile measurements developed and successfully operated at the Norunda site. Wind-profile measurements, performed with sonic anemometers, were fairly straightforward and are not treated here. Humidity and carbon dioxide measurements from a number of heights were made with a single gas analyzer to primarily estimate the associated gradients. One single analyzer was used in order to increase relative accuracy and thus avoid between-instrument variations. The system contained a specially designed continuous-flow mixing-chamber system for reducing turbulent fluctuations of water vapor and CO_2 concentration. Measured temperature and humidity differences were compared with data from a reversing-thermometer/psychrometer system to assess the accuracy of the new system. Measured CO_2 gradients were compared for the same purpose with profiles, theoretically deduced from eddy-correlation fluxes. Distributions of measured differences over different height intervals were used to assess the reliability of flux–profile analysis presented by Mölder et al. (1999).

2. Design of the system

a. Temperature subsystem

Air temperature was measured differentially with copper-constantan thermocouples between a given level and the uppermost level (100.6 m), where an absolute temperature measurement was made. A standard copper-constantan wire was used to produce the single-junction thermocouples, which had an approximate sensitivity of 39 μV K^{-1} (slightly depending on the temperature of the reference point). A (long) time constant of around 50 s comparable to the one in still water, was achieved by embedding the junctions in metal tubes and epoxy compound. The temperature sensors were placed in double radiation shields that were ventilated at a rate of 3.5

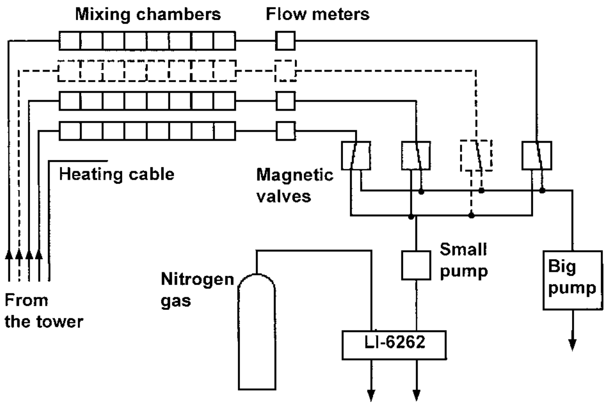

FIG. 1. Principal scheme of the fixed-sensor system for humidity and CO_2.

m s^{-1}. Radiation shields were made of plastic tubes. The outer tube had a diameter of 50 mm and had a surface with good reflectance properties both in the shortwave and the longwave parts of the radiation spectrum.

The thermometer ventilation was monitored in order to guarantee the accuracy of the temperature measurements. Airborne debris (pollen, other organic matter, insects) gradually accumulated on the fans. Initially, this stopped some fans. To avoid such problems, the fans at the four lowest levels were cleaned twice during spring and autumn periods. The original visual inspection was complemented by a measurement of the voltage drop over resistors connected in series with the fans. An obstruction of a fan resulted in a short time increase in the current. A flag was implemented in the datalogging system to detect such a short-term increase.

b. *Water vapor and carbon dioxide subsystem*

Water vapor and carbon dioxide measurements were based on an IR gas analyzer (type LI-6262; Li-Cor Inc., Lincoln, Nebraska). Air from the different measurement levels on the tower was sucked down to an equipment shed where the analyzer was situated (Fig. 1). The air was transported in plastic tubes (HD-polythene, 4-mm inner diameter) of equal lengths (140 m) in order to guarantee the same resistance from all intake levels. The tubes were thermally insulated and ran parallel to a heating cable to prevent condensation of water in the tubing. In the equipment shed, the air from each tube passed into a series of eight 1.05-L continuous-flow mixing chambers made of thin sheet metal. The connection between the chambers was via a series of 2-mm holes, drilled alternately at opposite sides, a bit off center. The holes created a strongly increased turbulence to ensure adequate mixing—mixing within the tubes was limited. The cascade of chambers guaranteed a much more efficient mixing than a single volume of similar size (Oja 1994, personal communication). An advantage of the present mixing system was that it did not consist of any moving parts. The cascade of chambers and the small pump were regularly checked for leakage by breathing on them. The breath air has high CO_2 content and gives a large signal jump in the case of leakage. The membranes in the pump were changed once a year.

The flow rate in the system could be checked and adjusted by flow meters and was kept at around 3 L min^{-1}. The flow meters were followed by the magnetic valves with two positions. In Fig. 1, the first valve on the left is switched so that the air is passed by the small pump to the analyzer for measurement. All other magnetic valves are switched so that the air is sucked by a common big pump. This guarantees a synchronous flow in all tubes. Subsequently, the second valve (measurement level) is switched via the small pump to the analyzer and air from the first level is taken over by the big pump. Consecutive levels were measured in 12-s steps.

The gas analyzer was operated in its absolute mode with a 0.1-s response time. Pure nitrogen gas (with negligible water and CO_2 content) was sent through its reference cell at approximately 10 mL min^{-1}. The chopper circuit was not connected to the nitrogen circuit because of leakage problems and the ordinary scrubber was used there. Pure nitrogen gas was taken from a 40-L cylinder that lasted for 1.5 years. The scrubber in the chopper circuit was changed at 2-month intervals.

The gas analyzer was protected against intrusion of water or dust. The tube inlets were positioned within the thermometer's radiation shields to protect against water. Particulates were removed by small sintered metal inlet filters. As filters became dirty the flow rate dropped; therefore, filters required regular washing with water and soap. Filters were cleaned/changed with intervals from 3 weeks to 3 months. An additional Li-Cor-recommended filter was installed just before the analyzer's inlet. This filter was changed a few times a year.

c. *Installations and data processing*

Measurements were performed continuously since June 1994 at the following heights: 8.5, 13.5, 19, 24.5, 28, 31.7, 36.9, 43.8, 58.5, 73, 87.5, and 100.6 m. The first three levels were situated inside the forest, the fourth was level with the tree tops, and the other eight were above the forest. The signals were fed via multiplexers into a datalogger (CR-10; Campbell Inc., Leicestershire, United Kingdom). The sampling interval was 6 s for temperature data and 5-min averages were stored. In the case of the gas analyzer, all raw data in 12-s steps were stored. Air pressure was needed for evaluation of gas analyzer signals and was measured by a Vaisala (PTA 427; Helsinki, Finland) pressure sensor. The data processing of CO_2 signals included both the pressure-broadening and the dilution corrections (Li-Cor, 1990).

Data from the logging system have been temporarily stored on a local network server at the Central Tower Site in Norunda. Data from this server have been automatically transferred to the NOPEX Central Office in Uppsala via a modem every night since early 1994. This allowed regular ''in-house'' data-quality control without the need to drive to the forest.

3. Data for evaluation

a. Thermometer Interchange System for temperature and water vapor data

In order to check the accuracy of temperature and water vapor differences a comparison was made with data from a highly accurate Thermometer Interchange System (TIS; Lindroth and Halldin 1990) for the periods from 13 June to 14 July and from 17 to 28 August 1995. The TIS system consists of four automatically wetted psychrometers, connected two and two in pairs for differential dry and wet temperature measurement. A reversing system switches the positions of the psychrometers pairs every 5 min. Taking averages over two consecutive 5-min periods minimizes systematic errors (no data are recorded during the first minute after each reversal). The absolute values of dry and wet temperature are measured by one of the psychrometers in the upper pair. The TIS system was attached to the Norunda tower with its psychrometer inlets some 1.5 m apart in the west-southwestern direction so that the upper psychrometer was level with the profile-system sensors at 43.8 m. The other two TIS levels, 39.3 and 34.8 m, did not coincide with any of fixed-sensor levels. Profile system data from 24.5, 28, 31.7, 36.9, 43.8, and 58.5 m were therefore approximated with second-order polynomials in order to deduce profile-system values at 34.8 and 43.8 m. The total height interval of the TIS was only 9 m, that is, a minor part of the tower height.

b. CO_2 concentration differences

There was no other system available to evaluate the accuracy of the measured carbon dioxide profiles. The measured CO_2 gradients above the forest during the daytime appeared to be extremely small, and their order of magnitude was checked by an alternative method. It was assumed that the flux–profile relationships for temperature and humidity (Mölder et al. 1999) were also valid for carbon dioxide. The necessary scales and stability parameters were deduced from direct eddy-correlation measurements (Grelle and Lindroth 1996). Note that the eddy-correlation system employs a similar Li-Cor gas analyzer for measurement of CO_2 fluctuations. The CO_2 differences, deduced from the flux data as well as measured, were calculated for the period of 29 June–31 August 1995.

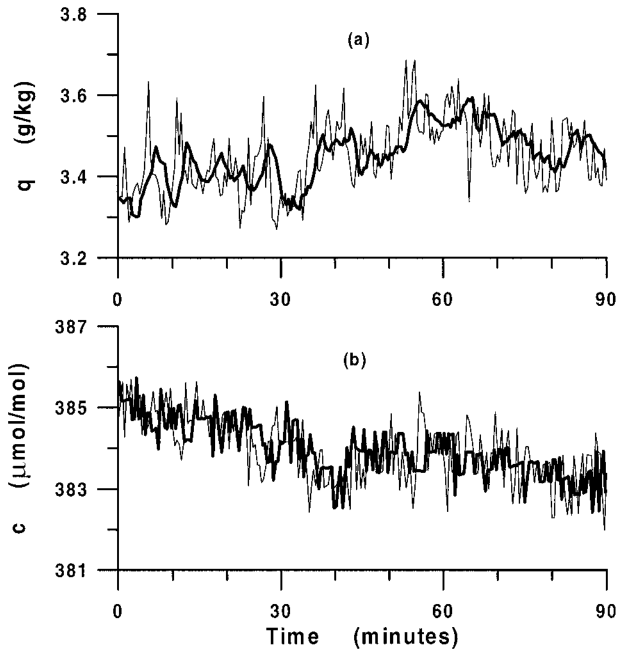

FIG. 2. (a) Water-vapor and (b) CO_2 signals from air sucked directly through the tubing (thin lines) and additionally through a cascade of mixing chambers (thick lines). The data in each curve were taken in 24-s steps. A time shift of 2 min between filtered and unfiltered signals can be observed in the water vapor curve.

4. Evaluation of the system

a. Improvement because of the mixing chambers

The gas-analyzer system was originally designed to be operated in a differential mode and without any mixing system. However, it turned out that the output of the analyzer was highly fluctuating with this design. The fluctuations were of the same order of magnitude or higher than average differences between the lowest and the highest level. The time required to return to a given level (after going through the other 11 levels) was 2 min 24 s. Since individual records gave instantaneous values of turbulent water vapor content and CO_2 concentration, unacceptably long averaging times were required to form meaningful averages for all levels. In its original year of operation only the difference between 31.7 and 100.6 m was therefore measured in order to maintain reliable data.

In the second year of operation, the cascade chambers started to act as an efficient low-pass filter for the fluctuating data. In an experiment on 16 May 1997, the system was analyzed for 1.5 h with air coming from the same point in the tower (50-m height) alternately through a cascade of chambers or directly to the gas analyzer. The time interval between the same type of measurement was 24 s. Note that although the filtered curve in Fig. 2a is also varying, the high-frequency fluctuations are removed and the filtered curve represents a phase-shifted running mean. In the actual measurement program, where 12 levels were measured, the sampling time interval for an individual level was 2 min, 24 s. Even with such a low sampling frequency, 30-min mean values gave reliable results.

The tubing and mixing system introduced a time delay in the recording of a water vapor content or CO_2 concentration. This time delay was originally determined from a forced step change of concentration to be 5 min. In a longer-lasting part of the 16 May experiment, the time delay was estimated to about 2 min during normal running conditions because of the mixing chambers. This estimate was done by visually fitting the filtered and nonfiltered water vapor signals (Fig. 2a). Since the transport time in the tubes was 30 s, this gave a total time shift of 2.5 min.

The effect of filtering was much less obvious for CO_2 (Fig. 2b) than for water vapor. The mixing chambers reduced variations, but not very much. This was quite natural because (i) the average CO_2 concentration had very small vertical gradients and fluctuations in a point caused by turbulent eddies should be small indeed, and (ii) the variations in Fig. 2b reflect the analyzer's noise.

b. Estimated measurement accuracy

The resolution of temperature measurement in the TIS system is given as 0.0007 K by Lindroth and Halldin (1990). The accuracy of the TIS system in this specific situation was tested experimentally on 11–12 June and 28 August–5 September 1995. For this purpose, the system was run with the psychrometer pairs mounted at the same level (when a reversal occurred, the psychrometers only moved by 1–2 cm). Deviations from zero during this experiment indicated the actual measurement error. The TIS was sensitive to wind direction because of its close position to the tower. Typical errors in 30-min data, with winds from favorable directions, were less than 0.01 K for temperature and 0.002 g kg^{-1} for humidity measurement. With winds through the tower and intensive solar radiation, the temperature error could reach 0.1 K.

The sensitivity of thermocouples relative to a melting ice reference was tested in the 0–40°C temperature range. An excellent agreement was found with the polynomials developed by the National Bureau of Standards (Powell et al. 1974). This nonlinearity was taken into account through offline calculations. The resolution of a single temperature measurement (absolute or differential), set by the logger, was about 0.01 K (Campbell Scientific 1994). The additional radiation error was estimated from a shading experiment to be 0.07–0.1 K for an absolute measurement. It was assumed that the radiation error in differences was of the order of 0.01 K for height differences of 5–10 m and maybe 0.02 K over greater height intervals because of greater differences in wind speed.

The absolute error in the gas analyzer measurement consists of an offset and a sensitivity error. The offset has been checked occasionally by letting the same nitrogen gas through both the sample and reference cells. It could usually be taken into account with an accuracy of 10 mV, corresponding to 0.08 g kg^{-1} in humidity and 2.5 μmol mol^{-1} in CO_2 measurements. The sensitivity has been checked twice a year by a water vapor generator (LI-610; Li-Cor Inc., Lincoln, Nebraska) and a CO_2 reference gas (400 μmol mol^{-1}), and it was stable within 1% over a 3-yr period from spring 1994 to spring 1997. Deviations from Li-Cor's own calibrations were 3%–4% for both humidity and CO_2.

The 1% sensitivity error was negligible when estimating errors in concentration differences. The resolution of the logger was 0.333 mV (Campbell Scientific 1994). The observed noise was of the order of 1 mV and its contribution to concentration-difference errors was expected to diminish by averaging. Thus, an error of 1 mV could be expected in 30-min average values from a single level. For differences between two levels, it would be double, 2 mV, which is equivalent to about 0.015 g kg^{-1} in humidity and 0.5 μmol mol^{-1} in CO_2 measurements.

c. Comparison with TIS data and calculated CO_2 gradients

Individual temperatures measured at one level by the two different systems typically deviated by 0.1 K, and in rare cases even with 0.2 K. Deviations in absolute values of humidity were usually less than 0.2 g kg^{-1}, but some peaks reached 0.3 g kg^{-1}, which corresponds to 3% and 4% of the absolute value.

The period from 16 to 24 June was chosen for analysis because winds blew from ''good'' directions, that is, not through the tower to either the TIS or the fixed-sensor system (Figs. 3, 4). Another good period, from 29 June to 8 July, which gave similar results, is not presented here. Daytime temperature differences over 9 m were 0.3 K at maximum with deviations in differences within 0.03 K, which was the expected error. During the nighttime temperature differences reached 1 K and corresponding deviations were considerably higher. Humidity differences during days were only 0.03–0.1 g kg^{-1}, and differences between the two systems were less than 0.015 g kg^{-1}. During nights, much higher gradients and errors occurred.

Daytime CO_2 differences (Fig. 5) reached -1.5 μmol mol^{-1} (flux was downward) and were within 0.5 μmol mol^{-1}. Much greater gradients and deviations occurred during nocturnal inversions. Those deviations are not shown since this would have obscured the daytime data.

Differences between the two systems were mostly random (Fig. 6; a few points out of the scale are not shown). The positive, daytime temperature differences had a totally random scatter around the 1:1 line. Positive daytime humidity differences show a slight tendency to lie systematically above the 1:1; that is, the fixed-sensor system gave marginally higher values than the TIS system. There is also a slight systematic tendency that the

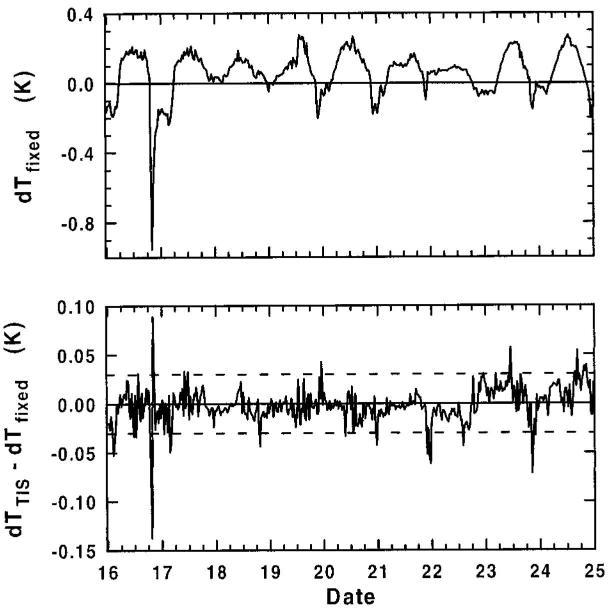

FIG. 3. Temperature difference between 34.8 and 43.8 m measured by the fixed-sensor system (above), and deviations in differences between the fixed and the reversing systems (below). The broken lines show the estimated error limits, ± 0.03 K. Data are from Jun 1995.

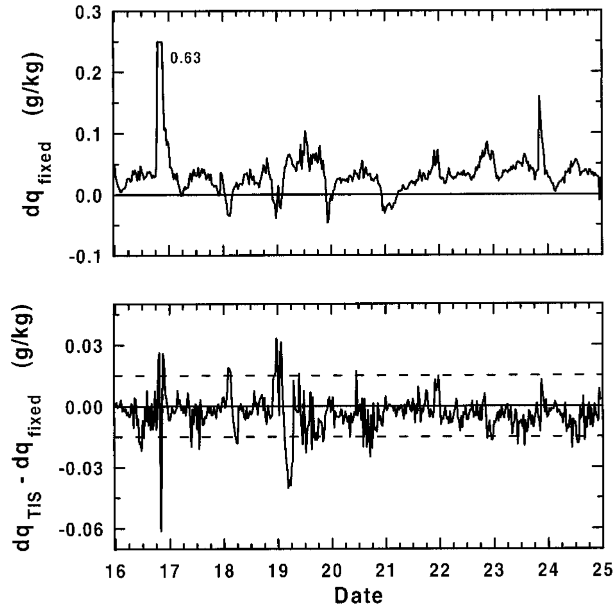

FIG. 4. Specific humidity difference between 34.8 and 43.8 m measured by the fixed-sensor system (above), and deviations in differences between the fixed and the reversing systems (below). The broken lines show the estimated error limits, ± 0.015 g kg^{-1}. Data are from Jun 1995.

fixed-system CO_2 differences are more negative than the estimated ones.

d. Nighttime problems

Considerable deviations between the TIS and fixed-system humidity data could occur during the nighttime (Fig. 4). On some nights, such as 16–17 June, very large positive gradients occurred, whereas on other nights negative gradients (condensation) occurred. In both cases, this erroneous behavior was attributed to condensation in the tubing. It was clear that it was condensation in the tubes because the ambient relative humidity never exceeded 95%, and was more typically 70%–80%, so no saturated air was sucked into the tubes. This indicated that the insulation and heating were not sufficient, or that the short unprotected parts of tubes on the booms could have caused this trouble. The insulation and heating was, nevertheless, a great improvement compared with a similar system. The authors' experience with such a system without insulation and heating, operated over a grass field, was rather dissatisfying—tubes were so full of condensation water that no gradients were measurable at night—and it took 3–4 h in the morning until the system started to work properly again.

Nighttime comparisons of temperature and CO_2 measurement also indicated some problems. One reason could be that nighttime turbulence is very intermittent in stably stratified conditions and, thus, that all meteorological variables vary strongly even horizontally. Spatially separated sensors should not give identical re-

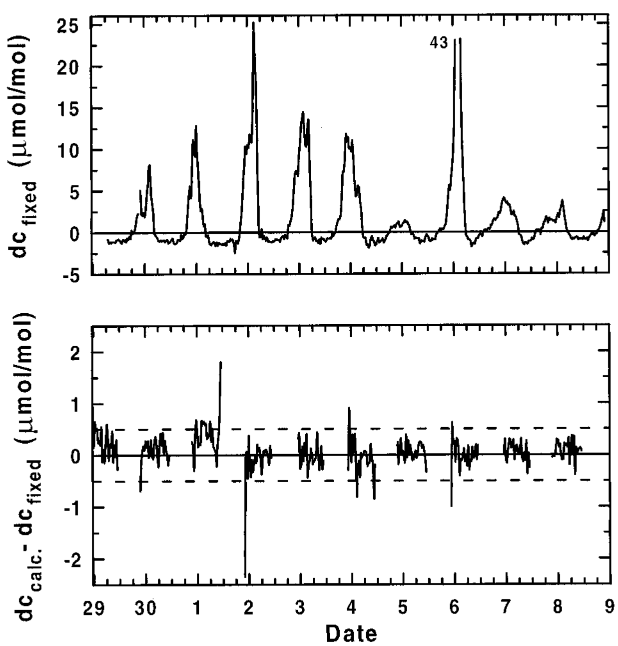

FIG. 5. Difference in CO_2 concentration between 24.5 and 87.5 m measured by the fixed-sensor system (above), and daytime deviations in differences between measured and calculated values (below). The broken lines show the estimated error limits, ± 0.5 μmol mol^{-1}. Data are from Jun–Jul 1995.

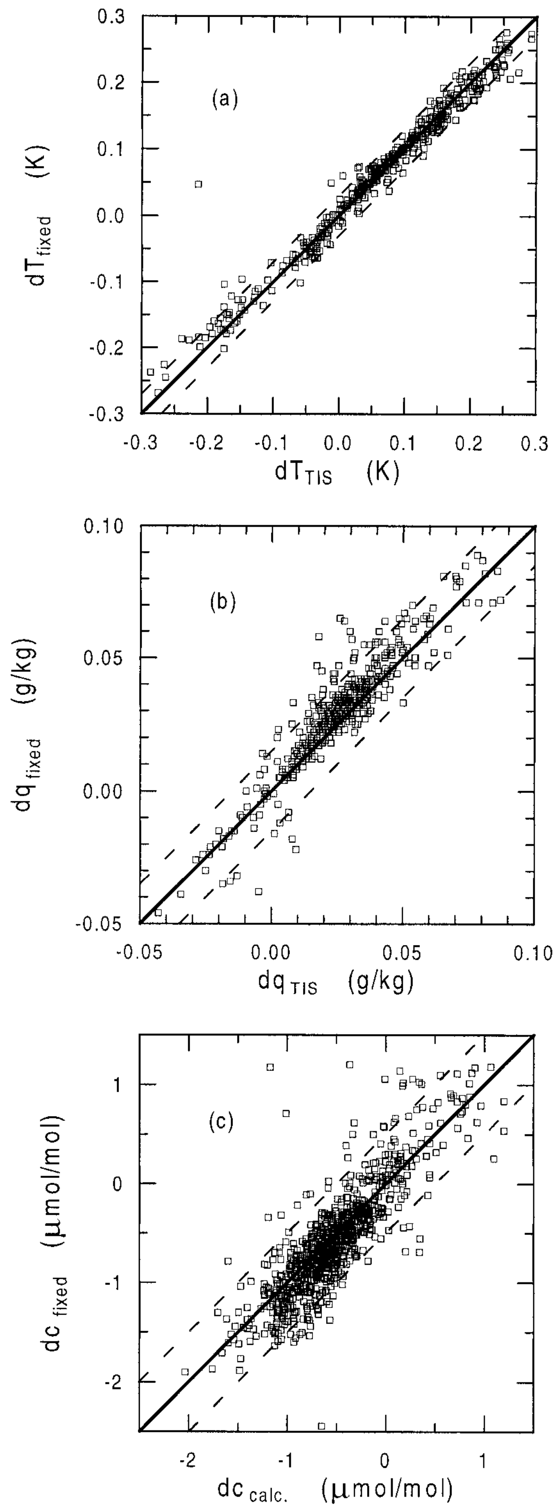

FIG. 6. (a) Temperature and (b) humidity differences between 34.8 and 43.8 m measured by the fixed-sensor system vs TIS measurement. (c) Measured CO_2 differences between 24.5 and 87.5 m vs calculated values.

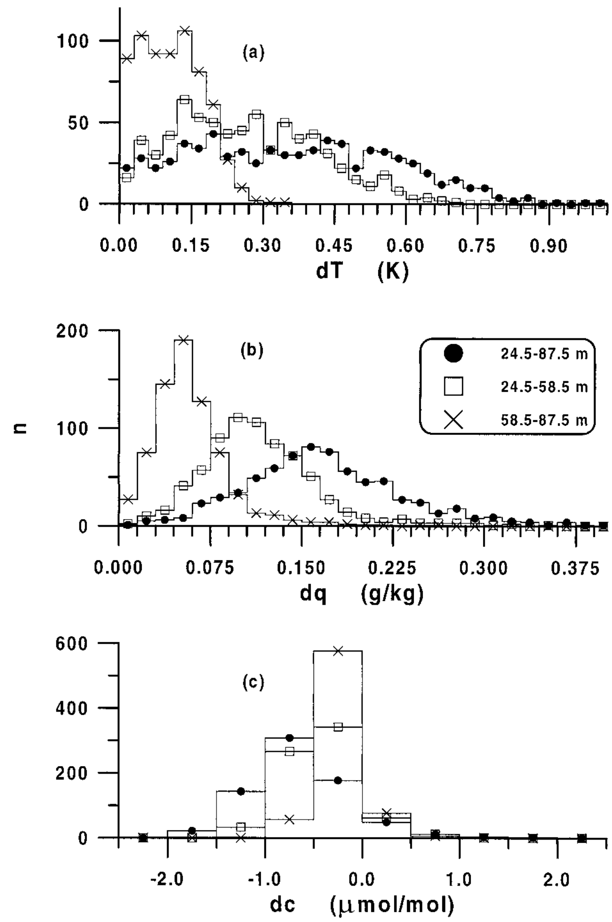

FIG. 7. Distributions of differences in (a) potential temperature, (b) specific humidity, and (c) specific CO_2 content over the full height interval (24.5–87.5 m; filled points); the roughness sublayer (24.5–58.5 m, cubes); and the layer above the roughness sublayer (58.5–87.5 m, crosses). The lowest level fits with the tree tops. The middle level is at the top of the assumed roughness sublayer. The data are restricted to unstably stratified days.

sults under such conditions. In addition, condensation warming followed by evaporation cooling could possibly have occurred on temperature sensors.

e. Distributions of differences and measurement accuracy

Previous arguments allowed the following differential measurement errors, 0.03 K for temperature, 0.015 g kg^{-1} for humidity and 0.5 μmol mol^{-1} for carbon dioxide, to be ascribed for the fixed-sensor system. The fixed-sensor system is only meaningful to deploy if these errors are smaller than commonly occurring gradients (Fig. 7). This requirement is especially important if data should be used for determination of flux-profile relationships and possible subsequent flux calculations.

If the criterion for useful data is set such that the measured difference must be 10 times the error (i.e., errors being 10% of the measured quantities), this will correspond to 0.3 K for temperature, 0.15 g kg^{-1} for humidity, and 5 μmol mol^{-1} for CO_2 measurements. Applying this criterion for the full height interval, more than half the temperature and humidity data are acceptable. Only half of the temperature data and a quarter of the humidity data remain in the roughness sublayer. Almost nothing is left above the roughness sublayer. A weaker criterion, five times the error (20%), allows much more data to be considered as useful; most of the temperature and humidity differences for the full height interval and for the roughness layer and about a quarter of the top-layer data remain. The CO_2 differences were very small, most of them were only two to three times the estimated error, both over the total interval and in the roughness sublayer. Above the roughness sublayer, the CO_2 differences were of the same size or smaller than the error.

f. Operation and maintenance

Different requirements are placed on measurement systems that are only operated during short-time, intensive field campaigns with permanent supervision and those systems that are to deliver high-quality, continuous data for periods of many years. The additional maintenance in the latter case can be broken down into three parts: (i) regular calibration, (ii) regular cleaning/replacement/inspection of various parts, and (iii) supervision to detect malfunctioning system behavior and necessary repair.

During the first 3-yr period of operation, maintenance operations of the fixed-sensor system have gradually become more efficient. Operations such as, for example, inlet-filter cleaning, have been improved such that cleaning/replacement frequency has been reduced from once per 3 weeks to once per 3 months. Remote-quality control through the computer network has allowed the number of field visits to be minimized. Regular visits to inspect the system every 2–3 weeks have been sufficient to allow for all maintenance operations. If the system is going to be run for still longer periods, further automation of the maintenance is needed to secure its long-term stability, while at the same time keeping labor costs at an acceptable level.

5. Conclusions

Profile measurements above and within forest stands must meet very high accuracy requirements and few (if any) systems have been presented where this accuracy has been demonstrated over the full height of a tall tower and over longer time periods. The fixed-sensor system presented in this paper has been operated for 3 years with daytime accuracies of 0.03 K for temperature, 0.015 g kg^{-1} for humidity, and 0.5 μmol mol^{-1} for carbon dioxide differences and, thus, demonstrates that profile measurements are possible for a variety of purposes. The system has not yet been evaluated during winter and nighttime conditions.

The shown accuracies in vertical profiles of water vapor and carbon dioxide were achieved thanks to (i) the use of a single gas analyzer that eliminated instrument-to-instrument variations, (ii) very efficient cascade-type mixing chambers that smoothed out large turbulent fluctuations of concentrations, and (iii) the high stability of the analyzer's sensitivity where variations were within 1% over a 3-yr period.

Temperature and humidity gradients could normally always be trusted during daytime and growth-period conditions. Gradients of CO_2 only exceeded their error limits by a factor of 2–3 and should be used with care; acceptable results may be obtained by using the entire height interval and by assuming similar profile forms as for temperature and humidity. The carbon dioxide data may complement nighttime eddy-correlation measurement.

Further improvement of the system is possible and may guarantee its use during nighttime and winter conditions.

1) The gas-analyzer offset was normally constant with only a slight temperature variation, but sudden changes sometimes occurred. Offset has been checked visually twice a month during intensive measurement campaigns. The development of an automatic offset control is a future task.
2) The mixing in the chambers can be made more efficient by placing the cascades in the tower near the inlets where the chamber pressures are close to atmospheric. This alternative would require heating of the cascades. Another possibility would be to place individual pumps before each cascade.
3) The tubes on the booms should be thermally insulated, and a heater near the inlet would be desirable as well.
4) Data from the system is presently logged together with other measurements and there is no time left for repeated measurements at a given level. Since the needed flush time is 8–10 s, then the remaining 2–4 s (of 12 s) could be used to reduce the noise at each level by doing repeated measurements with a separate datalogger.

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stored in the System for Information (SINOP) in NOPEX.

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