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AN INFRARED ABSORPTION HYGROMETER AND ITS APPLICATION TO THE STUDY OF THE WATER VAPOR FLUX NEAR THE GROUND

By

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Abstract

A new infrared absorption hygrometer for the purpose of water vapor fluctuation measurement developed by the present authors is described. The 1.90μ water absorption band and 1.65μ non-absorption band light signals are used to detect the water vapor contents within the optical sensing path of 0.8 m. The new instrument can respond to the fluctuations of about 1 cps at most. Field measurement using this new instrument was made at Shionomisaki, and the results are also discussed in this paper.

1. Introduction

The principle of using the infrared energy absorption by water molecule has been excepted to be used in an instrument for measurement of the water vapor contents of the atmosphere. The principle was first discovered by Fowle in 1912. Since Fowle's work, the instruments of various design for meteorological use have been developed mainly by the investigators of the United States, e.g., Foskett and Foster [1943], Foskett *et. al.* [1953], Wood [1958], Cramer *et. al.* [1962], Vaughan [1963], Post and Lucas [1964] and Tank and Wergin [1965], and Elagina of U.S.S.R. [1962]. Though the most of the instruments are aimed to make absolute measurement in routine observations and any attemp to make a quick response sensor has not yet brought about fruitfull results except by Elagina. The authors have undertaken the program to develope the quick response infrared hygrometer, having double 40 cm sensing optical paths and using 1.90μ absorption and 1.65μ reference bands, which has the compatible response character to the sonic anemometer-thermometer developed in Kyoto University, for the purpose of atmospheric turbulence studies, particularly evaporation from various kinds of the earth surfaces. The basic theory and the description of the testing instrument and the resultes of the test observations are presented in this paper.

2. Description of the new infrared hygrometer

The infrared hygrometer constructed at Kyoto University has double 40 cm sensing optical paths and uses the 1.90μ water vapor absorption band and 1.65μ non absorption band as the reference band. Isolating of light signal is made by means of the band-pass filter assemble on the rotating sector wheel which makes the beam of 1.90μ and 1.65μ alternately in 65 cps. A self-balancing null system is employed whereby the intensity of the absorption band, which is attenuated by the water vapor, is always kept equal to that of the reference band which is attenuated by the compensating filter.

The compensating filter passes only water vapor absorption band and is driven by a balancing motor. The position of the compensating filter is therefore an index of the amount of the water vapor in the sensing path. The block digram of this instrument is shown in Fig. 1. The light source is an tungsten

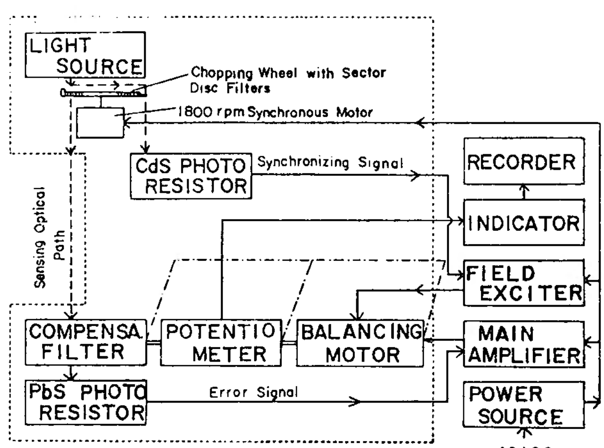

Fig. 1. The block diagram of the new infrared hygrometer.

lamp for cine-projecter operated by a regulated low voltage D. C. power source. The beam from the light bulb is collimated by a collimator and chopped by the rotating disc with isolating filters. The disc also generates synchronizing signal for the power supply of balancing motor. The beam enters into the sensing path through a window and reflected at the other end. After reflecting, the beam backs over the same path and is brought into the dry chamber again. When the water vapor exists in the sensing path, the compensating filter cuts into the beam to attenuate the intensity of reference band to the same intensity as the absorption band signal. The position of the compensating filter is detected by a potentiometer making water contents signal.

The intensity of the signal is detected by a PbS sensor, the temperature of which is not regulated. As the null method is employed, there is no restrict requirement for doing so. Nevertheless, the problem revealed through the test that zero point of this instrument moves a little depending on the temperature of the PbS sensor. The error signal detected by PbS sensor is pre-amplified and then lead to main amplifier. The external apearance of this instrument is shown in Fig. 2. The compensating filter moves into the beam, and the areal

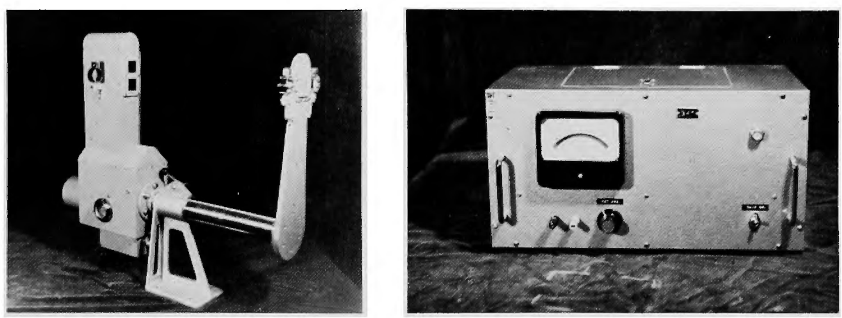

Fig. 2. The outlooks of the new infrared hygrometer.

ratio of compensating filter in the signal beam (x) is related to the absorption rate of water vapor contents in the sensing-path. The absorption of infrared ray by water vapor can be approximated by the following equation (Post and Lucas [1964]).

$$A=\beta\sqrt{V}, \tag{1}$$

where A is the absorption rate, β the absorption constant and V the total water equivalent depth in the path.

Then the intensity of two kind optical signals are shown as

$$\left.\begin{aligned} I_1&=I_{01}(f_1)_1(1-A_1)[(1-x)+x(f_1)_1], \\ I_2&=I_{02}(f_2)_2(1-A_2)[(1-x)+x(f_1)_2], \end{aligned}\right\} \tag{2}$$

where I_0 is source intensity and I incoming intensity of the signal, suffixs 1 and 2 mean the absorption and the reference bands, and $(f_1)_2$ is transmissivity of the 1st band filter to the 2nd band signal. For the intensities I_{01} and I_{02} are not so different that they can be assumed to be equal. And A_1 is expressed by Equation (1) where A_2 is considered equal to zero and $(f_1)_2$ is also nearly equal to zero. The instensities of two signals are kept equal in this instrument and I_1 should equal to I_2. Therefore, the relation as the following is introduced,

$$(f_1)_1(1-A_1)[(1-x)+x(f_1)_1]=(f_2)_2(1-x). \tag{3}$$

Thus

$$A_1=\frac{(f_1)_1-(f_2)_2+[(f_1)_1^2-(f_1)_1+(f_2)_2]x}{(f_1)_1[1-\{1-(f_1)_1\}x]}. \tag{4}$$

From the above equation, the absorption of the water vapor, A, can be computed. The values of transmissivities of the particuler filters used in the present instrument are as follows

$$(f_1)_1=0.26 \quad \text{and} \quad (f_2)_2=0.28. \tag{5}$$

And then the water vapor content can be estimated from Eq. (1) using $\beta=2.2$ for 1.9μ absorption band. It was cleared by the calibration test that the relation of Equation (4) is not definite but depends on the electronical circuit paramters. Thus the calibration curve of this instrument is mainly determined experimentally. It requires nearly a second to respond the rapid changes in full scale of this instrument. The moving speed of the compensating filter is almost constant without regarding to the amplitude in this servo system. Therefore, it can be expected the instrument to follow up to about one cps fluctuations with moderate amplitude.

3. Performace and field test

The testing instrument was completed and tested in the early spring of 1966 (Fig. 2). Soon some deficiencies in instability of the power source of servo amplifier and balancing system were found. After some improvements, the revised form of the instrument was completed in the end of 1966. Calibration of the instrument was conducted in the moist chamber with an Assmann psychrometer. The calibration curve is shown in Fig. 3. The problem arose from that the zero indication of the instrument drifts slowly with the temperature increasing of PbS sensor. The cause of this drift has not been revealed but it prevents to use this instrument for absolute humidity measurement. Though the

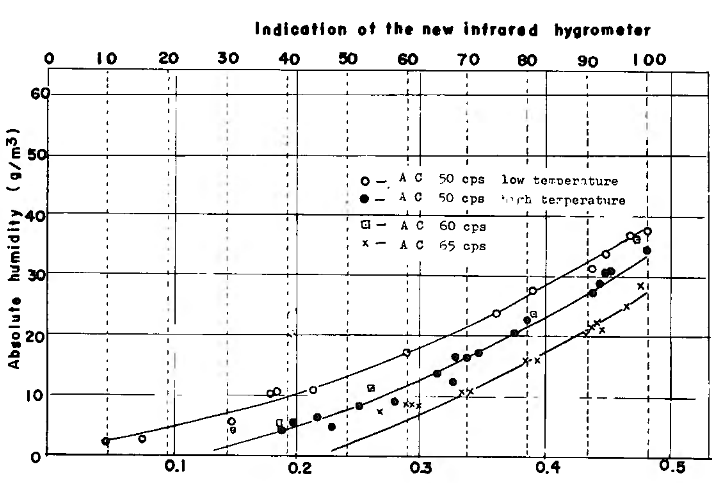

Fig. 3. The caliblation curve of the new infrared hygrometer.

zero point drifts, the calibration curves do not change their forms. Therefore, this instrument does not loose the utility value in use as the fluctuation sensor which is the main purpose of the present study.

The minimum resolving power is about 0.05 gr/m^3 of precipitable water. This limitation is mainy caused by the noise of the error signal which comes from the irregularity of the rotating of disc wheel and other causes.

The field test was made at Shionomisaki Wind Effect Laboratory of Kyoto University, in the end of 1966. The experimental field is at the south-western part of a flat penisula. The open sweet potato field extends for about 1 km to upwind with scattering trees or hedges. The testing site is open bare soil extending about 50 m to upwind side.

The infrared hygrometer and the sonic anemometer were installed at the height of 1.5 m, setting both sensing paths side by side. And mast profile measurements of wind speed, air temperature and humidity were made just near these instruments.

4. The results of the observations

The observations were made for several cases, the related conditions of which are shown in Table 1 and Fig. 4 a, b, c.

Throughout the observations, a thermocouple psychrometer having enough small time constant to be compatible with the infrared hygrometer was placed in the vicinity of the infrared hygrometer and comparison was made with both instruments. Fig. 5 shows an example of the traces of the new infrared hygrometer and water vapor pressure measured by the thermocouple psychrometer (Run 3). Both traces can be regared to be similiar for long period changes. However, they are a little different for very short period changes. This may be caused from the fact that the infrared hygrometer measures a line averaged value at a time and the psychrometer a time averaged value at a point. In this case standard deviation of water vapor pressure measured by the infrared hygrometer is 0.189 mb and 0.177 mb by the thermocouple psychrometer. The comparison of simultaneous indictions of the infrared hygrometer and thermocouple psychrometer averaged over 2.5 sec are shown in Fig. 6.

The slope of the calibration curve is reproduced in this figure, which shows that chamber calibration is also valid for the field observations. Thus this calibration slope is used in the reduction of water vapor content from the infrared hygrometer indication. The spectra of water vapor pressure fluctuations of Run 3 are shown together with that of vertical velocity component measured by the sonic anemometer in Fig. 7. The averaging time in this case is 0.5 sec and sampling duration 7 min. And the sonic anemometer records were smoothed

Table 1. Observed values and related parameters

Run No.	Start Time	Sampling Duration	Wind Speed (m/sec)					Air Temperature (°C)					Vapor Pressure (mb)			
			U_{23}	U_{63}	U_{153}	U_{300}	U_{600}	θ_{20}	θ_{60}	θ_{150}	θ_{300}	θ_{600}	e_{20}	e_{60}	e_{150}	e_{300}
3	Dec. 20 '66 11 : 25	7 min.	3.9	4.6	4.8	5.5	5.7	16.7	16.5	16.9	16.1	16.1	11.57	11.31	10.41	10.47
221	Dec. 24 '66 10 : 00	10 min.	3.3	3.7	3.8	4.3	4.3	13.1	13.0	12.8	12.7		8.00	7.79	—	6.20
222	12 : 00	5 min.	4.3	4.9	5.3	5.9	6.5	15.1	15.0	14.2	14.2		8.26	7.98	—	7.41
223	14 : 00	6 min.	4.3	5.0	5.1	5.9	6.6	15.2	15.3	14.4	14.2		8.04	7.54	—	7.41
224	16 : 00	8 min.	3.4	4.2	4.2	4.6	5.1	13.1	13.3	12.9	12.8		7.58	7.58	—	7.50
225	18 : 00	2 min.	4.9	6.8	6.5	7.2	8.4	10.9	11.1	11.0	11.1		6.99	7.26	—	7.26
226	23 : 00	3 min.	4.5	6.0	5.4	6.7	6.6	8.9	8.9	8.9	8.9		6.23	7.14	—	7.14

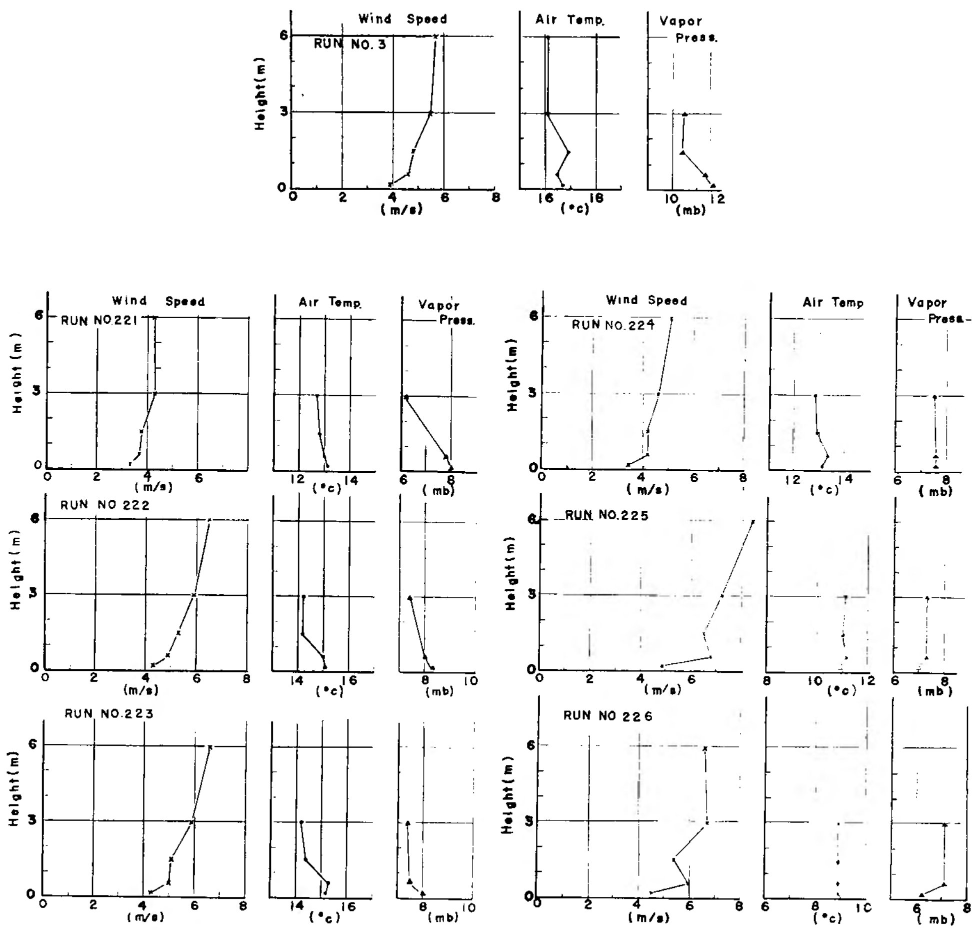

Fig. 4. The mean profiles of wind speed, air temperature and water vapor pressure.

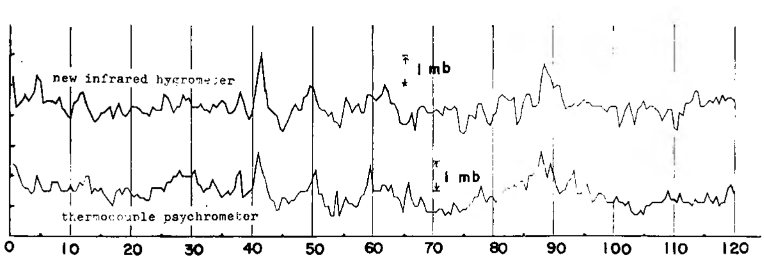

Fig. 5. An example of the water vapor record obtained by the new infrared hygrometer and the thermocouple psychrometer.

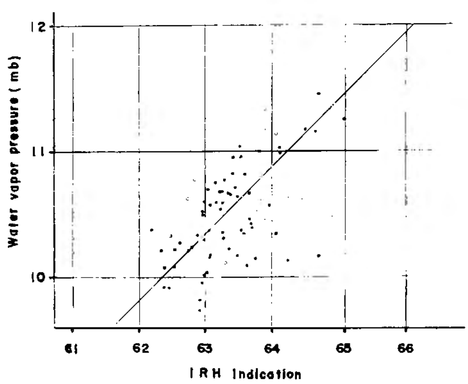

Fig. 6. The comparison of instantaneous values of atmospheric vapor pressure obtained by the new infrared hygrometer with thermocouple indications over 2.5 sec.

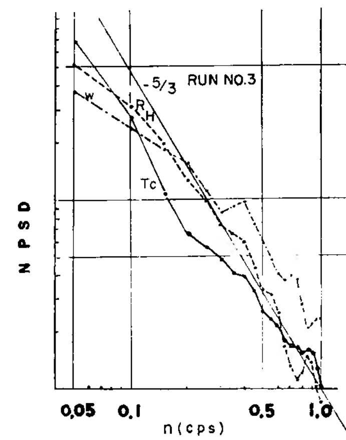

Fig. 7. The power spectra of vertical velocity (W) and water vapor pressure fluctuations obtained by the new infrared hygrometer (RH) and the thermocouple psychrometers (Tc).

by moving average technique over 0.5 sec for the purpose of response character matching with the infrared hygrometer. The both spectra of water vapor pressure estimates by infrared hygrometer and thermocouple psychrometer are almost similar and well approximated by minus five thirds law as shown by Elagina [1963]. Next six runs on 24th are two hourly successive observations to see the time changes of evaporation. The sky was clear throughout the day. The evaporation rate estimated from the fluctuation measurements by the eddy correlation method (Mitsuta [1967]) is shown in Table 2. The both data of

Table 2. Observed values and related parameters

Run No.	σ_e (mb)	σ_w (m/sec)	E (mm/hr)	E^* (mm/hr)
3	[σ_t: 0.177] 0.189			
221	0.50	0.31	0.13	0.24
222	0.57	0.32	0.10	0.29
223	0.46	0.34	0.06	0.29
224	0.64	0.37	0.18	0.06
225	0.33	0.46	0.08	−0.05
226	0.15	0.49	−0.04	−0.05

σ_e: Standard deviation of water vapor pressure obtained by the new infrared hygrometer.
σ_w: Standard deviation of vertical velocity obtained by the sonic anemometer.
E: Evaporation rate estimated from the eddy correlation method.
E^*: Evaporation rate estimated from heat balance method after [Ageta (1967]).
σ_t: Standard deviation of water vapor pressure obtained by the thermo-couple psychrometer.

water vapor content and vertical velocity component were read for every 0.5 sec.

The sonic anemometer data which are much quicker in high frequency fluctuation response were smoothed by the process as mentioned before. The total sampling durations are from 2 min. to 10 min., which seems to be a little shorter than the criteria for flux measurement presented by Min-Yui Chou [1966].

Some error might be resulted from this shortness of the duration. Evaporation rate in the daytime is about 0.1 mm/hr, and −0.01 mm/hr at the midnight. The time change of evaporation is shown in Fig. 8. The time of shifting from evaporation to condensation is between 20 and 23 o'clock, which is later than the estimation from profile by the indirect measurement (Ageta [1967]). But on the whole the estimation by indirect measurement shown in the end of the table agrees fairly well to the value obtained by this direct method.

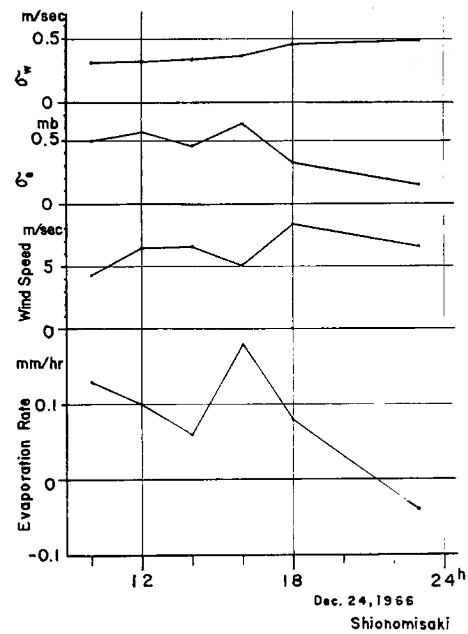

Fig. 8. Time changes of evaporation rate and other parameters.

5. Detailed studies on the transport mechanism

To see the contribution of various size of eddies to the vapor transport mechanism, cospectral analysis of vapor and vertical velocity was made. The power spectra and cospectra of Runs 221-226 are shown in Figs. 9 and 10. The ordinate of Fig. 10 is spectral density of cospectrum multiplied by frequency, and the abscissa being logarithm of frequency. The area under the courve is proportional to the total covariance or the flux. As is seen in these figures, low frequency eddies have controlling effects on the total covariance. On the other hand high frequency range has little effects on the transport.

The position of cospectral peak is not clear in some cases, because the descending tendency in low frequency side cannot be seen on the cospectra. It shows that the sampling duration might be considered too short in such cases and the longer sampling duration is expected in the future study. The error caused from this low frequency cutoff is not easy to estimate but the fact that

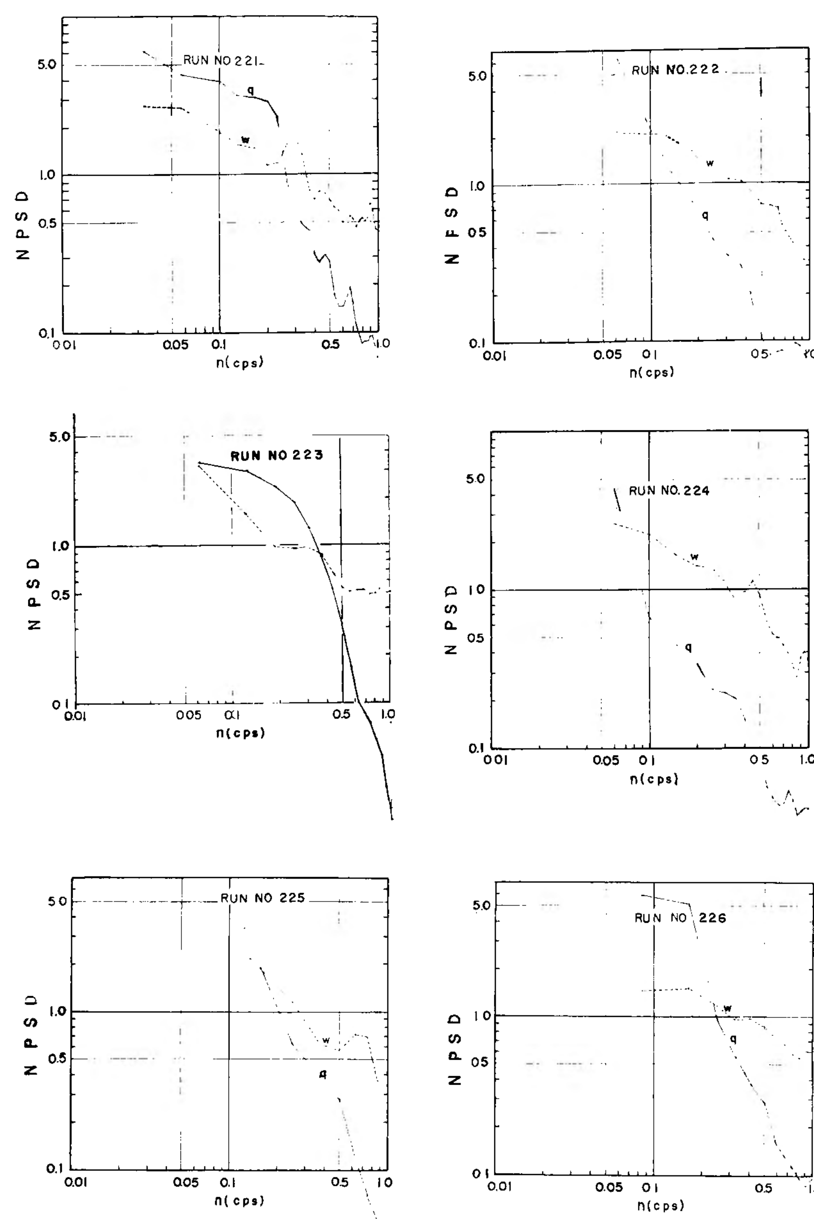

Fig. 9. The spectra of vertical velocity and water vapor pressure.

the results of this direct measurement is smaller than those of indirect measurement in most cases might be partly reduced to this point.

The cospectral peak in the low frequency side tends to displace from case to case depending mainly on the spectral shape of the vertival wind component.

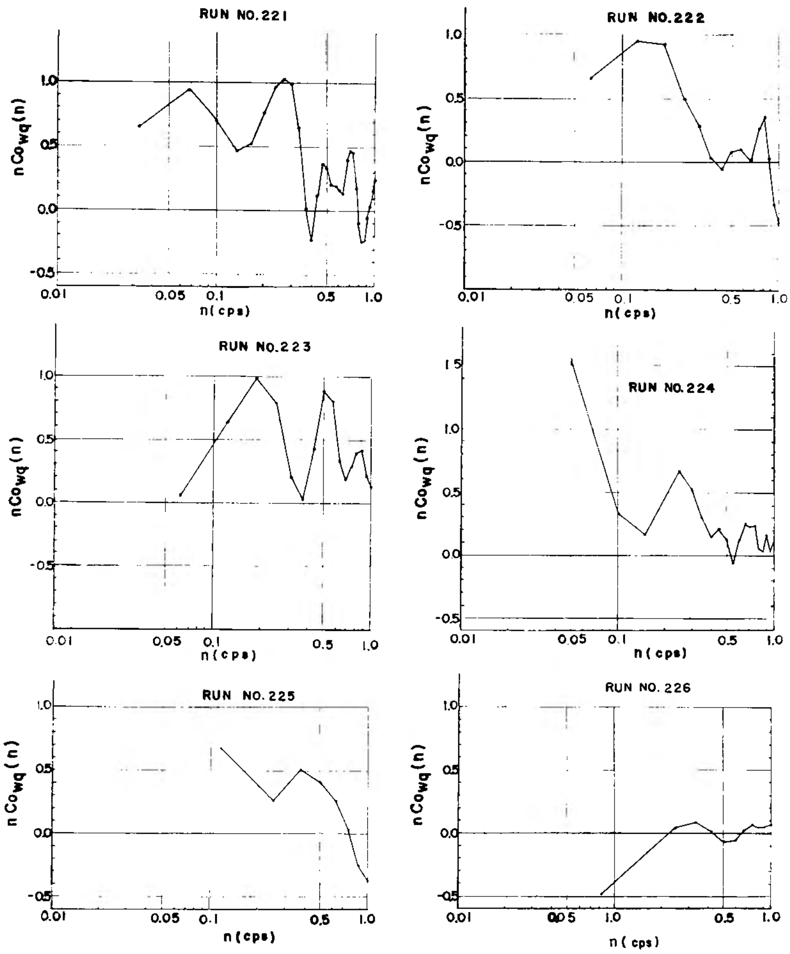

Fig. 10. The co-spectra between vertical velocity and water vapor pressure.

The transport in the inertial subrange is small and fluctuates even in its sign, and counter-gradient flux is seen in relatively high narrow frequency bands in some cases. These situations suggest that transport mechanism should be analyzed from the spectral point of view.

6. Conclusions

Direct measurements of water vapor flux by the use of a new infrared hygrometer and a sonic anemometer were made and almost satisfactory results were obtained. This method is more reliable and rather easier in data handling than other existing methods of water vapor flux estimation.

The evaporation rates obtained are about 0.1 to 0.2 mm hr in the daytime on clear winter day and condensation of the order of 0.05 mm/hr is observed at the midnight.

There are some instrumental problems, such as stability of the infrared hygrometer and matching of the response character of the both fluctuation sensors. These points should be improved to make a practical water vapor flux sensor in this configuration.

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