Behavior of Winds in the Lowest 200 m in Central Tsukuba Science City

by

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Abstract

A meteorological observation tower at Tsukuba Science City is equipped with mean wind, temperature and humidity sensors, together with instruments for the measurement of their short period fluctuations at seven levels (including the top of the tower) ranging from 10 m to 213 m above the base of the tower.

The general statistical properties of wind data for one year are discussed in this paper together with the tower facilities including the data acquisition system.

The annual arithmetic mean wind speeds increase from 3.14 m/s at the 25 m level to 6.09 m/s at the top level. The annual mean wind speed at the 25 m level is highest during the daytime and one at the 213 m level at night. Monthly relative frequency distribution of wind speed can be well simulated with Weibull distribution.

Annual relative frequency of wind direction has three clear peaks, which are very similar to the climatological data obtained at the Tateno Aerological Observatory near the Meteorological Research Institute.

The characteristics of vector wind speed are examined and the monthly mean profiles from May to September seem to be explained by the geostrophic wind.

The power spectra of wind speed in summer and fall have a remarkable peak of daily cycle and a relatively large peak with 3-4 days period in winter and spring.

1. Introduction

The meteorological observational tower 213 m tall and equipped with meteorological instruments has been operating since 1977.

The wind, air temperature and humidity data at seven levels of the tower have been collected, mainly in order to investigate the structure of the planetary boundary layer. This report documents the instrumentation, data recording equipments installed and some results of the general statistical properties of the wind data obtained from the tower.

2. Tower site and structure.

The meteorological observation tower is located at about 20 km south of Mt. Tsukuba

and about 10 km west of Lake Kasumigaura and in the center of Tsukuba Science City as shown in Fig. 1. This area is a part of the Kanto Plain and then, the planetary boundary layer may be scarcely affected by topography. The tower is a guyed open lattice design with a height of 213 m and the structure is of galvanized steel with three legs spaced 4 m apart. In the center of the tower, a three-man elevator with a maximum capacity of 250 kg can go up and down manually or automatically from 10 m to 200 m. At six levels (10, 25, 50, 100, 150 and 200 m), there are landings and three booms at an angle of 120° to each other, to which the instruments will be attached. The booms were set in the direction, respectively, of S, NE and NW based upon the climatological wind direction

Fig. 1. Location of the meteorological observation tower.

Fig. 2. Location of the instrumental boom and its structure.

data.

The length of the boom is 6 m outward from the side of the tower as shown in Fig. 2. In the case of repairing or adjustment of the instruments, we can easily slide only the instrumental stand by hand.

3. Instrumentation and data acquisition system.

The instruments and data acquisition system of the tower are divided into two groups. The one is to measure the mean profiles of wind speed, wind direction, air temperature and humidity, and the other is to measure the statistical properties of these elements such as variances, correlations and covariances between two elements. The details of the instruments and data acquisition system are discussed in another paper (Hanafusa et al., (1979)).

A. Mean measurement.

A-1. Horizontal wind.

Horizontal wind speed and direction are measured at all the six instrumented tower levels and at the top of the tower. The wind instrument at each level is mounted on a boom 6 m apart from the the body of the tower as shown in Fig. 2 except at the top of the tower. In order to investigate the effects of the tower, some results of the wind tunnel test using the 1/20 scale model tower are shown in Fig. 3. These figures show the distribution of the ratio of wind speed measurements to the standard wind speed in the cases of the three kinds of wind direction, and the shaded part indicates that the tower effect is somewhat larger than 5% of the standard wind speed. In the worst case when the wind direction is at right angles to the side of the tower, the relative error to the standard wind speed is at the most 2% at the end point of the boom and the pattern of the wind speed distribution is not changed by the value of the standard wind speed. Accordingly, the effect of the tower can be avoided by the relative error smaller

than 2% by using three anemometers of the same type on the three booms at the angle of 120° at one floor, if the wind direction is almost constant from the top of the tower to the ground surface.

At the top of the tower, three different kinds of anemometer are set on each on its own 2.0 m mast as shown in Fig. 4. In the Aerovane model MV-110, wind speed information is produced by a propeller-driven DC generator, and the wind direction, by a AC synchro. On the other hand, in the Aerovane model FF-3R, wind speed information is obtained by an AC generator and wind direction, by a AC synchro. The basic characteristics of the two anemometer systems are listed in Table 1. The third anemometer is a two-dimensional sonic anemometer with 20 cm path length.

One of the three anemometer sensors at each of the six levels is selected by the signal of the wind direction from the anemometer, MV-110, at the top of the tower in order to avoid tower shadow effect, and is connected with a main chassis automatically.

A-2. Temperature.

Temperature measurements are made at all six tower levels by two independent systems on two booms (NE and S), and at the top of the tower, considering the tower effects. The temperature sensor is Pt resistance which is $100.0\ \Omega$ at 0°C . The sensor for the measurement of air temperature is placed under a radiation screen and ventilated at about 7 m/s. The absolute accuracy of this thermometer has been found to be within 0.3°C by the calibration test with a standard glass bulb thermometer and the response time is a few minutes.

A-3. Relative humidity.

It is very difficult to measure the relative humidity with high accuracy and continuity at the present time. In our case, we have experimentally adopted the capacitance type hygrometer named HUMICAP, which is manufactured by the the Visala Company in Finland. The principle of this hygrometer

Fig. 3. Wind speed distribution around the tower.
(by wind tunnel experiment)

(a) = 0°

(b) = 30°

(c) = 90°

— instrumental boom

is that relative humidity can be expressed by the function of the capacitance of the polymer. The details of the hygrometer is described by Suntola (1963). The range of the measurement is from 0% to 100%, the accuracy of the hygrometer, 3%, and the

temperature coefficient, about $0.05\%/^\circ\text{C}$. The sensor is placed under the same radiation screen together with a temperature sensor described above.

Table 1. Specifications of two aerovane-type anemometers.

	FF-3R	MV-110
Wind speed	AC-generator	DC-generator
Wind direction	AC synchro	AC synchro
Starting wind speed	within 2 m/sec	within 0.4 m/sec
Range of measurement	2-90 m/sec	0.4-50 m/sec
Maximum wind speed	over 100 m/sec	over 60 m/sec
Accuracy of wind speed	± 0.5 m/sec within 10 m/sec $\pm 5\%$ over 10 m/sec	± 0.3 m/sec within 10 m/sec $\pm 3\%$ over 10 m/sec
wind direction	$\pm 5^\circ$	$\pm 3^\circ$
Propeller rotating	2500 RPM/60 m/sec	2400 RPM/20 m/sec
Power of electricity	AC 33 V/60 m/sec	DC 680 mV/20 m/sec

Fig. 4. Location of instruments at the top of the tower.

- (A) Aerovane-type anemometer (MV-110)
- (B) Thermometer-Hygrometer
- (C) Two-dimensional sonic anemometer (DA-200)
- (D) Aerovane-type anemometer (FF-3R)

B. Statistical properties.

The statistical properties of wind, air temperature and humidity fluctuations are the most important quantities in investigation of the planetary boundary layer. The measure-

ment of these statistical properties for a relatively long period requires improvements in the data acquisition system as well as instruments.

The newly developed three-dimensional sonic anemometer-thermometers are used to measure fluctuations in three components of wind and air temperature, and the fine thermocouple psychrometer is used to measure humidity fluctuations.

B-1. Three-dimensional sonic anemometer-thermometer.

The details of the new sonic anemometer-thermometer are discussed in another paper (Hanafusa et al., (1980)). The characteristics of the measurement system are described briefly in this paper. One sonic sensor is placed on each boom at each floor and one of them is selected by the signal of the wind direction by the two-dimensional sonic anemometer at the top of the tower. The probe of the sonic anemometer is one head system as shown in Fig. 5. This system has no mechanism of zero shift of the different path of the span. The simple shape exerts less shadow effect on the wind field than the traditional one. The new calculation method which uses the reciprocal of the sonic pulse

Fig. 5. The new single head sonic anemometer-thermometer: (a) Wind antenna specifications, (b) Main chassis, Junction box, and Wind antenna (from left to right)

Table 2. Specifications of a new-type sonic anemometer thermometer

	Anemometer	Thermometer
Measuring mode	Time-sharing multiplex transmission/reception switchover type ultrasonic pulse emission, ~ 20 Hz per channel.	
Measuring range	$0 \sim \pm 30$ m/s	Central temperature: $-10^{\circ} \sim 40^{\circ}\text{C}$ Temperature deviation: $0 \sim \pm 5^{\circ}\text{C}$
Accuracy	1%	1%
Minimum resolution	0.5 cm/s	0.025 $^{\circ}\text{C}$
Frequency resolution	10 Hz	10 Hz
Analog output	OUT 1: 0 to ± 1 V/10 m/s 8 V max	OUT 1: 0 to ± 1 V/50 $^{\circ}\text{C}$
	OUT 2: 0 to ± 1 V/full scale	OUT 2: 0 to ± 1 V/ $\pm 5^{\circ}\text{C}$
Digital output	Full scale *U: $\pm 5, \pm 10, \pm 25, \pm 50$ m/s	
	**W: $\pm 1, \pm 2, \pm 5, \pm 10$ m/s	
Operating temperature	Main unit: -10° to 40°C ,	Probe and junction box: -20° to 50°C
Power supply	AC 100/115/220 V $\pm 10\%$	50/60 Hz

* U: Horizontal component. ** W: Vertical component.

time difference can avoid the effect of atmospheric conditions such as air temperature, humidity and atmospheric pressure on wind measurement, which is the theoretically unavoidable fault in the traditional one. There is a clinometer in the pre-amplifier box beneath the probe in order to check and monitor the attitude of the probe all the time. The characteristics of the sonic anemometer are described in Table 2.

B-2. Thermocouple psychrometer.

To measure humidity fluctuations, the copper-constantan thermocouple psychrometer with a diameter of 80 m μ is attached inside of the sonic anemometer-thermometer.

The wet-bulb sensor is covered by a fine gauze thread wound at the pitch of 5 turns to 1 cm. The 90% amplitude gain in frequency response of a fine thermocouple psychrometric hygrometer (wire diameter being 0.08 mm) is about 0.4 cps at 5.0 m/s and 20°C.

The water supply to the wet bulb thermometer is carried out automatically at constant time intervals, which can be changed from 20 min. to 12 hours. The transistor thermometer

is sealed in the sensor unit for the measurement of standard temperature.

C. The data acquisition system.

All the signals from aerovane-type anemometers, resistance thermometers and capacitance hygrometers are recorded on the cassette tapes and printed out on the routine chart digitally as well as the analog chart monitorially. An example of the digital chart is shown in Fig. 6.

The signals from sonic anemometer-thermometers and fine thermocouple psychrometers are pre-processed by the component analog computing circuit with low pass filter whose cutoff frequency is 0.0073 Hz in the output side (Hanafusa (1971a, b)). The output signals are sampled by the slow speed scanner one or two times per minute per channel and recorded on the magnetic tapes in digital form with GP-1500 data acquisition system.

In addition to these data acquisition systems, a small computer whose memory is 96 kw is installed in order to gather raw data, monitor the signals and analyse the data in

METEOROLOGICAL DATA										METEOROLOGICAL TOWER, MRI									
No	DATE	TIME	ELEMENT	ARM	H E I G H T										SUB TOWER (25m)	REMARK			
					213 m DA-200	213 m FF-3R	213 m	200 m	150 m	100 m	50 m	25 m	10 m						
0282	1980 08 15	19 00	WD(deg)	C	59	70	66	74	74	74	74	70	70	62					
			WS(m/s)		13 0	11 2	11 0	9 4	9 5	8 8	6 5	5 4	4 6	6 7					
			Ta(°C)				23 1	22 2	22 4	22 4	23 9	23 5	24 2						
			Tb(°C)					22 3	22 5	23 0	24 2	23 3	24 3						
			Hc(%)				81	79	82	83	81	85	72						
			Hb(%)					87	87	84	79	87	77						
0283	1980 08 15	20 00	WD(deg)	C	61	71	70	75	76	73	75	71	71	67					
			WS(m/s)		10 2	8 5	8 2	7 0	7 3	7 0	6 2	5 0	4 0	5 0					
			Ta(°C)				21 9	20 9	21 1	21 1	22 3	22 2	22 7						
			Tb(°C)					20 7	20 9	21 8	22 8	22 1	22 7						
			Hc(%)				87	83	86	89	84	89	74						
			Hb(%)					92	92	88	83	91	82						
0284	1980 08 15	21 00	WD(deg)	C	61	68	67	73	71	69	73	66	64	64					
			WS(m/s)		10 7	8 5	8 4	7 2	7 4	6 8	6 0	4 8	4 0	5 7					
			Ta(°C)				20 7	19 8	20 0	20 0	21 2	21 1	21 8						
			Tb(°C)					19 8	20 0	20 7	21 6	21 0	21 8						
			Hc(%)				89	88	89	93	88	92	76						
			Hb(%)					96	95	91	85	94	83						
0285	1980 08 15	22 00	WD(deg)	C	63	75	73	80	82	75	67	64	64	66					
			WS(m/s)		8 8	8 0	7 6	6 8	6 9	6 1	4 8	3 6	2 9	6 0					
			Ta(°C)				20 1	19 1	19 5	19 4	20 6	20 5	21 1						
			Tb(°C)					19 1	19 4	20 1	21 0	20 4	21 2						
			Hc(%)				90	87	87	92	87	92	75						
			Hb(%)					95	94	90	85	93	83						
0286	1980 08 15	23 00	WD(deg)	C	58	71	68	71	73	68	69	71	73	63					
			WS(m/s)		9 4	7 6	7 2	6 1	5 4	4 8	4 4	3 8	3 4	3 3					
			Ta(°C)				19 9	18 8	19 2	19 1	20 3	20 2	20 7						
			Tb(°C)					18 7	19 1	19 8	20 7	20 1	20 9						
			Hc(%)				90	88	88	93	88	93	76						
			Hb(%)					96	95	91	86	94	84						
0287	1980 08 16	00 00	WD(deg)	C	62	73	71	75	77	74	69	68	66	64					
			WS(m/s)		10 1	8 6	8 2	7 0	6 9	6 2	5 0	3 8	3 3	5 4					
			Ta(°C)				19 5	18 5	18 8	18 7	19 9	19 7	20 4						
			Tb(°C)					18 3	18 7	19 4	20 3	19 7	20 3						
			Hc(%)				89	87	88	92	88	92	76						
			Hb(%)					94	94	90	85	94	84						

Fig. 6. Example of digital meteorological data sheet.

Fig. 7. Block diagram of the observation and the data acquisition system.

real time. The auto-correlation coefficient, cross correlation coefficient, and power spectrum can be computed easily in real time by this system.

The block diagram of the observational systems and data acquisition system are shown in Fig. 7.

4. Characteristics of wind speed.

The data treated in this paper consist of the average wind speed and direction observed every hour during 12 months from 1 October 1977 to 30 September 1978. The numbers of the data missing are listed in Table 3. There was no observation with aerovane at the height of 10 m in this experiment. The data present good statistical information except April's data and wind direction for a few months.

4.1 Monthly and annual relative frequency distributions.

Relative frequency distributions of the

wind speed, arithmetic mean wind, the standard deviation, skewness, and kurtosis were calculated for each level for each month and for the year.

The arithmetic mean of a set of observations is the sum of the observations divided by the number of observations. The arithmetic mean wind speed for month m at a given level is

$$V_m = \frac{1}{n_d} \sum_{d=1}^{n_d} \left(\frac{1}{24} \sum_{h=1}^{24} V_{hd} \right), \dots \dots \dots (1)$$

where V_{hd} represents the wind speed at hour h ($h=1 \sim 24$) on day d ($d=1 \sim n_d$) for month m ($m=1 \sim 12$). The number of days in a month is n_d .

Moments of the distributions will be used to describe the distributions in terms of the mean. The moments of a set of observations are defined in terms of deviations from an arbitrary origin (chosen here to be the arithmetic mean). The k -th moment about the annual arithmetic mean V_y is

Table 3. Percentage of data missing from Oct. 1977 to Sept. 1978.

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sept.	Total
213 m	W.S. 0.0(0)	0.0(0)	0.0(0)	0.0(0)	0.0(1)	0.0(0)	10.1(73)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	0.9(75)
	W.D. 0.0(0)	0.0(0)	0.0(0)	0.0(0)	0.0(1)	0.0(0)	10.0(72)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	0.9(74)
200 m	W.S. 0.0(0)	6.5(47)	0.0(0)	0.0(0)	0.0(1)	0.0(0)	10.3(74)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	1.4(123)
	W.D. 0.0(0)	0.0(0)	0.0(0)	0.0(0)	0.0(2)	0.0(0)	10.0(72)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	0.9(75)
150 m	W.S. 0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(1)	0.0(0)	10.0(72)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	0.9(75)
	W.D. 17.3(129)	13.1(94)	0.0(0)	0.0(0)	8.6(58)	0.0(0)	9.9(71)	0.0(2)	0.0(1)	0.0(0)	0.0(0)	13.0(95)	5.0(450)
100 m	W.S. 0.0(0)	0.0(0)	0.0(0)	0.0(0)	0.0(1)	0.0(0)	10.3(74)	0.0(1)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	0.9(77)
	W.D. 0.0(0)	0.0(0)	0.0(0)	0.0(0)	0.0(1)	0.0(0)	10.1(73)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	0.9(75)
50 m	W.S. 0.0(0)	23.0(168)	0.0(0)	0.0(0)	0.0(1)	5.8(43)	10.4(75)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	3.3(286)
	W.D. 1.3(10)	22.9(165)	0.0(0)	0.0(0)	0.0(3)	0.0(2)	10.0(72)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	3.0(253)
25 m	W.S. 0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(1)	5.1(38)	10.3(74)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	1.3(115)
	W.D. 0.0(0)	0.0(0)	0.0(0)	0.0(0)	0.0(1)	5.2(39)	10.1(73)	0.0(0)	0.0(1)	0.0(0)	0.0(0)	0.0(0)	1.3(114)

() : Number of missing data

W.D. Wind direction

W.S. = Wind speed

$$M_{yk} = \frac{1}{12} \sum_{m=1}^{12} \left\{ \frac{1}{n_d} \sum_{d=1}^{n_d} \left[\frac{1}{24} \sum_{h=1}^{24} (V_{hd} - V_y)^k \right] \right\}, \dots (2)$$

and the k -th moment about the monthly arithmetic mean V_m is

$$M_{mk} = \frac{1}{n_d} \sum_{d=1}^{n_d} \left[\frac{1}{24} \sum_{h=1}^{24} (V_{hd} - V_m)^k \right], \dots (3)$$

The first moment is the algebraic mean of the deviations from the mean and it becomes zero. Thus the first moment expresses the basic properties of the arithmetic mean. The second moment is the mean of the squares of the deviations and is called the variance. The square root of the second moment is called the standard deviation. The third moment is the algebraic sum of the cubes of the deviations divided by the number of observations. The third moment divided by the cube of the standard deviations is called skewness and is a measure of the symmetry of frequency distributions. The fourth moment is the mean of the fourth powers of the deviations. The fourth moment divided by the fourth powers of the standard deviation is called kurtosis, which is a measure of the relative sharpness or flatness of the frequency distributions.

The frequency distributions of the wind speed for the year (Fig. 8) show that both mean and range and the difference between the maximum and minimum values increase with height from the ground surface to the top of the tower. The vertical profile of the annual mean wind speed can be expressed approximately by 1/3 power law. The vertical profile for the annual data is shown in Fig. 9, together with the profiles by the season (Summer; June, July, August, Fall; September, October, November, Winter; December, January, February, Spring; March, April, May). Generally speaking, the seasonal means increase at all levels from summer through spring. The winter profile is nearly the same as the profile of the year and this tendency is very similar to what is obtained from Oklahoma's data (Crawford (1970)).

The ratios of the standard deviation of the annual arithmetic mean wind speed to

Fig. 8. Annual relative frequency distribution of wind speed in 1.0 m/s intervals for each level.

Fig. 9. Annual and seasonal vertical profiles of the arithmetic mean wind speed.

the annual mean wind speed are between 0.55 and 0.59, except at level 1 (25 m) where it is of 0.66. The skewness which is positive at all levels, increases gradually from 0.78 at the top of the tower to 1.67 at the ground surface level. The values of the flatness at all levels indicate that the frequency distributions are flatter than the normal curve and this value is the largest at the lowest level as shown in Fig. 10.

Monthly mean wind speeds show considerable variation from month to month as shown in Table 4 and Fig. 11. The magnitude of the variation from month to month is largest at the top of the tower. The

Fig. 10. Statistical properties of mean wind speed for one year.

Fig. 11. Variation of monthly mean wind speed.

monthly mean wind speed tended to reach a maximum during June and a minimum during July at all levels. There is no occurrence of inversion in the monthly mean wind speed. Monthly values of the ratio of the standard deviation to the mean wind speed vary from 0.46 in November at level 2 to 0.80 in February at level 6.

As shown previously, the frequency distributions of the monthly mean wind speed are fairly far from the normal distributions, and there have been some trials to apply another formula to express the frequency distributions of the mean wind speed.

In recent years, increasing attention has been paid to the development of the technique for determining the availability of the wind power resources, the versatility of the Weibull distribution (Weibull (1957)), and its wide application in meteorology and hydrology is well known. The Weibull distribution has been proposed for the analysis of intensity of destruction and is expressed generally by three parameters. In the application of this formula to the distributions of the mean wind speed, the formula can be expressed by only two parameters under the assumption that the frequency of zero wind speed is zero.

The Weibull distribution for wind speed V is expressed by the probability density function (wind speed frequency curve)

$$P(V)dV = (k/C)(V/C)^{k-1} \cdot \exp(-(V/C)^k)dV, \dots\dots(4)$$

Table 4. Arithmetic wind speed, standard deviation of the arithmetic mean wind, skewness and kurtosis of the monthly and annual relative frequency distributions of wind speed.

(a) Arithmetic mean wind speed (m/s)

Level	month Height	10	11	12	1	2	3	4	5	6	7	8	9	Mean
	(m)													
6	213	5.30	6.26	5.51	6.31	6.86	6.65	6.80	5.73	7.16	4.91	6.30	5.55	6.09
5	200	5.24	6.18	5.18	6.02	6.57	6.42	6.58	5.43	6.77	4.68	5.96	5.39	5.85
4	150	4.96	5.68	4.98	5.54	6.10	5.99	6.08	5.17	6.41	4.48	5.60	5.12	5.49
3	100	4.35	4.96	4.46	4.75	5.35	5.23	5.30	4.59	5.71	3.96	5.00	4.41	4.83
2	50	3.45	3.71	3.53	3.72	4.52	4.23	4.26	3.81	4.83	3.25	4.21	3.43	3.90
1	25	2.66	2.99	2.73	3.03	3.46	3.16	3.51	3.22	4.20	2.61	3.46	2.79	3.14

(b) Standard deviation of the arithmetic mean wind speed (m/s)

Level	month Height	10	11	12	1	2	3	4	5	6	7	8	9	Mean
	(m)													
6	213	2.77	3.28	3.75	4.13	3.89	4.02	3.98	2.90	4.04	2.46	3.94	2.76	3.59
5	200	2.74	3.22	3.46	3.82	3.62	3.76	3.94	2.58	3.75	2.23	3.67	2.61	3.38
4	150	2.49	2.88	3.15	3.46	3.33	3.44	3.61	2.42	3.52	2.05	3.42	2.39	3.10
3	100	2.04	2.38	2.67	3.00	2.84	2.94	3.16	2.13	3.19	1.80	3.00	2.07	2.68
2	50	1.51	1.71	2.11	2.47	2.49	2.25	2.83	1.84	2.93	1.58	2.72	1.58	2.27
1	25	1.26	1.62	1.82	2.41	2.13	1.92	2.54	1.78	2.75	1.48	2.60	1.57	2.08

(c) Skewness of the frequency distribution of wind speed

Level	month Height	10	11	12	1	2	3	4	5	6	7	8	9	Mean
	(m)													
6	213	0.53	0.46	1.28	1.04	0.61	1.13	1.08	0.40	0.55	0.21	0.77	0.29	0.78
5	200	0.48	0.32	1.20	0.99	0.58	1.02	1.12	0.32	0.55	0.09	0.74	0.22	0.94
4	150	0.38	0.32	1.13	1.02	0.65	0.99	1.07	0.45	0.63	0.05	0.80	0.21	0.90
3	100	0.28	0.35	1.07	1.04	0.81	1.12	1.21	0.44	0.77	0.07	0.94	0.19	1.00
2	50	0.27	0.64	1.32	1.20	1.02	0.61	1.41	0.61	0.94	0.39	1.14	0.59	1.24
1	25	0.71	1.31	2.23	1.74	1.57	1.32	1.92	1.19	0.97	0.67	1.28	1.06	1.67

(d) Kurtosis of the frequency distribution of wind speed

Level	month Height	10	11	12	1	2	3	4	5	6	7	8	9	Mean
	(m)													
6	213	2.71	2.69	4.39	3.73	2.97	4.76	4.41	2.93	3.07	2.38	3.34	2.70	4.16
5	200	2.59	2.41	4.25	3.68	3.01	4.53	4.67	2.95	3.16	2.33	3.31	2.62	4.13
4	150	2.53	2.54	4.19	3.76	3.18	4.64	4.56	3.26	3.39	2.40	3.58	2.69	4.25
3	100	2.41	2.92	4.23	3.88	3.85	5.29	5.11	3.29	3.69	2.46	4.07	2.85	4.78
2	50	2.69	4.15	5.30	4.54	4.79	3.52	5.76	3.30	3.80	2.89	4.46	3.42	5.64
1	25	3.43	5.52	6.93	6.14	6.64	5.48	7.26	5.48	3.62	3.03	4.54	4.63	6.92

where C is the scale factor (units of speed) and k , the shape factor (dimensionless). The equivalent cumulative probability function (wind speed duration curve) is

$$P(V \leq V_x) = \int_0^{V_x} P(V) dV \\ = 1 - \exp[-(V_x/C)^k] \dots (5)$$

Accordingly, the mean wind speed, $\bar{V}$, and the variance of the wind speed, σ_V^2 , can be expressed as follows by using Γ function:

$$\text{Mean: } \bar{V} = \int_0^\infty V P(V) dV \\ = C \Gamma\left(1 + \frac{1}{k}\right) \dots (6)$$

$$\text{Variance: } \sigma_V^2 = \int_0^\infty V^2 P(V) dV - \bar{V}^2 \\ = C^2 \left[\Gamma\left(1 + \frac{2}{k}\right) - \left\{ \Gamma\left(1 + \frac{1}{k}\right) \right\}^2 \right] \dots (7)$$

After all, it is very useful to determine the parameters of C and k . The relation between V/C and k is shown in Fig. 12. Roughly speaking, the value of C is greater

Fig. 12. Relation between V/C and K in the Weibull distribution.

than the value of $\bar{V}$ by about 10%.

In order to estimate two parameters of C and k by using observed wind data, the methods of maximum likelihood or of fitting the Weibull curve to a cumulative distribution function are often used. In this study, the simplest method which used the Weibull distribution chart was carried out as follows: First, a cumulative frequency of mean wind speed is plotted on the Weibull chart and the value of C corresponding to the value of 63.2% of all data can be read on the Weibull chart as shown in Fig. 13. Then the value

Fig. 13. An example of estimation of C on the Weibull chart.

of $P(V_x \leq 1.0)$, which corresponds to the accumulative frequency of 1 m/sec, can be read out. Finally, the value of k can be estimated by the following equation:

$$k = -\ln[-\ln\{1 - P(V \leq V_x)\}] / \ln C \dots (8)$$

The results of computation are shown in Table 5 and Fig. 14 for each month at each level. The vertical profiles of C for each month are very similar to the wind profile and the maximum value can be found in June. The values of C range from 5.2 to 7.8 at the top of the tower and 2.4 to 4.2 at the lowest level.

On the other hand, the annual means of k at all levels are almost the same value of 1.7 though monthly variations of k are very large. The value is nearly equal to the standard value in Japan (Mitsuta et al. (1979)). As for the variation of k with

Table 5. Monthly values of k and C in the Weibull distribution.

Month \ Height	213 m		200 m		150 m		100 m		50 m		25 m	
	C	K	C	K	G	K	C	K	C	K	C	K
10	5.3	1.84	5.4	1.76	5.2	1.94	4.5	1.91	3.5	2.10	2.5	2.71
11	6.5	1.65	6.6	1.63	6.0	1.63	5.2	2.02	3.8	2.22	2.8	1.83
12	5.4	1.60	5.0	1.63	4.9	1.75	4.5	1.65	3.1	1.82	2.4	1.92
1	6.2	1.53	6.0	1.51	5.5	1.50	4.8	1.43	3.7	1.44	2.5	1.21
2	7.3	1.68	6.9	1.72	6.2	1.69	5.5	1.95	4.7	1.79	3.5	1.58
3	7.0	1.52	6.7	1.62	6.1	1.65	5.3	1.84	4.3	1.79	3.0	1.53
4	6.8	1.74	6.5	1.88	6.2	1.75	5.3	1.78	4.2	1.49	3.3	1.47
5	6.2	1.92	5.6	1.92	5.4	1.96	4.8	2.11	3.6	2.05	3.2	1.63
6	7.8	1.50	7.5	1.48	6.8	1.55	5.8	1.69	4.8	1.50	4.2	1.37
7	5.2	1.87	4.8	1.89	4.4	2.08	4.0	1.88	3.4	1.76	2.4	1.42
8	6.2	1.44	6.0	1.39	5.8	1.41	5.2	1.52	4.2	1.43	3.2	1.11
9	6.2	1.63	5.5	2.05	5.2	1.94	5.0	1.73	3.4	2.28	2.7	1.58
Mean	6.3	1.66	6.0	1.71	5.6	1.74	5.0	1.79	3.9	1.81	3.0	1.61

Fig. 14. Monthly variation of k and C in the Weibull distribution.

height, the smallest value can be found at the top of the tower and at the lowest level (25 m).

The values of wind speed and standard deviation of mean wind speed estimated by using equations (6) and (7) are compared with real raw data, and the results are shown in Figs. 15 and 16, respectively. From Fig. 15,

Fig. 15. Comparison of the mean wind speeds estimated by the Weibull distribution with those obtained by real raw data.

we can see the observed mean wind speeds are somewhat larger than the calculated ones, that is, by about 10%. Fig. 16 shows that there is a linear relation between the calculated standard deviation of the mean wind speed and the measured ones, though the points scatter over a fairly wide range.

Fig. 16. Same as Fig. 15, but for the standard deviations.

4.2 Change of the wind speed with time.

The annual mean diurnal change of the wind speed is shown in Fig. 17, where it is found that the occurrence time of the maximum wind speed is progressively late with the height of measurement level. The time change of the wind speed is examined by

Fig. 17. Annual mean diurnal change of wind speed.

the hourly data on each month and summarized in Tables 6a and 6b. The largest magnitude of wind speed variations can be found at the top of the tower and then it becomes smaller gradually with the decrease of the height of measurement. These tables roughly show that the difference of occurrence times of the maximum speed between the top of the tower and the lowest level is larger in winter than in summer. In order to investigate this phenomenon more quantitatively, harmonic analysis has been carried out for the monthly mean wind data.

One may calculate the finite version of a Fourier series which will pass through these N data values ($N=24$ in our case). For any point t in the interval $(0, 23 \text{ hour})$, the mean wind speed $V(t)$ can be expressed by the finite trigonometrical series with the coefficients of A_k and B_k as follows:

$$V(t) = A_0/2 + \sum_{k=1}^{N/2} A_k \cos\left(\frac{2\pi kt}{N}\right) + \sum_{k=1}^{N/2-1} B_k \sin\left(\frac{2\pi kt}{N}\right). \quad \dots\dots\dots (9)$$

At the particular points $t=n$; $n=1, 2, \dots, 24$, where $T_p=24$,

$$V_n = A_0/2 - \sum_{k=1}^{N/2} A_k \cos\left(\frac{2\pi kn}{N}\right) + \sum_{k=1}^{N/2-1} B_k \sin\left(\frac{2\pi kn}{N}\right). \quad \dots\dots\dots (10)$$

The coefficients A_k and B_k are given by

$$\left. \begin{aligned} A_k &= \frac{2}{N} \sum_{n=1}^N V_n \cos \frac{2\pi kn}{N} \\ B_k &= \frac{2}{N} \sum_{n=1}^N V_n \sin \frac{2\pi kn}{N} \end{aligned} \right\} \begin{aligned} k &= 1, 2, \dots, \frac{N}{2}-1 \end{aligned} \quad \dots\dots\dots (11)$$

The equation (10) can be rewritten by the following simple form:

Table 6. Change of monthly mean wind speed with time.

	Height	Time																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
October	213	5.58	5.42	5.55	5.21	5.16	4.96	5.32	5.13	4.42	4.35	3.79	3.56	3.99	3.93	4.59	5.19	5.55	6.40	6.72	7.00	6.62	6.57	5.97	6.17
	200	5.52	5.35	5.52	5.13	5.10	5.06	5.33	5.05	4.33	4.24	3.75	3.54	3.94	3.90	4.58	5.17	5.47	6.32	6.55	6.83	6.46	6.49	5.91	6.10
	150	5.24	5.07	5.25	4.87	4.88	4.92	4.76	4.72	3.97	3.91	3.55	3.36	3.81	3.78	4.48	5.07	5.31	5.98	6.13	6.43	5.96	6.05	5.68	5.82
	100	4.57	4.44	4.73	4.17	4.20	3.97	3.94	4.11	3.51	3.41	3.25	3.18	3.50	3.47	4.21	4.63	4.89	5.22	5.08	5.40	5.00	5.15	5.21	5.08
	50	3.55	3.81	4.08	3.40	3.38	3.14	3.37	3.39	2.56	2.70	2.78	2.79	2.92	2.89	3.69	3.93	3.93	3.94	3.52	3.77	3.63	3.80	3.92	3.86
	25	2.45	2.50	2.48	2.20	2.24	2.36	2.55	2.51	2.21	2.44	2.65	2.49	3.00	2.66	3.34	3.35	3.22	3.10	2.72	2.74	2.56	2.70	2.79	2.62
November	213	6.45	6.51	5.73	5.87	6.08	5.69	6.28	5.93	5.85	5.71	5.10	4.51	4.96	5.30	5.90	6.71	6.98	7.25	7.03	7.81	7.75	7.44	6.90	6.41
	200	6.63	6.53	5.61	5.66	6.12	5.63	6.17	5.84	5.63	5.39	4.86	4.63	4.85	5.07	5.71	6.52	6.89	6.95	6.88	7.63	7.60	7.32	7.10	6.57
	150	5.95	6.03	5.11	5.37	5.39	5.10	5.40	4.96	4.98	4.88	4.48	4.26	4.61	4.91	5.56	6.30	6.38	6.55	6.42	7.24	6.96	6.82	6.48	6.26
	100	5.38	5.11	4.52	4.68	4.64	4.50	4.47	3.87	3.98	3.91	3.87	4.02	4.24	4.45	5.21	5.67	5.69	5.74	5.68	6.29	5.88	6.03	5.60	5.56
	50	3.83	3.75	3.43	3.56	3.85	3.47	3.22	3.06	2.79	3.20	3.56	3.50	3.90	3.76	4.31	4.36	4.00	3.84	3.87	4.21	4.01	4.05	3.92	3.70
	25	2.78	2.65	2.38	2.37	2.43	2.19	2.46	2.16	2.24	2.72	3.13	3.20	3.38	3.60	4.06	3.98	3.63	3.35	3.14	3.43	3.02	3.37	3.16	2.95
December	213	6.40	5.83	6.10	5.77	5.48	5.36	5.26	4.98	5.02	4.86	4.63	4.72	4.45	4.67	5.12	5.38	5.61	5.67	6.17	6.09	5.92	5.90	6.21	6.55
	200	6.07	5.50	5.71	5.31	5.09	5.01	4.96	4.75	4.69	4.45	4.22	4.22	4.29	4.37	4.74	5.13	5.37	5.39	5.84	5.75	5.52	5.69	5.96	6.25
	150	5.96	5.34	5.55	5.21	4.84	4.82	4.78	4.56	4.64	4.35	4.04	4.09	4.06	4.05	4.65	4.97	5.10	5.07	5.46	5.40	5.28	5.54	5.71	5.96
	100	5.55	4.83	5.02	4.56	4.39	4.12	4.33	4.35	4.50	3.81	3.42	3.43	3.72	3.75	4.25	4.43	4.47	4.44	4.73	4.79	4.66	5.05	5.25	5.21
	50	4.06	3.63	3.85	3.44	3.79	3.58	3.53	3.62	3.18	2.52	2.96	3.19	3.16	3.25	3.64	3.86	3.66	3.46	3.52	3.45	3.59	3.91	4.14	3.77
	25	2.75	2.57	2.65	2.47	2.55	2.38	2.28	2.24	1.95	2.06	2.61	3.10	3.11	3.27	3.45	3.45	2.88	2.77	2.69	2.72	2.86	2.71	3.02	2.85
January	213	7.07	6.36	6.63	6.16	6.26	6.72	6.75	6.37	6.09	5.89	6.09	5.54	5.73	6.36	6.25	6.22	6.30	6.03	6.49	6.43	6.23	6.26	6.49	6.86
	200	6.76	6.06	6.36	5.83	6.03	6.64	6.51	6.05	5.82	5.64	5.65	5.28	5.40	6.05	5.95	5.90	5.95	5.77	6.32	6.20	5.81	5.89	6.11	6.46
	150	6.20	5.52	5.50	5.20	5.59	6.05	5.93	5.54	5.17	5.37	5.12	4.86	5.11	5.63	5.71	5.66	5.37	5.45	5.75	5.66	5.15	5.32	5.93	6.03
	100	5.32	4.65	4.64	4.78	4.72	5.05	4.86	4.83	4.58	4.58	4.22	4.19	4.58	5.03	5.12	4.94	4.70	4.61	4.73	4.64	4.39	4.55	5.12	5.12
	50	4.13	3.48	3.68	3.72	3.51	3.60	3.57	3.60	3.17	3.27	3.25	3.52	4.04	4.35	4.44	4.06	3.93	3.75	3.91	3.82	3.40	3.50	3.87	3.80
	25	3.06	2.58	2.60	2.64	2.57	2.50	2.59	2.34	2.33	2.85	2.96	3.57	3.57	4.01	4.41	4.03	3.64	3.26	3.29	2.79	2.82	2.75	3.00	2.84
February	213	8.07	8.05	7.92	7.72	7.32	7.60	7.10	6.77	6.70	5.40	4.49	5.33	5.30	6.24	6.39	6.33	6.66	6.76	7.56	7.28	7.13	6.90	7.57	7.89
	200	7.61	7.50	7.52	7.36	7.02	7.31	6.78	6.45	6.38	5.13	4.28	5.11	5.11	6.01	6.21	6.24	6.45	6.50	7.35	7.07	6.98	6.60	7.15	7.39
	150	7.17	6.92	6.96	6.79	6.52	6.79	6.25	5.74	5.60	4.65	4.01	4.75	4.91	5.81	6.07	6.04	6.19	6.14	6.72	6.45	6.50	6.09	6.68	6.67
	100	6.25	5.89	5.79	5.63	5.42	5.81	5.38	4.83	4.65	3.97	3.77	4.36	4.54	4.46	5.67	5.65	5.79	5.54	5.79	5.62	5.67	5.22	5.79	5.87
	50	4.97	4.57	4.34	4.19	4.19	4.71	4.35	3.91	3.41	3.47	3.53	4.05	4.38	5.36	5.27	5.10	5.49	4.89	4.92	4.84	4.68	4.29	4.67	4.78
	25	3.42	3.34	3.35	2.73	2.66	3.05	2.80	2.56	2.56	3.08	3.12	3.88	3.79	4.63	4.92	4.87	4.73	3.90	3.61	3.24	3.25	3.09	3.19	3.25
March	213	7.40	7.39	7.34	6.75	6.66	6.66	6.78	6.76	6.24	5.37	5.43	6.03	6.06	5.96	5.95	6.12	6.59	6.48	7.15	7.39	7.57	7.66	7.00	6.90
	200	7.12	7.06	6.98	6.40	6.29	6.20	6.42	6.33	5.94	5.18	5.28	5.95	6.01	5.85	5.80	6.00	6.42	6.41	6.98	7.24	7.40	7.35	6.80	6.70
	150	6.44	6.65	6.32	5.69	5.66	5.52	6.05	5.78	5.45	4.65	5.12	5.75	5.72	5.76	5.61	5.84	6.33	6.10	6.60	6.74	6.72	6.55	6.47	6.36
	100	5.28	5.71	5.29	4.65	4.62	4.65	5.10	4.80	4.56	4.25	4.72	5.25	5.25	5.41	5.31	5.53	5.94	5.53	5.73	5.90	5.63	5.39	5.60	5.43
	50	4.44	4.43	4.14	3.51	3.58	3.58	3.55	3.48	3.61	3.70	4.07	4.35	4.20	4.46	4.43	4.95	5.44	4.79	4.63	4.65	4.58	4.13	4.35	4.41
	25	3.03	2.83	2.73	2.23	2.20	2.33	2.34	2.22	2.64	3.12	3.61	4.07	4.03	4.28	3.92	4.13	4.49	3.47	3.14	3.07	3.15	2.79	3.07	2.87

Table 6. Continued.

	Height	Time																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
April	213	6.66	6.17	6.21	6.98	6.26	6.33	6.28	6.22	5.22	5.22	5.58	6.08	6.28	7.03	6.58	7.50	7.59	7.57	8.11	8.34	8.53	7.82	7.60	7.02
	200	6.55	6.04	6.13	6.77	6.05	6.04	6.00	5.87	4.91	4.99	5.43	5.93	6.22	6.83	6.80	7.28	7.46	7.29	7.80	7.98	8.12	7.27	7.34	6.80
	150	5.81	5.53	5.83	6.15	5.44	5.53	5.35	5.07	4.19	4.49	5.23	5.77	5.89	6.41	6.59	7.00	7.14	6.76	7.19	7.34	7.55	6.69	6.64	6.34
	100	4.71	4.81	4.87	5.10	4.39	4.45	4.58	3.96	3.49	4.06	4.95	5.44	5.57	5.96	6.23	6.50	6.55	6.11	6.25	6.27	6.28	5.61	5.66	5.50
	50	3.53	3.40	3.56	3.53	3.19	3.31	3.18	2.73	2.92	3.45	4.50	4.57	4.84	5.36	5.59	6.04	5.70	5.49	5.35	5.20	4.79	4.24	4.04	3.78
	25	2.51	2.37	2.43	2.53	2.36	2.47	2.33	2.09	2.63	3.33	4.00	4.27	4.61	4.96	5.39	5.39	5.10	5.06	4.41	3.76	3.46	3.03	3.06	2.83
May	213	5.04	5.26	5.44	5.84	5.74	5.50	5.42	5.29	4.94	4.43	4.82	4.73	5.16	5.19	5.83	6.18	6.45	6.92	6.95	7.09	6.73	6.45	6.34	5.68
	200	4.74	4.94	5.17	5.39	5.39	5.15	5.11	4.95	4.66	4.28	4.65	4.57	4.99	4.98	5.44	5.89	6.27	6.65	6.67	6.83	6.34	6.00	5.88	5.30
	150	4.49	4.60	4.90	5.11	5.01	4.70	4.89	4.45	4.54	4.25	4.58	4.49	4.94	5.02	5.40	5.64	6.27	6.52	6.27	6.32	5.85	5.58	5.36	4.84
	100	4.05	4.10	4.42	4.55	4.51	4.11	4.02	3.61	4.00	3.93	4.26	4.18	4.61	4.81	4.99	5.25	5.89	6.09	5.60	5.15	4.64	4.87	4.50	4.10
	50	3.12	3.28	3.41	3.59	3.32	3.19	3.05	2.87	3.56	3.41	3.75	3.79	4.06	4.45	4.65	4.85	5.26	5.30	4.74	4.09	3.62	3.72	3.35	3.04
	25	2.39	2.68	2.56	2.67	2.42	2.49	2.37	2.61	3.11	3.22	3.48	3.62	3.63	4.05	4.28	4.28	4.66	4.44	3.75	3.36	3.13	3.00	2.58	2.40
June	213	7.43	7.17	6.65	6.54	6.69	6.32	6.05	5.86	5.78	5.92	5.88	6.11	6.96	7.46	7.99	8.50	8.52	8.41	8.70	8.47	7.67	7.56	7.56	7.55
	200	6.98	6.73	6.25	6.19	6.30	5.92	5.63	5.51	5.49	5.69	5.59	5.89	6.62	7.21	7.71	8.11	8.13	7.90	8.17	7.85	7.20	7.04	7.13	7.14
	150	6.17	6.33	5.83	5.75	5.79	5.33	5.18	4.99	5.16	5.44	5.38	5.84	6.51	7.16	7.66	7.98	7.92	7.65	7.81	7.30	6.73	6.57	6.70	6.59
	100	5.21	5.54	4.90	4.92	5.04	4.48	4.45	4.31	4.58	5.01	4.95	5.52	6.12	6.77	7.11	7.53	7.45	7.15	7.01	6.26	5.82	5.62	5.78	5.62
	50	4.14	4.19	3.60	3.76	3.86	3.69	3.47	3.62	3.96	4.40	4.49	5.06	5.66	6.14	6.48	6.88	6.64	6.38	5.99	5.10	4.65	4.46	4.66	4.60
	25	3.37	3.21	3.03	3.09	2.98	2.99	2.84	3.31	3.45	4.07	4.16	4.87	5.10	5.56	5.73	6.62	6.11	5.79	4.99	4.17	3.84	3.78	3.97	3.86
July	213	5.65	5.18	4.86	4.59	4.56	4.04	3.86	2.97	2.66	2.84	3.34	4.03	4.16	4.38	4.89	5.35	5.49	5.93	6.30	6.99	7.03	6.45	6.34	5.98
	200	5.22	4.88	4.56	4.27	4.30	3.90	3.68	2.78	2.54	2.80	3.30	3.96	4.12	4.28	4.77	5.26	5.33	5.70	6.00	6.62	6.61	6.04	5.93	5.58
	150	4.71	4.46	4.16	3.85	3.93	3.71	3.60	2.54	2.50	2.69	3.22	3.92	4.11	4.38	4.75	5.35	5.34	5.71	5.87	6.27	6.19	5.59	5.51	5.11
	100	3.95	3.69	3.45	3.27	3.23	3.11	3.04	2.10	2.40	2.60	2.95	3.69	3.95	4.22	4.55	5.11	5.12	5.43	5.46	5.46	5.22	4.62	4.44	4.07
	50	2.89	2.46	2.57	2.24	2.29	2.34	2.02	1.85	2.25	2.39	2.78	3.38	3.48	3.95	4.29	4.71	4.72	4.89	4.72	4.29	3.99	3.42	3.07	2.97
	25	1.96	1.56	1.60	1.51	1.53	1.51	1.55	1.75	2.12	2.25	2.63	3.07	3.13	3.43	3.89	3.95	4.10	4.12	3.78	3.31	3.12	2.43	2.21	2.13
August	213	6.34	6.00	5.75	5.49	5.56	5.08	5.16	4.81	4.05	4.08	4.60	5.13	5.50	6.21	6.80	7.36	7.86	8.35	8.48	8.28	8.25	7.93	7.28	6.83
	200	5.91	5.67	5.44	5.16	5.25	4.81	4.89	4.57	3.82	4.01	4.45	4.94	5.29	5.93	6.53	7.16	7.54	7.93	7.96	7.74	7.68	7.35	6.73	6.29
	150	5.24	5.08	4.86	4.63	4.79	4.49	4.63	4.14	3.47	3.90	4.32	4.94	5.24	5.90	6.42	7.13	7.47	7.81	7.56	7.21	6.96	6.68	6.03	5.59
	100	4.53	4.14	4.11	4.15	4.18	3.89	4.02	3.42	3.17	3.69	4.11	4.69	4.98	5.58	6.06	6.69	7.03	7.22	6.74	6.22	5.89	5.55	4.99	4.88
	50	3.60	3.06	3.12	3.23	3.18	2.85	3.13	2.62	2.87	3.41	3.84	4.32	4.63	5.14	5.62	6.26	6.46	6.39	5.63	5.04	4.62	4.30	3.84	3.79
	25	2.67	2.42	2.32	2.36	2.19	2.04	2.11	2.12	2.56	3.07	3.29	3.59	4.22	4.77	5.16	5.65	5.64	5.61	4.85	4.08	3.56	3.20	2.91	2.72
September	213	5.41	5.30	5.63	5.37	5.19	5.31	5.55	5.84	5.55	4.85	4.65	4.64	5.14	5.35	5.63	5.81	5.69	5.69	6.55	6.58	6.51	6.03	5.57	5.47
	200	5.20	5.13	5.51	5.28	5.08	5.05	5.36	5.58	5.33	4.66	4.51	4.63	5.00	5.19	5.53	5.66	5.51	5.47	6.37	6.44	6.28	5.79	5.39	5.32
	150	5.13	4.90	5.22	5.01	4.65	4.56	4.98	5.09	4.98	4.41	4.41	4.52	4.78	5.03	5.41	5.56	5.34	5.28	6.04	6.05	5.81	5.38	5.08	5.18
	100	4.38	4.12	4.32	4.18	3.92	3.83	4.09	4.07	4.03	3.81	3.79	4.19	4.35	4.59	5.03	5.07	4.84	4.75	5.16	5.11	4.82	4.48	4.40	4.44
	50	3.25	3.02	3.25	3.02	2.89	2.92	2.94	2.92	2.97	3.07	3.21	3.60	3.76	3.91	4.41	4.34	4.12	3.75	4.02	3.71	3.42	3.12	3.27	3.40
	25	2.32	2.06	2.26	2.32	2.18	2.11	2.15	2.24	2.63	2.88	2.93	3.36	3.71	3.85	3.98	3.67	3.83	3.20	3.14	2.67	2.46	2.23	2.32	2.46

Table 7. Harmonic analysis of annual mean time change of wind speed.

Height	$A_0/2$	a_1	a_2	a_3	$\phi_1(^{\circ})$
213(m)	6.09	0.95	0.31	0.07	307
200	5.85	0.91	0.29	0.07	305
150	5.49	0.86	0.26	0.07	295
100	4.83	0.77	0.24	0.06	280
50	3.90	0.74	0.29	0.06	252
25	3.14	0.93	0.30	0.07	229

$$V_n = \frac{A_0}{2} + \sum_{k=1}^{N/2-1} a_k \cos\left(\frac{2\pi kn}{N} + \phi_k\right) + \frac{a_{N/2}}{2} \cos \frac{2\pi kn}{2}, \quad \dots (12)$$

where $a_k = \sqrt{A_k^2 + B_k^2}$, $\phi_k = \tan^{-1} \frac{B_k}{A_k}$

The calculated results for annual mean wind speed is shown in Table 7. The am-

plitude of the first harmonic component and the ratios of the second harmonic and third harmonic ones to the first one for 213 m height wind data are plotted in Fig. 18.

From these results, the time variations of wind speed are almost nearly simulated by the first harmonic component. Accordingly, the change of wind speed with time can be assumed to be expressed as follows:

$$V_n = A_0/2 + \sqrt{A_1^2 + B_1^2} \cos(2\pi ft + \phi_1). \quad \dots (13)$$

ϕ_1 are plotted against the measuring height as shown in Fig. 19. It is found that ϕ_1 changes almost linearly with $\log z$. The time variations of wind speed for every month are shown in Fig. 20, where we find considerable month to month variations.

Harmonic analysis was carried out for the time variation of wind speed for every

Fig. 18. Comparison of the amplitude of the first term and ratios of the second and third ones to the first one for 213 m height annual mean wind data.

— first term (a_1)
 - - - a_2/a_1
 - · - a_3/a_1

Fig. 19. Dependency of ϕ_1 on height for annual mean wind data.

Table 8. Harmonic analysis of monthly mean time change of wind speed.

Year	Month	Height (m)	$A_0/2$	First harmonic component		a_2	a_3	Year	Month	Height (m)	$A_0/2$	First harmonic component		a_2	a_3
				a_1	ϕ_1							a_1	ϕ_1		
1977	Oct.	213	5.30	1.19	319	0.61	0.07	1978	Apr.	213	6.80	1.15	289	0.35	0.33
		200	5.24	1.16	320	0.59	0.07			200	6.58	1.11	287	0.30	0.30
		150	4.96	1.10	318	0.49	0.07			150	6.08	1.12	280	0.28	0.32
		100	4.35	0.90	312	0.28	0.13			100	5.39	1.11	262	0.29	0.24
		50	3.45	0.51	316	0.23	0.23			50	4.26	1.32	241	0.34	0.15
	Nov.	25	2.66	0.37	239	0.13	0.14			25	3.51	1.49	224	0.40	0.04
		213	6.26	0.99	307	0.58	0.18		May	213	5.73	0.86	291	0.54	0.16
		200	6.18	1.05	312	0.51	0.22			200	5.43	0.83	285	0.53	0.14
		150	5.68	1.07	304	0.37	0.16			150	5.17	0.78	272	0.47	0.12
		100	4.96	1.03	297	0.20	0.12			100	4.59	0.72	257	0.42	0.14
	Dec.	50	3.71	0.43	275	0.19	0.15			50	3.81	0.85	234	0.41	0.17
		25	2.99	0.70	241	0.22	0.22			25	3.22	0.95	220	0.25	0.16
		213	5.50	0.80	335	0.08	0.15		Jun.	213	7.16	1.25	277	0.42	0.11
		200	5.18	0.81	332	0.09	0.17			200	6.77	1.17	275	0.41	0.13
		150	4.98	0.78	336	0.05	0.20			150	6.41	1.23	263	0.45	0.10
		100	4.46	0.70	340	0.02	0.26			100	5.71	1.28	249	0.49	0.12
		50	3.53	0.36	336	0.15	0.22			50	4.83	1.40	235	0.45	0.17
1978	Jan.	25	2.73	0.37	250	0.81	0.18			25	4.20	1.45	226	0.42	0.24
		213	6.32	0.31	359	0.08	0.20		Jul.	213	4.91	1.73	302	0.10	0.30
		200	6.02	0.31	6	0.14	0.19			200	4.68	1.59	298	0.11	0.28
		150	5.54	0.22	353	0.10	0.26			150	4.48	1.50	289	0.18	0.25
		100	4.75	0.12	352	0.14	0.27			100	3.96	1.36	274	0.26	0.16
	Feb.	50	3.72	0.23	254	0.27	0.17			50	3.25	1.31	251	0.29	0.08
		25	3.03	0.64	225	0.41	0.16			25	2.61	1.27	234	0.18	0.09
		213	6.86	1.16	356	0.44	0.22		Aug.	213	6.30	1.89	286	0.44	0.15
		200	6.57	1.06	353	0.48	0.19			200	5.96	1.74	282	0.43	0.12
		150	6.10	0.93	346	0.51	0.20			150	5.60	1.68	271	0.49	0.09
		100	5.35	0.67	328	0.47	0.24			100	5.00	1.56	260	0.50	0.03
		50	4.52	0.55	277	0.43	0.25			50	4.21	1.58	244	0.47	0.09
	Mar.	25	3.46	0.77	221	0.54	0.18			25	3.46	1.63	235	0.46	0.18
		213	6.65	0.80	342	0.17	0.09		Sep.	213	5.56	0.49	297	0.38	0.08
		200	6.42	0.76	331	0.12	0.10			200	5.39	0.48	295	0.34	0.08
		150	5.99	0.65	316	0.04	0.04			150	5.12	0.50	287	0.22	0.02
		100	5.23	0.55	282	0.10	0.03			100	4.41	0.53	274	0.15	0.04
		50	4.23	0.63	263	0.18	0.17			50	3.43	0.58	237	0.24	0.05
		25	3.16	0.84	212	0.40	0.06			25	2.79	0.82	210	0.30	0.04

$$x_n = \frac{A_0}{2} + \sum_{k=1}^{N/2-1} \left[A_k \cos \frac{2\pi kn}{N} + B_k \sin \frac{2\pi kn}{N} \right] + A_N/2 \cos \frac{2\pi(N/2)n}{2},$$

$$a_1 = \sqrt{A_1^2 + B_1^2} \quad \phi_1 = \tan^{-1} \frac{B_1}{A_1} \quad a_2 = \sqrt{A_2^2 + B_2^2} \quad a_3 = \sqrt{A_3^2 + B_3^2}$$

Fig. 20. Monthly mean time change of wind speed.

month and the values of $A_0/2$, a_1 , a_2 , a_3 and ϕ_1 are listed in Table 8. The amplitudes of each harmonic component and the relative ratios for 213 m height wind data are shown in Fig. 21. From these results, roughly speaking, the relative ratio is a little larger in the lower atmosphere in cold seasons than in warm seasons. The values of ϕ_1 are plotted against $\log z$ in Fig. 22. This figure shows that the values of ϕ_1 are almost linear against $\log z$ in warm seasons, though they are nearly constant with height higher than 50–100 m in cold seasons (except February and March). This fact may indicate that in a warm period the planetary boundary layer lower than about 200 m can be considered as one layer on the whole but in a cold period, the layer below 200 m must be divided into two layers which have different characteristics from each other in modeling the atmospheric boundary layer.

5. Characteristics of wind direction.

5.1 Monthly and relative frequency distribution.

The annual frequency distribution of the wind direction in 22.5° intervals (Fig. 23) has three peaks, which are ENE, SSW (except S at 25 m level) and NW. This tendency is closely similar to the climatological distribution of the wind direction obtained at the Tateno Aerological Observatory as shown in Fig. 24. This may confirm that the direction in which the three instrumental booms are placed is very suitable for routine meteorological observation.

The seasonal variations of the wind direction are shown in Fig. 25. The outlines of characteristics of seasonal variation in the wind direction can be deduced as follows: The dominant wind direction changes from northeasterly in fall to northwesterly while there is a large peak accounting for more

Fig. 21. Same as Fig. 18, but for monthly mean wind.

Fig. 22. Dependency of ϕ_1 on height for monthly mean wind data.

Fig. 23. Annual frequency distribution of wind direction.

than 25% of all the occurrences around the southern direction in summer.

Fig. 24. Climatological wind direction distribution at the Tateno Aerological Observatory.

5.2 Hourly change of the wind direction.

The hourly change of the wind direction was examined at 22.5° intervals. The hourly changes of the annual mean frequency distribution of the highest level (213 m) and the lowest level (25 m) are shown in Fig. 26. Three peaks can be found for every hour, though the NW peak is relatively small at 18 h and 21 h. The difference of the distribution of the wind direction between the two heights is relatively small in the daytime than at night. This may indicate that the mixing in the boundary layer is more active in the daytime than at night.

The hourly changes of the seasonal mean frequency distribution of the wind direction are shown in Fig. 27. This figure shows that there is no remarkable difference among the hourly variations of the wind direction of the four seasons, except that the number for

Fig. 25-1.

Fig. 25-2.

Fig. 25. Seasonal variations of wind direction.

Fig. 26. Change of wind direction with time for 213 m and 25 m heights.

— 213 m, 25 m.

the NW wind direction increases in early morning in fall.

6. Characteristics of vector wind.

South-north and east-west components of vector wind are calculated by using the following relations:

$$\text{East-west component } U_{EW} = U \sin \theta$$

$$\text{South-north component } U_{SN} = U \cos \theta$$

where, U is the scalar wind speed, θ the wind direction.

The annual mean distributions of U_{EW} and U_{SN} are shown in Fig. 28 at every height and the statistical values are shown in Table 9. The shape of the frequency distribution is more similar to the Gauss distribution rather than to the scalar wind speed distribution as discussed in Chapter 4. The shape of the distribution becomes sharper with decrease in the height of measurement and the differences between the frequency

Fig. 27. Seasonal variation of wind direction with time.

— 213 m, 25 m.

Fig. 28. Annual mean distribution of vector wind speed.

Fig. 29. Mean vertical distribution of vector wind speed.

Table 9. Statistical values of annual mean vector wind speed.

Height	U_{EW}	U_{SN}	σU_{EW}	σU_{SN}	SK_{EW}	SK_{SN}	KUR_{EW}	KUR_{SN}
218(m)	0.08	-0.09	5.10	4.85	-0.45	-0.64	3.36	3.60
200	0.15	-0.19	4.87	4.60	-0.41	-0.47	3.33	3.52
150	0.32	0.35	4.22	4.52	-0.38	-0.43	3.44	3.54
100	0.47	-0.27	3.74	3.99	-0.33	-0.49	3.26	3.79
50	0.46	0.25	2.99	3.23	-0.40	-0.72	3.99	4.82
25	0.07	0.04	2.59	2.70	-0.81	-1.22	5.17	6.04

U_{EW} : Mean value of EW component.

σU_{EW} : Standard deviation of EW component.

SK_{EW} : Skewness of EW component.

KUR_{EW} : Kurtosis of EW component.

U_{SN} : Mean value of SN component.

σU_{SN} : Standard deviation of SN component.

SK_{SN} : Skewness of SN component.

KUR_{SN} : Kurtosis of SN component.

distributions of U_{EW} and U_{SN} are relatively large at the top and the lowest level.

The statistical values of the vector wind speed for each month are listed in Table 10 and the mean vertical distributions of the vector wind are shown in Fig. 29. The profiles from May to September, roughly speaking the warm period, seem to be simulated by the geostrophic wind. The mean shear

of the wind direction between 200 m and 25 m range from 22° to 32° and these values are considered to be proper. Quantitative discussion on this will be presented in another paper in near future.

7. Power spectra of wind speed.

The power spectra of wind speed are calculated by the Blackman-Turkey method,

Table 10. Statistical values of monthly mean vector wind speed.

Year	Month	Height (m)	U_{EW}	U_{SN}	$\sigma_{U_{EW}}$	$\sigma_{U_{SN}}$	SK_{EW}	SK_{SN}	KUR_{EW}	KUR_{SN}
1977	Oct.	213	2.84	1.97	3.62	3.28	-0.05	-0.59	2.36	4.22
		200	2.82	1.98	3.51	3.27	0.00	-0.35	2.40	3.33
		150	2.16	2.46	2.83	2.94	0.45	0.06	2.59	2.45
		100	2.02	1.80	2.86	2.75	0.10	-0.55	2.32	3.35
		50	1.39	1.73	2.00	2.19	0.36	-0.64	2.90	3.48
		25	0.57	1.26	2.04	1.60	0.27	-0.40	2.27	4.28
	Nov.	213	1.12	1.29	5.04	4.64	-0.18	-1.23	2.24	4.48
		200	1.15	0.80	4.90	4.54	-0.10	-0.85	2.21	3.49
		150	1.03	1.83	4.07	4.30	-0.14	-1.00	2.32	4.13
		100	0.96	1.45	3.71	3.67	0.00	-1.25	2.14	4.71
		50	0.53	1.26	2.50	2.62	0.13	-1.12	2.61	5.08
		25	0.04	0.77	2.33	2.36	-0.09	-1.90	2.07	7.62
	Dec.	213	-1.62	1.60	5.24	3.43	-0.41	-0.70	3.17	5.84
		200	-1.38	0.77	4.57	3.92	-0.50	-0.81	3.59	4.41
		150	-1.11	2.28	4.19	3.27	-0.41	-0.41	3.36	4.98
		100	-0.84	2.08	3.62	2.99	-0.28	-0.24	3.31	4.40
		50	-0.55	1.92	2.53	2.56	-0.55	-0.30	4.16	4.75
		25	-1.27	0.66	2.46	1.63	-0.88	-0.58	5.68	6.60
1978	Jan.	213	-2.96	2.11	5.51	3.65	-0.44	-0.25	3.26	3.32
		200	-2.75	1.92	5.18	3.57	-0.48	-0.14	3.35	3.20
		150	-2.02	2.49	4.41	3.59	-0.58	-0.02	3.56	3.13
		100	-1.62	2.20	3.75	3.16	-0.46	0.24	3.60	3.37
		50	-1.16	1.85	2.87	2.64	-0.71	0.40	3.86	3.84
		25	-1.67	0.61	2.83	1.94	-1.28	0.47	5.42	4.28
	Feb.	213	-1.92	2.90	5.94	3.84	-0.07	-0.40	2.49	4.11
		200	-1.80	2.74	5.58	3.79	-0.09	-0.27	2.50	3.93
		150	-1.24	3.40	4.65	3.69	-0.22	-0.17	2.82	3.83
		100	-0.87	2.74	4.14	3.35	-0.20	-0.06	2.80	4.11
		50	-0.57	1.77	4.00	2.64	-0.37	0.68	3.22	5.72
		25	-1.24	1.29	2.94	2.14	-0.45	0.16	3.62	4.14
	Mar.	213	-0.21	1.35	6.49	4.06	-0.62	-0.55	3.08	4.05
		200	-0.12	1.13	6.23	3.91	-0.62	-0.50	3.10	3.90
		150	0.22	1.84	5.33	3.98	-0.63	-0.39	3.17	3.58
		100	0.35	1.43	4.66	3.48	-0.64	-0.28	3.21	3.58
		50	0.64	1.00	4.21	2.25	-0.57	-0.04	3.08	4.47
		25	-0.12	0.74	3.07	1.08	-0.63	-0.84	3.29	6.23
	Apr.	213	-0.29	-1.52	5.39	5.28	-0.22	-0.09	2.59	4.45
		200	-0.19	-1.49	5.24	5.14	-0.19	0.04	2.54	4.95
		150	0.28	-0.92	4.70	4.94	-0.18	0.01	2.70	4.62
		100	0.46	-0.95	4.10	4.30	-0.27	-0.01	2.70	5.05
		50	0.65	-0.61	3.58	3.47	-0.50	-0.34	3.47	6.45
		25	-0.03	-0.34	3.05	2.96	-1.09	-0.46	4.80	5.81
	May	213	1.42	-1.97	4.19	4.14	-0.44	-0.08	3.69	2.18
		200	1.44	-1.94	4.02	3.76	-0.36	0.06	3.33	2.29
		150	1.69	-1.46	3.73	3.71	-0.32	0.22	3.27	2.64
		100	1.73	-1.16	3.31	3.22	-0.30	0.09	3.24	2.68
		50	1.45	-0.79	2.80	2.71	-0.31	-0.22	3.39	2.59
		25	1.25	-0.49	2.48	2.39	-1.15	-0.58	3.11	2.93

Table 10. Continued.

1978	Jun.	213	-0.91	-4.12	4.29	5.59	0.46	-0.22	2.65	2.29
		200	-0.93	-3.82	4.29	5.09	0.41	-0.20	2.44	2.40
		150	-0.47	-3.50	3.96	5.02	0.33	-0.20	2.36	2.39
		100	-0.23	-3.16	3.50	4.53	0.24	-0.29	2.35	2.50
		50	-0.17	-2.72	2.91	3.99	0.10	-0.46	2.37	2.62
		25	0.40	-2.44	2.04	3.86	-0.08	-0.57	3.55	2.63
	Jul.	213	0.91	-2.55	3.25	3.50	0.29	-0.26	2.19	2.27
		200	0.91	-2.44	3.26	3.08	0.22	-0.12	2.17	2.42
		150	1.13	-2.26	3.00	2.97	0.20	0.03	2.27	2.43
		100	1.23	-1.91	2.60	2.65	0.15	0.03	2.51	2.32
		50	1.16	-1.43	2.12	2.27	0.18	-0.24	2.70	2.45
		25	1.13	-0.95	1.57	2.08	0.40	-0.68	3.11	2.97
	Aug.	213	-0.34	-3.50	4.00	5.18	0.52	-0.39	2.47	2.83
		200	-0.32	-3.21	3.99	4.76	0.43	-0.29	2.40	3.10
		150	-0.02	-2.94	3.62	4.62	0.42	-0.29	2.46	3.01
		100	0.26	-2.57	3.16	4.17	0.35	-0.43	2.48	3.11
		50	0.29	-2.10	2.61	3.71	0.16	-0.62	2.53	3.30
		25	0.58	-1.71	1.83	3.49	0.24	-0.88	3.58	3.78
	Sep.	213	2.54	1.78	4.01	3.57	-0.47	-0.84	3.23	3.94
		200	2.52	1.64	3.84	3.47	-0.41	-0.57	2.96	3.52
		150	2.11	1.52	3.63	3.56	-0.15	-0.43	2.37	3.27
		100	1.92	1.51	3.11	2.33	-0.12	-0.72	2.49	4.09
		50	1.25	1.31	2.50	2.17	0.03	-1.02	2.72	4.78
		25	0.76	1.08	2.28	1.82	-0.26	-1.19	4.10	6.53

U_{EW} : Mean value of EW component.

$\sigma_{U_{EW}}$: Standard deviation of EW component.

SK_{EW} : Skewness of EW component.

KUR_{EW} : Kurtosis of EW component.

U_{SN} : Mean value of SN component.

$\sigma_{U_{SN}}$: Standard deviation of SN component.

SK_{SN} : Skewness of SN component.

KUR_{SN} : Kurtosis of SN component.

using hourly wind speed data. In making the time series of the wind data, the missing data represented by those before them.

The calculated power spectra for each level are shown in Fig. 30. Peaks with about one day period are found at every level and the magnitude becomes greater with height. At higher levels it is found a small peak with

about 3~4-day period, which corresponds to the passage of an anticyclone or a cyclone as reported by Van der Hoven (1957) and Ishizaki et al. (1967).

Compared with the seasonal variation of power spectra of wind speed at a height of 213 m (Fig. 31), the spectra in summer and fall have a remarkable peak of one day period. On the other hand, the spectra in winter and spring have a relatively significant peak of the 3~4-day period though a weak peak can be found with the frequency of about one day. This fact is very interesting, reflecting that the planetary boundary layer of 200 m thickness may be controlled mainly by solar energy with one day cycle in summer and fall, and by the synoptic scale disturbance such as a cyclone or anticyclone with 3~4-day cycle in winter and spring.

Fig. 30. Power spectra of wind speed.

Fig. 31. Seasonal variation of power spectra of wind speed at 213 m height.

8. Summary and conclusions.

The characteristics of the wind speed and direction were examined by the hourly mean wind data from October 1977 to September 1978.

Though no definite conclusion can be deduced from only one-year data, some interesting phenomena have been found as follows.

The annual arithmetic mean of the wind speed increases with height from 3.14 m/sec at the lowest level (25 m) to 6.09 m/sec at the top level (213 m). The vertical profiles of wind speed in winter is nearly the same as the profile of annual mean wind speed. Monthly relative frequency distribution can be well simulated with the Weibull distribution.

There are considerable month-to-month variations in the values of the mean wind speed. This variability increases with height.

The hourly variations of the monthly mean wind speed indicate that in the warm period, the planetary boundary layer lower than 200 m can be considered one layer as a whole, but in the cold period, the layer from the ground up to 200 m must be divided into two layers which have different characteristics from each other.

The monthly mean profiles of vector wind from May to September seem to be well expressed by the geostrophic wind and the mean wind shear of the layer from the ground up to 200 m range 22° to 32° .

The seasonal characteristics can be found in the power spectra of the wind speed. The power energy with one day period is dominant in summer and fall. On the other hand, the power spectra in winter and spring have a relatively strong peak with 3~4-day period.

In our future studies, the behaviour of wind in the lowest 200 m will be examined in relation to the weather conditions as well as atmospheric stability.

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