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Intercomparison of Fast Response Carbon Dioxide Sensors under Field Conditions

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Abstract

This paper describes the comparison of fast response carbon dioxide sensors developed in Japan, Canada, and USSR. The comparison experiments were carried out at Winnipeg, Canada in 1986, and Zvenigorod, USSR in 1987. In this study, the Japanese sensor was chosen as a reference, and other sensors were compared with the reference.

1. Introduction

The eddy correlation technique is the most promising method to measure the turbulent fluxes of physical quantities. In recent years several sensors have been developed for measuring the turbulent flux of carbon dioxide by this technique (e.g., Brach *et al.*, 1981[1]; Elagina and Lazarev, 1984[2]; Ohtaki and Matsui, 1982[3]; Ohtaki and Seo, 1976[4]). These sensors are based on the same measuring principle: absorption of the 4.3 μm infrared beam by carbon dioxide. Substantial data have been accumulated using these instruments (e.g., Desjardins *et al.*, 1982[5]; Ohtaki, 1980[6], 1984[7] and 1985[8]; Volkov *et al.*, 1986[9]). It is possible to evaluate their dynamic response from the analysis of data obtained. However, field experiments, wherein direct comparison can be made, yield much more information concerning their characteristics.

Two experiments comparing the various carbon dioxide sensors were made in Winnipeg, Canada in 1986 and in Zvenigorad, USSR in 1987. Agricultre Canada (hereinafter referred to as AC), University of Nebraska Lincoln (UNL), and Okayama University (OU) participated in the Winnipeg experiment, and Institute of Atmospheric Physics, USSR Academy of Sciences (AP) and OU in the Zvenigorod experiment.

Results of a preliminary analysis of the Zvenigorod experiment were reported by Volkov *et al.*, 1989[10]. In this paper, we compare the dynamic responses of the carbon dioxide sensors developed by OU, AC and AP. The comparison of the UNL sensor

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with others will be presented in a separate study.

2. Field experiments

2.1. Winnipeg experiment

The first intercomparison experiment, organized by the AC, was carried out on a wheat field of 1 km × 1.5 km at Winnipeg, Canada from 6 to 20 July, 1986. The surrounding area was also planted in wheat. The crop height grew from 60 to 80 cm during the experiment. **Photo. 1** shows all sensors mounted on a pantograph mast of 3 m height above the ground.

The carbon dioxide-humidity sensor of OU is the revised version of prototype model developed by Ohtaki and Seo, 1976[4]. This sensor measures fluctuations of carbon dioxide and humidity at the same time. The sensing path length is 20 cm. The noise level of the sensor is about 0.3 ppm for carbon dioxide measurements and about 0.1 g m^{-3} for humidity measurements. The zero drift in an hour is within 1 ppm for carbon dioxide and 0.2 g m^{-3} for humidity. The time constant of the sensor is about 0.01 sec. Detailed characteristics of the sensor are described in previous papers (Ohtaki, 1984[7]; Ohtaki and Matsui, 1982[3]). The fluctuations of wind velocity and temperature were measured by a Kaijo Denki sonic anemometer-thermometer (DAT-390).

The carbon dioxide sensor of AC was the revised version of prototype model (Brach et al., 1981[1]) with an open sensing path length of 20 cm. The time constant of the sensor was about 0.2 sec. The wind velocity was measured by a Kaijo Denki sonic anemometer.

We had much rain during the Winnipeg experiment. The carbon dioxide flux was measured by the AC sensor on July 15 and 16, 1986. 38 runs of 15 minutes each were obtained during that period. On July 17, the AC sensor was left outside during the
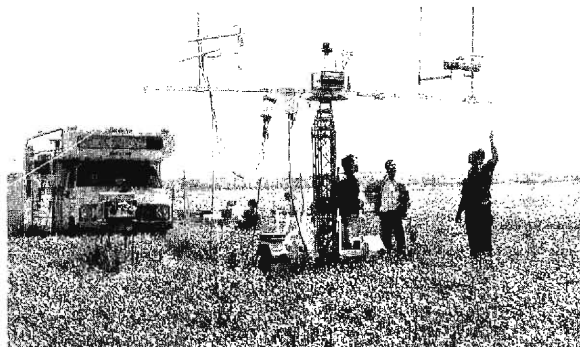

Photo. 1.   Instrumental set-up for comparison experiment at Winnipeg, Manitoba, Canada in 1986. Sensor assembly of OU (left), AC (center), and UNL (right). All sensors are mounted at 3 m height above the ground. Wheat height is 80 cm.
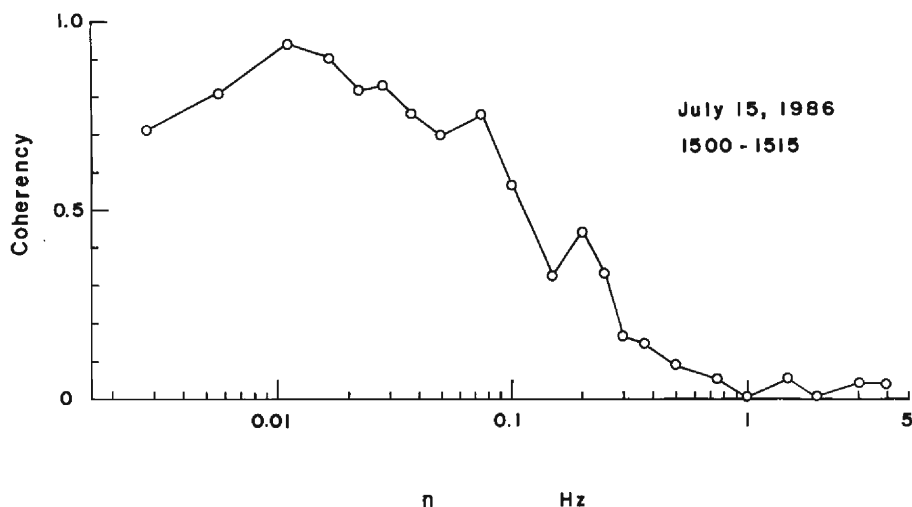
Fig. 1. Coherency between carbon dioxide fluctuations measured with OU and AC sensors. Coherency is defined by $\sqrt{C_o(n)^2 + Q(n)^2} / \sqrt{S_{ou}(n) \cdot S_{ac}(n)}$, where $S_{ou}(n)$ and $S_{ac}(n)$ are power spectra of time series of OU and AC data, and $C_o(n)$ and $Q(n)$ denote cospectrum and quadrature spectrum between data of OU and AC. Data were collected from 1500 to 1515 on July 15, 1986 at Winnipeg, Canada.

rain. The waterproofing of the optical housings was not sufficient, and the electric circuits at the connector part were shorted under the high moisture conditions at the test run on July 18. After that accident, the AC sensor did not recover during the comparison experiments. Therefore, we had to determine the calibration factor for data measured on July 15 and 16. **Fig. 1** shows the coherency between signals of OU and AC sensors. The coherence is larger than 0.7 in low frequency ranges below 0.07 Hz, and it decreases gradually with increasing frequency. This decrease in coherency at higher frequencies is partly due to the difference in frequency response between the sensors and partly dur to the separation (2 m) of both sensors. However, the high coherency in low frequencies enables us to determine the sensitivity of the AC sensor. For standardization of the AC sensor, we selected data of OU and AC in the period 1500 to 1515 on July 15, 1986. Taking into account the results of coherency analysis, we used for comparison the average values from 300 digital data sampled at an interval of 0.1 sec. The results showed that the sensitivity of the AC sensor was 80 mg m^{-3} per volt. The sensitivity of the OU sensor was determined using the standard gas of carbon dioxide.

2.2 Zvenigorod experiment

The second comparison experiment, organized by the AP, was made on a field (1 km $\times$ 0.4 km) in Zvenigorod, USSR from 23 July to 5 August, 1987. The field was covered with cut grass of 20 cm high during July, and the field was plowed in August. All sensors of AP and OU were mounted at 1.5 m above the ground and the separation of carbon dioxide sensors was 70 cm (**Photo. 2**). The fetch was about 400 m for the
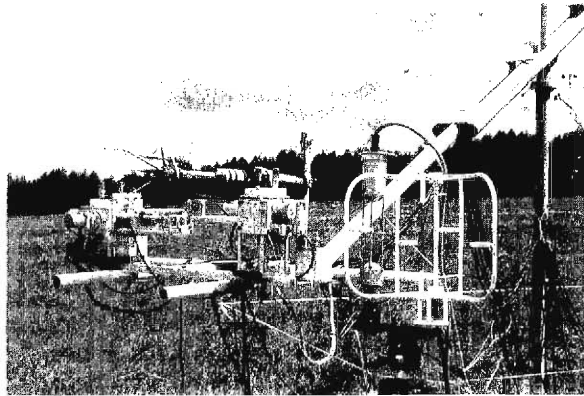
Photo. 2. Instrumental set-up for comparison experiment at Zvenigorod, USSR in 1987. Sensor assembly of OU (right), and AP (left). Sensors are mounted at 1.5 m height above the ground. Grass height is 20 cm.

prevailing winds.

The AP sensor adopts a multipass cell with 16 cm distance between mirrors and the total pathlength amounting to 130 cm. The general specifications of the sensor are reported by Elagina and Lazarev, 1984[2]. The design of this sensor is quite similar to that of an infrared hygrometer reported by Elagina, 1962[11]. The respective sensitivities of the OU and AP sensors were determined before the experiment using the same standard gas of carbon dioxide. The carbon dioxide signal from the AP sensor was smoothed by a low-pass filter with a time constant of 0.1 or 0.5 sec. 37 runs of 17 minutes were made during the experiment. Out of these, 8 runs measured under the time constant mode of 0.1 sec were chosen for comparison in this study. The coherency of OU and AP signals was about 1 in the frequency of 0.005 to 0.01 Hz (Volkov *et al.*, 1989[10]).

The wind velocity was measured by a sonic anemometer, which was a phase difference type reported by Tsvang *et al.*, 1973[12].

The sensors of OU were the same as used in the Winnipeg experiment except for the sonic anemometer-thermometer (Kaijo Denki Co. DAT-310). This sonic anemometer has a sensing path length of 20 cm.

The general specifications of the carbon dioxide sensors of OU, AC and AP are summarized in **Table 1**. Specifications of the UNL sensor are also included in the table for reference.

The analogue outputs from the OU, AC and AP sensors were digitized and recorded at a rate of 10 Hz on a floppy disk of the OU data acquisition system. Turbulence statistics and spectral densities were calculated using digital data of 15 min duration for the Winnipeg experiment and 17 min duration for the Zvenigorod experiment.

Table 1. General specifications of sensors

	OU	AC	AP	UNL
Path length (cm)	20	20	16×8	20×4
Heater	Ceramic	Nichrome wire	Tungsten lamp	Pt wire
Detector	PbSe	PbSe	InSb	PbSe
Measuring range (ppm)	± 100	0–1300	± 100	± 175
Noise (ppm)	0.8	5	—	0.2
Drift (ppm/h)	1	—	—	0.5

3. Results and discussion

3.1. Carbon dioxide

In order to examine the frequency response of the carbon dioxide sensor, the power spectral densities were calculated. The normal power spectra of OU and AC data multiplied by frequency n are shown in **Fig. 2a**. The OU data show the $-2/3$ power slope in the high frequency range above 0.3 Hz, indicating the existence of an inertial subrange. The AC data included a relatively large component in the frequency range from 0.3 to 2 Hz compared with the OU data. It is noted that the power spectrum of AC falls off more rapidly than the $-2/3$ power slope in the frequencies above 1 Hz. This is due to the smoothing effect of the low-pass filter with a relatively large time constant at the final stage of the electronic circuit.
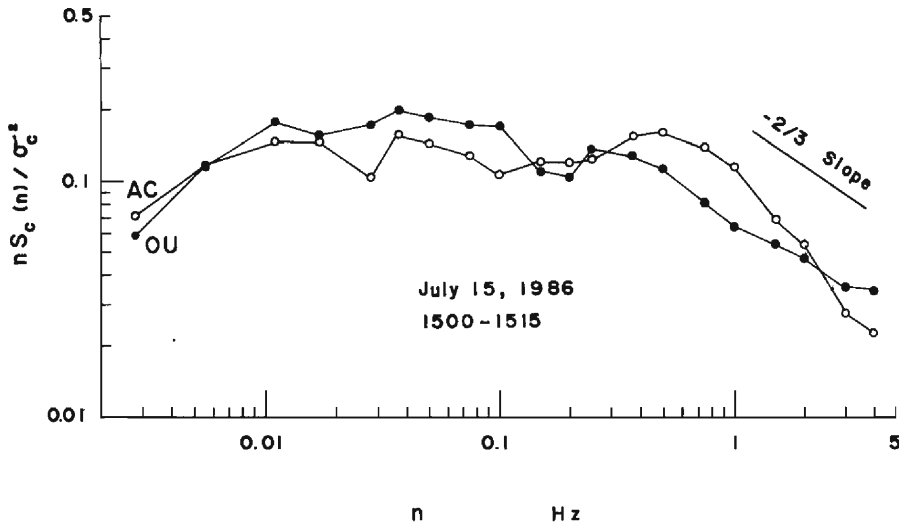

Fig. 2a. Normalized power spectra of carbon dioxide fluctuations measured with OU and AC sensors. Based on measurements at Winnipeg during 1500–1515 on July 15, 1986: Wheat=80 cm height. Temperature=26.4°C, wind speed=1.7 m s^{-1} and Monin-Oboukhov stability parameter= -0.24 at the measuring height of 300 cm above the ground.
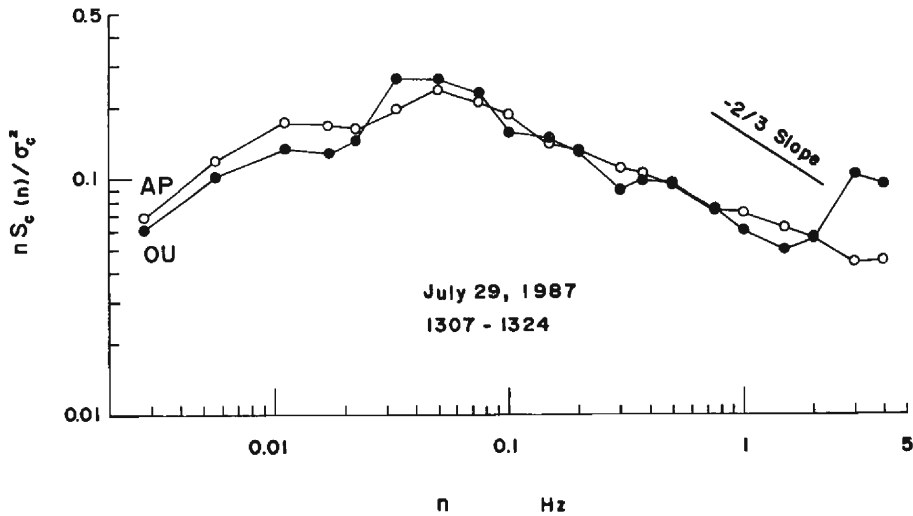
Fig. 2b. Normalized power spectra of carbon dioxide fluctuations measured with OU and AP sensors. Based on measurements at Zvenigorod during 1307–1324 on July 29, 1987. Grass=20 cm height. Temperature 17.7°C, wind speed=2.5 m s^{-1} and Monin-Oboukhov stability parameter=-0.07 at the measuring height of 150 cm above the ground.

The normalized power spectra of OU and AP data are plotted in **Fig. 2b.** The power spectral shapes for AP and OU data are basically similar, representing a $-2/3$ power slope in the high frequency range. It is apparent that the power spectrum of OU
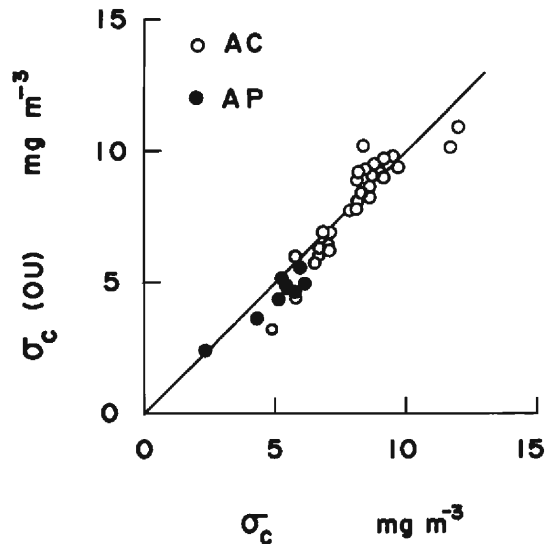

Fig. 3. Comparison of standard deviation of carbon dioxide fluctuations measured with sensors of OU and AC (○), and sensors of OU and AP (●). The solid line represents one to one correspondence.

is affected by noise in the frequency range above 2 Hz. This is due to the insufficient sealing of the detector housing of the sensor. The cooling air of the infrared source leaked into the detector housing during the operation. After the Zvenigorod experiment, the leakage effect was minimized by separating the cooling air line from the detector housing.

Fig. 3 shows the relationship of standard deviations of carbon dioxide fluctuations for AC and AP sensors to those for the OU sensor. The solid line in the figure shows the 1 : 1 line. The data plotted are within ±20 per cent around the line.

3.2. Vertical wind

To estimate the carbon dioxide flux by the eddy correlation technique, the vertical wind sensor is an important one. As described in the previous section, OU and AC used the sonic anemometer-thermometers of Kaijo Denki Co., and AP the sonic anemometer of a phase difference type. **Fig. 4a** shows the power spectral estimates of OU and AC normalized by their variances in vertical wind velocity. The spectral shapes for OU and AC data are very close to each other for the whole frequency range analyzed. The spectra show a slope 1 in low frequencies below 0.2 Hz, and $-2/3$ in high frequencies above 0.3 Hz. These spectral shapes are very similar to the well known ones for vertical wind velocity reported by Kaimal *et al.*, 1972[13].

The normalized power spectral estimates of OU and AP are shown in **Fig. 4b**. The spectral shapes are basically similar. It is, however, noted that the AP spectrum shows much energy in the low frequency range below 0.01 Hz compared to the OU spectrum. This spectral difference is ascribed to the drift in low frequency ranges of
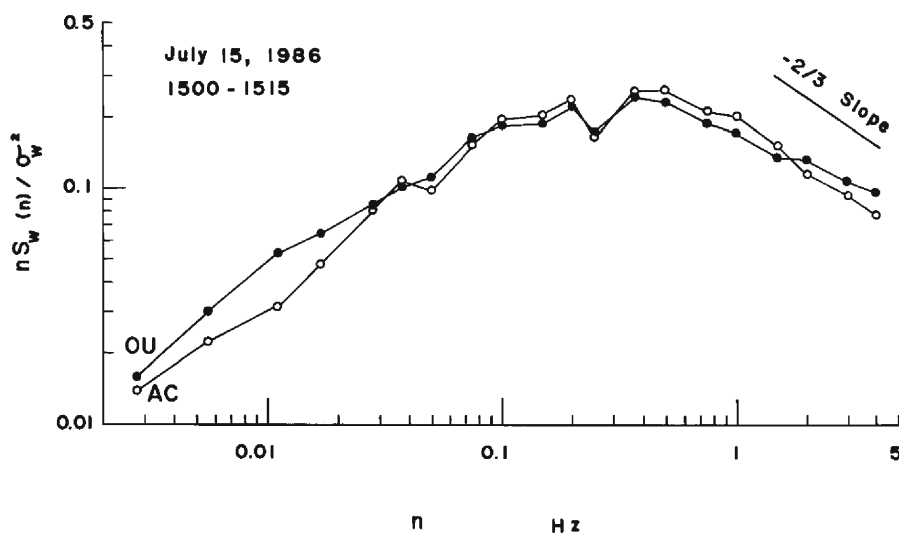

Fig. 4a. Normalized power spectra of vertical wind velocity measured with OU and AC sensors. Based on measurements at Winnipeg during 1500–1515 on July 15, 1986. Measuring conditions are shown in Figure 4a.
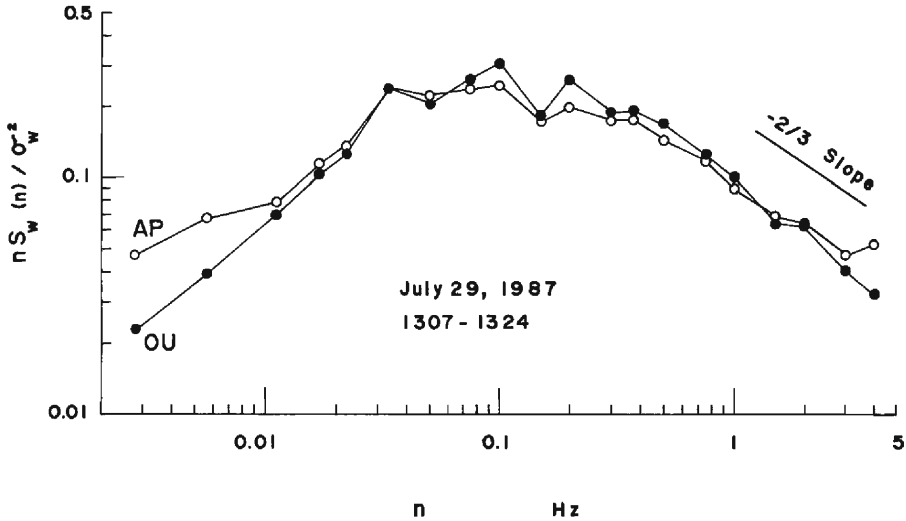
Fig. 4b. Normalized power spectra of vertical wind velocity measured with OU and AP sensors. Based on measurements at Zvenigorod during 1307–1324 on July 29, 1987. Measuring conditions are shown in Figure 2b.

the AP sensor.

The individual values of standard deviation of vertical wind velocity measured by OU, AC and AP sensors are plotted in **Fig. 5**. As expected from the results of power
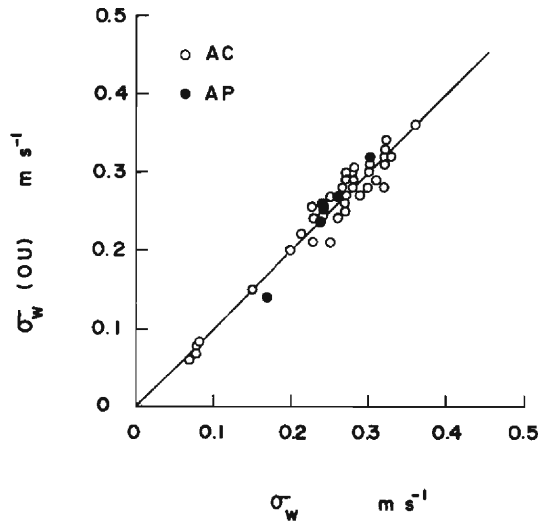

Fig. 5. Comparison of standard deviation of vertical wind velocity fluctuations measured with sensors of OU and AC (○), and sensors of OU and AP (●). The solid line represents one to one correspondence.

spectra, the respective standard deviations obtained for OU, AC and AP are in good agreement. The mean values over the whole run agree within 15%.

3.3 Covariances between vertical wind and carbon dioxide

Fig. 6a shows a typical example of *wc*-cospectra of OU and AC. In the coordinates adopted, $nC_{wc}(n)$ vs. log n, the area under the curve over a frequency interval Δn is proportional to the spectral contribution to covariance. The OU curve shows that the *wc*-cospectrum extends over the frequency range from 0.002 to 3 Hz. These values of lower and upper limiting frequencies are within the range of other *wc*-cospectra measured over vegetated fields (e.g., Ohtaki, 1980[6] and 1984[7]; Anderson and Verma, 1985[14]). It is obvious that the *wc*-cospectrum of AC is limited within frequencies from 0.02 to 0.5 Hz. Comparing the area under the curves of *wc*-cospectra for AC and OU, we find that the covariance of AC is about 50% of the OU one. In particular, the high frequency loss is remarkable. This is partly associated with oversmoothing in high frequency fluctuations of carbon dioxide due to relatively large time constant of the AC sensor (0.2 sec), and partly due to the configuration of the sensor array. The vertical wind sensor and the carbon dioxide sensor of AC were not as the same place, so that the apparent *w–c* correlation is reduced on small eddy scales.

Fig. 6b shows the *wc*-cospectra of OU and AP. It is noted that the *wc*-cosprctrum of AP shows fairly good agreement with that of OU in high frequencies above 0.05 Hz. The large component in low frequencies below 0.02 Hz is certainly associated with the instrumental drift of the AP vertical wind sensor.

Values of $\overline{w'c'}$ measured by OU, AC and AP are plotted in **Fig. 7**. It is obvious that the means over all the runs of AC gave results systematically about 50% smaller than that of OU. On the other hand, AP values are plotted around the line representing one to one correspondence with those of OU.
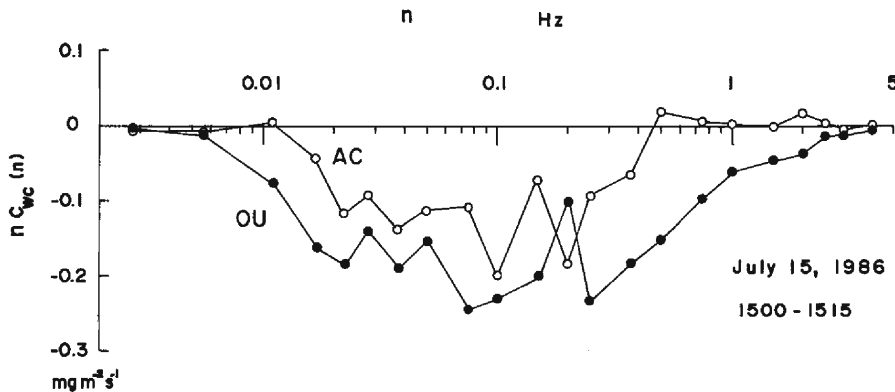

Fig. 6a. Cospectra of carbon dioxide and vertical wind velocity measured with sensors of OU and AC. Based on measurements at Winnipeg during 1500–1515 on July 15, 1986. Measuring conditions are shown in Figure 2a.
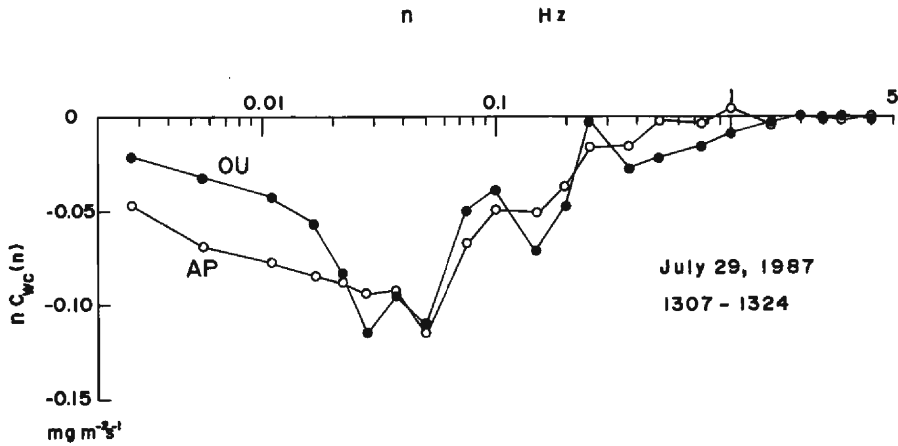
Fig. 6b. Cospectra of carbon dioxide and vertical wind velocity measured with sensors of OU and AP. Based on measurements at Zvenigorod during 1307–1324 on July 29, 1987. Measuring conditions are shown in Figure 2b.
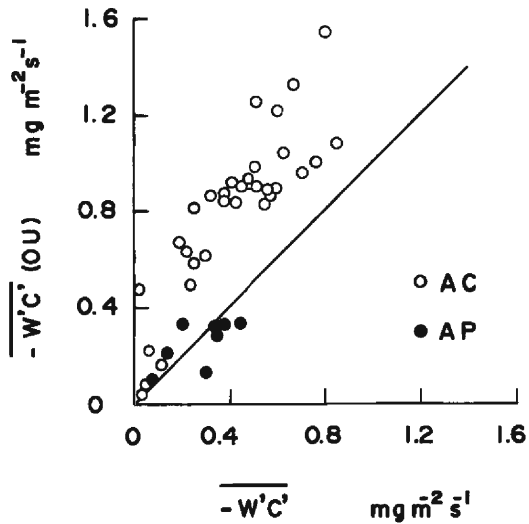

Fig. 7. Comparison of vertical fluxes of carbon dioxide measured with sensors of OU and AC ($\bigcirc$), and sensors of OU and AP ($\bullet$). The solid line represents one to one correspondence.

4. Concluding remarks

The intercomparison experiments of fast response carbon dioxide sensors, developed by OU, AC and AP, were carried out in Winnipeg, Canada in 1986, and in

Zvenigorod, USSR in 1987.

Normalized power spectra of carbon dioxide measured by the OU and AP sensors followed $-2/3$ power slope in high frequency ranges, indicating the slope of spectrum in intertial subranges. We know that there are no appreciable contributions to the flux from frequencies in the inertial subrange. This means that the OU and AP sensors are adequate to measure the carbon dioxide flux in the atmospheric boundary layer. The normalized power spectraum of the AC sensor falls off rapidly and does not show a well defined $-2/3$ power slope in high frequencies. This denotes that the high frequency loss of the AC sensor is serious in flux measurements. In fact, the means of all the runs of AC show systematic underestimation of about 50% compared with that of OU.

Here, we would like to comment on some aspects of the carbon dioxide sensor of AC. The AC sensor used in the present experiment was the second version. The improved sensor (third version) was fixed to the aircraft to measure the carbon dioxide flux in the upper layers during the experiment. After the Winnipeg experiment, the fourth version carbon dioxide sensor, which can simultaneously measure fluctuations in carbon dioxide and water vapor, has been completed.

Acknowledgements

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