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Regression equations between mean wind power density and mean hourly wind speed during the monsoon season

D. A. MOOLEY* and S. S. ARALIKATTI

Indian Institute of Tropical Meteorology, Pune

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सार—मानसून के मौसम में प्रचुर पवनों वाले कुछ चुनिन्दा भारतीय स्टेशनों के प्रति घण्टा पवन वेग आंकड़ों का उपयोग करते हुए प्रत्येक दिन व मास के लिए दैनिक व मासिक पवन शक्ति घनत्व माध्य व दैनिक व मासिक पवन वेग माध्य अभिकलित किये गये हैं। मानसून मासों के लिये दैनिक शक्ति घनत्व माध्य तथा दैनिक पवन वेग माध्य के घन के बीच तथा मासिक शक्ति घनत्व माध्य तथा मासिक पवन वेग माध्य के घन के बीच सहसंबंध गुणांक अभिकलित किये गए हैं। देखा गया है कि ये सहसंबंध निरंतर अति उच्च (> 0.92) तथा अपरिवर्तनशील हैं। मानसून ऋतु में इस अतिनिकट तथा अपरिवर्तनशील संबंध को ध्यान में रखते हुए दैनिक पवन शक्ति घनत्व माध्य तथा दैनिक पवन वेग माध्य के घन के बीच, साथ ही मासिक पवन शक्ति घनत्व माध्य तथा मासिक पवन वेग माध्य के घन के बीच समाश्रयण समीकरण ज्ञात किए गए हैं। इन समीकरणों के स्थिरांकों का पवन वेग माध्य से एक रैखिक संबंध दृष्टिगोचर हुआ है। मानसून के मौसम में पवन वेग माध्य से पवन शक्ति घनत्व माध्य आकलित करने के लिये इन समीकरणों को स्वतन्त्र आंकड़ों पर लागू किया गया और विभिन्न स्थानों से प्राप्त उनके आकल सामान्यतया शक्ति माध्य के 15 प्रतिशत के भीतर ही पाए गए। ये शक्ति माध्य मानसून के मौसम की किसी स्वतंत्र अवधि के प्रति घण्टा पवन वेग माध्य से अभिकलित किए गए। मानसून ऋतु में पवन शक्ति घनत्व माध्य आकलन के लिये इन समीकरणों में भारत के बहुत सारे स्टेशनों से एकत्रित किए कप एनिमोमीटर (पवनमापी) से प्राप्त आंकड़ों के पवन वेग माध्य पर लागू होने की क्षमता है।

ABSTRACT. Utilising the hourly wind speed data of some selected Indian stations with good wind regime during the monsoon season, mean daily and monthly wind power density and mean daily and monthly wind speeds have been obtained for each day and for each month. From these, correlation coefficients between mean daily power density and cube of mean daily wind speed and also between mean monthly power density and cube of mean monthly wind speed have been computed for the monsoon months. These correlations are found to be consistently very high (>0.92) and stable. In view of this very close and stable relationship, regression equations have been obtained between the mean daily wind power density and the cube of mean daily wind speed, as well as between the mean monthly wind power density and the cube of mean monthly wind speed during the monsoon season. The constants in these equations are found to have a linear relationship with the mean wind speed. These equations were applied to independent data to estimate the mean wind power density for the monsoon season from the mean wind speed and the estimates for the different stations were generally found to be within 15 per cent of the mean power for the season as computed from the hourly wind speed data for the independent period. The equations have the potential of application to mean wind speed from the cup anemometer data which are available from a large number of stations in India, for estimation of mean wind power density during the monsoon season.

1. Introduction

In recent years, there has been an attempt to exploit renewable sources of energy, like the sun, the wind, the tides etc. Efforts are also being made to devise wind mills which can operate at relatively lower wind speeds and which can be used for drawing water. There is also a growing awareness that wind energy should be exploited in the rural areas of India for the betterment of the farmer. In view of this situation, there is an increasing demand for the information in respect of the wind power available at different places in India. Studies on wind and wind power in India and the associated problems have been made by Bhatia (1952), Sil (1952), Venkiteswaran (1952), Nilkantan (1956), Ramdas and Ramakrishnan (1956), Ramiah (1956), Venkiteswaran (1962), Tewari (1978), Srinivasa, Narsimha and Govinda Raju (1979), Tewari *et al.* (1979) and Mooley (1983). For computation of wind power at a place, hourly winds are required. Now hourly wind data are available at a limited number of stations and as such power computations can be made for these stations only. However, at many stations in the country, mean daily wind and mean monthly wind, based on the 24-hour run of the wind as measured on the cup anemometer

*Retired Scientist.

TABLE 1

Stations for which hourly wind data have been used

Station	Lat. (°N)	Long. (°E)	Altitude (m)	Ht. of mast* (m)	Years of hrly wind data
Ahmedabad	23°04′	72°38′	55	14.8	1969-72
Bhopal	23°17′	77°21′	523	11.7	1969-74
Bombay (Colaba)	18°54′	72°49′	11	25.9	1969-73
Gopalpur	19°16′	84°53′	17	9.7	1969-73
Hyderabad (Begumpet)	17°27′	78°28′	545	18.5	1969-73
Madras (Meenambakkam)	13°00′	80°11′	16	33.0	1970-74
Mormugao	15°25′	73°47′	62	15.0	1969-73
New Kandla	23°00′	70°13′	14	33.3	1969-72
Tiruchirapalli	10°46′	78°43′	88	23.0	1969-74
Tuticorin	08°48′	78°09′	4	9.9	1969-74

*Height of anemograph mast head above ground

are available. The main purpose of the paper is to obtain an empirical relationship between the mean wind for the day/month and the mean wind power during the monsoon season when the wind power potential over the country is high, so that this relationship could be used for locations where the mean daily or the mean monthly wind as obtained from the records of the cup anemometer readings is available.

2. Wind data

The India Meteorological Department maintains a network of stations (about 50) with self-recording wind instruments (Dines Pressure Tube Anemographs). From the 24-hour record of the wind, mean wind speed for each hour of each day is tabulated, and these tabulations are available at the Meteorological Office, Pune. Stations for this study are selected from areas of good wind regime. Table 1 gives the names and coordinates of these stations, height of the head of the anemograph mast and the period for which the hourly wind data could be obtained.

India Meteorological Department also maintains a network of about 400 observatories. At these observatories, the wind is measured by the cup anemometer at specific synoptic observations during the day. In addition, the total run of the wind during the 24-hour period from 0830 I.S.T. of the preceding day to 0830 I.S.T. of the current day as well as during the 9-hour day-time period from 0830 to 1730 I.S.T. of the day, is calculated from the cup anemometer readings. From these runs, mean wind speed during the day ending at 0830 I.S.T. of the day, as well as during the 9-hour day-time period ending at 1730 I.S.T. of the day is computed and recorded. From these, mean monthly wind speed and mean monthly day-time wind speed can be obtained.

The hourly wind data on punched cards for the selected stations with Dines Pressure Tube Anemograph were obtained from the Office of the Deputy Director General of Meteorology (Climatology & Geophysics), Pune, for the monsoon months for the years 1969-74, this being the period for which wind data were available with few gaps in the record.

3. Computation of mean wind power density

If wind blows at a constant speed V, ρ is air density and A is the area through which wind passes normally, then P, the constant power is given by

$$P = \tfrac{1}{2}\rho A V^3 \qquad (1)$$

The air density ρ is computed by using the formula

$$\rho = p/RT_v \qquad (2)$$

where p is mean monthly pressure, T_v is the mean monthly surface virtual temperature, R is the gas constant of dry air. If p is in dyne/cm^2 and ρ is in gm/cm^3, R for dry air is 2.8703×10^6. Using the monthly normal values of air temperature T and normal vapour pressure in air, monthly normal virtual temperatures T_v have been obtained. From the monthly normal values of pressure and virtual temperature, ρ, the air density is calculated for each of the stations and for each of the monsoon months.

Taking A equal to unit square metre, using ρ in kg/m^3, V_h, mean wind speed for the hour h, in metres per sec m. p. s.), we get $\bar{P}_d$ mean daily wind power density in watt/m^2 by using the formula :

$$\bar{P}_d = \tfrac{1}{2}\rho \sum_{h=1}^{24} V_h^3/24 = \tfrac{1}{2}\rho\, \overline{V_h^3} \qquad (3)$$

Similarly $\bar{P}_m$, the mean monthly wind power density is obtained by using the formula :

$$\bar{P}_m = \tfrac{1}{2}\rho \sum_{h=1}^{n} V_h^3/n = \tfrac{1}{2}\rho\, \overline{V_h^3} \qquad (4)$$

where n is the number of hours during a month (720 or 744)

$$\bar{V}_d,\ \text{mean daily wind speed} = \sum_{h=1}^{24} V_h/24$$

$$\bar{V}_m,\ \text{mean monthly wind speed} = \sum_{h=1}^{n} V_h/n$$

From the hourly wind speeds, $\bar{P}_d$, $\bar{P}_m$, $\bar{V}_d$ and $\bar{V}_m$ have been computed for each of the stations.

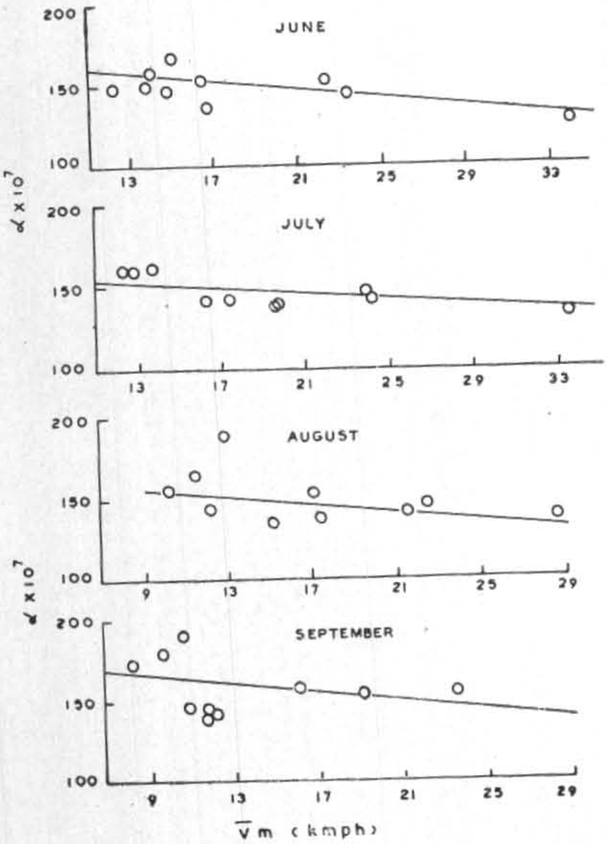

Fig. 1. Relationship between α and $\bar{V}_m$, *i.e.*, mean hourly speed for the month

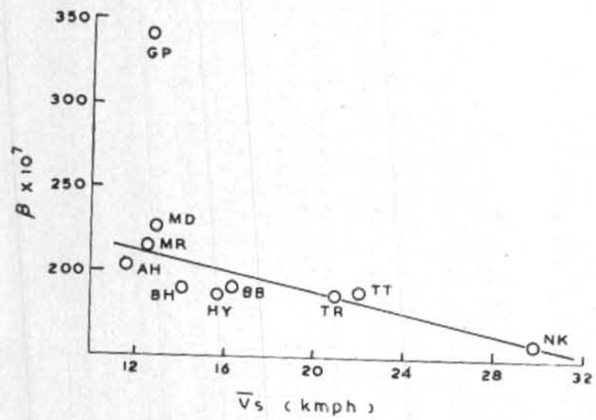

Fig. 2. Relationship between β and $\bar{V}_s$, *i.e.*, mean seasonal wind speed. Station abbreviations used are given in Table 6

4. Correlation coefficients between mean power and cube of mean wind

4.1. *Mean daily power ($\bar{P}_d$) and cube of 24-hour mean daily wind speed ($\bar{V}_d^3$)*

Utilizing the computed values of $\bar{P}_d$ and $\bar{V}_d$, correlation coefficients between $\bar{P}_d$ and $\bar{V}_d^3$ have been calculated for each of the monsoon months and for each of the stations and a frequency distribution of these 197 correlation coefficients has been prepared. Table 2 gives this frequency distribution for each of the months and for the whole season. It can be seen from this table that 93 per cent of the correlation coefficients for the monsoon months taken together are $\geqslant 0.92$. Particularly for the active monsoon month July, 92 per cent of the coefficients are $\geqslant 0.96$. For $n=30$, the value of r significant at 1 per cent level is 0.467. The relationship between the two parameters is very close and linear.

Table 3 gives for each of the monsoon months and for each of the stations, the lowest and the highest correlation coefficient between $\bar{P}_d$ and $\bar{V}_d^3$. For each of the stations, the variation of correlation coefficients from year to year and from one monsoon month to another is generally small. Variation of correlation coefficient from one station to another is also small. The correlation coefficients are thus stable over years, months and stations.

If the relationship between two parameters is really very close, it should be brought out even with a random sample. We have taken random samples of size 50 days for each of the monsoon months and for each of the stations. If M is the number of months of June for which data of $\bar{P}_d$ and $\bar{V}_d^3$ are available, the number of days randomly selected for each of the M months is approximately $50/M$. Correlation coefficients have been computed for these random samples. These are given in Table 4. The lowest coefficient is 0.923 and the highest is 0.997, and variation from one monsoon month to another and also from one station to another is small. Random samples are also found to have a very close, stable and linear relationship.

4.2. *Mean monthly power ($\bar{P}_m$) and cube of mean monthly wind speed ($\bar{V}_m^3$)*

From the computed values of $\bar{P}_m$ and $\bar{V}_m$, the correlation coefficients between $\bar{P}_m$ and $\bar{V}_m^3$ have been calculated for each of the stations. Table 5 gives the number of months for which computed $\bar{P}_m$ and $\bar{V}_m$ are available, and the correlation coefficient between $\bar{P}_m$ and $\bar{V}_m^3$. The correlation coefficient are very high and variation from station to station is very small. The relationship between the two variables $\bar{P}_m$ and $\bar{V}_m^3$ is thus very close, linear and possesses spatial stability.

5. Regression equations between mean wind speed and mean wind power density during monsoon

In view of the very close, stable and linear relationships, regression equations have been computed for both the daily and monthly time scales.

5.1. *Regression equations between the mean daily wind power density and the cube of the mean daily wind speed*

When the mean daily wind speed is near zero, the wind power density is almost zero, and as the mean speed increases wind power density also increases. The regression equation between $\bar{P}_d$, the mean daily power density and $\bar{V}_d^3$, the mean daily wind speed would be

$$\bar{P}_d = \alpha \, \bar{V}_d^3$$

where, α is the regression constant. Using the set of values of $\bar{P}_d$ and $\bar{V}_d$ for all the years for each month, α is computed for each of the monsoon months for each of the stations by following the Least Square Method. The values of α for the four monsoon months and for all the stations are given in Table 6. The values of the regression constant, denoted by α' have also been simil-

TABLE 2

Frequency distribution of correlation coefficients between mean daily power density ($\bar{P}_d$) and cube of 24-hour mean daily wind speed ($\bar{V}_d^3$)

	Class-interval of correlation coefficient											
	<.80	.800 –.819	.820 –.839	.840 –.859	.860 –.879	.880 –.899	.900 –.919	.920 –.939	.940 –.959	.960 –.979	.980 –.999	Total
Jun	0	0	0	1	0	1	0	4	3	18	21	48
Jul	0	0	0	0	1	0	0	1	2	12	32	48
Aug	0	1	0	0	1	1	2	5	5	9	27	51
Sep	2	0	1	0	1	1	1	2	4	12	26	50
Total	2	1	1	1	3	3	3	12	14	51	106	197
Percentage	1	.5	.5	.5	1.5	1.5	1.5	6	7	26	54	100

TABLE 3

Highest and lowest correlation coefficients between $\bar{P}_d$ and $\bar{V}_d^3$

Station	June		July		August		September	
	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest
Ahmedabad	.989	.895	.985	.962	.986	.936	.987	.767
Bhopal	.981	.923	.998	.965	.996	.893	.997	.970
Bombay (Colaba)	.995	.971	.997	.995	.994	.977	.998	.974
Gopalpur	.994	.949	.989	.977	.983	.940	.996	.954
Hyderabad (Begumpet)	.998	.963	.996	.974	.996	.929	.992	.978
Madras (Meenambakkam)	.981	.926	.955	.876	.954	.815	.986	.723
Mormugao	.977	.856	.990	.974	.985	.876	.975	.823
New Kandla	.998	.990	.998	.958	.997	.933	.982	.978
Tiruchirapalli	.997	.971	.994	.962	.995	.979	.990	.970
Tuticorin	.981	.969	.988	.966	.991	.951	.992	.912

TABLE 4

Correlation coefficients between mean daily wind power density ($\bar{P}_d$) and cube of 24-hour mean daily wind speed ($\bar{V}_d^3$) for a random sample of 50 days for monsoon months

Station	Jun	Jul	Aug	Sep
Ahmedabad	.976	.967	.961	.959
Bhopal	.984	.995	.985	.983
Bombay (Colaba)	.980	.995	.978	.995
Gopalpur	.984	.945	.933	.990
Hyderabad (Begumpet)	.994	.986	.968	.984
Madras (Meenambakkam)	.967	.930	.943	.923
Mormugao	.964	.986	.985	.959
New Kandla	.997	.994	.985	.983
Tiruchirapalli	.987	.989	.994	.979
Tuticorin	.987	.988	.983	.978

TABLE 5

Correlation coefficients between mean monthly power density ($\bar{P}_m$) and cube of mean monthly wind speed ($\bar{V}_m^3$) during monsoon season

Station	No. of months	Correlation coefficient
Ahmedabad	21	0.975
Bhopal	23	0.987
Bombay (Colaba)	16	0.957
Gopalpur	20	0.955
Hyderabad (Begumpet)	19	0.961
Madras (Meenambakkam)	17	0.969
Mormugao	20	0.979
New Kandla	19	0.989
Tiruchirapalli	24	0.981
Tuticorin	22	0.989

TABLE 6

Values of regression coefficients α (α') and β (β')

Station (Abbre.)	$\alpha \times 10^7$ (α') for Jun	Jul	Aug	Sep	$\beta \times 10^7$ (β') for monsoon season
Ahmedabad (AH)	157 (159)	158 (158)	156 (154)	178 (175)	202 (200)
Bhopal (BH)	148 (148)	140 (140)	135 (135)	139 (138)	188 (187)
Bombay (BB) (Colaba)	153 (157)	136 (137)	140 (140)	142 (140)	189 (196)
Gopalpur (GP)	145 (142)	158 (158)	165 (169)	144 (144)	340 (332)
Hyderabad (HY) (Begumpet)	136 (135)	138 (138)	153 (154)	146 (146)	186 (186)
Madras (MD) (Meenambakkam)	167 (177)	186 (190)	188 (187)	190 (190)	224 (225)
Mormugao (MR)	146 (144)	141 (141)	144 (144)	171 (168)	213 (212)
New Kandla (NK)	128 (128)	132 (133)	138 (141)	154 (154)	158 (163)
Tiruchirapalli (TR)	145 (144)	142 (142)	142 (141)	157 (155)	185 (184)
Tuticorin (TT)	154 (154)	146 (145)	147 (147)	153 (152)	187 (185)

Note : The regression equations are

$\bar{P}_d = \alpha \bar{V}_d^3$; $\bar{P}_m = \beta \bar{V}_m^3$, where,

P_d is mean daily wind power density (kw/m²)

$\bar{P}_m$ is mean monthly wind power density (kw/m²)

$\bar{V}_d$ is hourly mean wind speed for the day (kmph)

$\bar{V}_m$ is hourly mean wind speed for the month (kmph)

α' and β' are the regression constants obtained when wind speed data for 1971 are not considered.

arly computed by considering all the data except those of 1971. This has been done with a view to verify the relationships on independent data of 1971 which are available for all the stations. The values of α' will be used in the next section for verification. The values of α' are based on the data of 3 to 5 years while those of α are based on 4 to 6 years. It is seen from Table 6 that differences between α and α' are very small. In some cases the two are identical. This shows that when one year's data are added to those of 3 to 5 years, the values of the constant change little, and thus brings out the stability of the constants.

To examine if there is any relationship between α and $\bar{V}_m$, the mean monthly wind speed based on the whole record of the hourly values for the month, α was plotted against $\bar{V}_m$ separately for each of the monsoon months. Fig. 1 shows the plot of α against $\bar{V}_m$ for each of the monsoon months, June to September. From this figure it is seen that there is a broad linear relationship between α and $\bar{V}_m$. In Fig. 1, lines of close fit to the points have been drawn. This linear relationship can be used for estimating the value of α from the mean monthly wind speed.

TABLE 7

Percentage error in the estimation of the mean wind power during monsoon season by the daily and monthly regression relations

Station	% error in daily relation	% error in monthly relation
Ahmedabad	—12	—15
Bhopal	—26	—38
Bombay (Colaba)	3	14
Gopalpur	—15	—23
Hyderabad (Begumpet)	— 4	— 2
Madras (Meenambakkam)	—2	— 2
Mormugao	—14	— 9
New Kandla	0	— 7
Tiruchirapalli	—12	—11
Tuticorin	—10	—11

5.2. *Regression equations between mean monthly wind power density and mean monthly wind speed*

The regression equation for the monthly time scale would be

$$\bar{P}_m = \beta \bar{V}_m^3 \quad (5)$$

Using the set of values of $\bar{P}_m$ and, $\bar{V}_m$ for all the monsoon months, the regression constant β has been obtained for each of the stations for the monsoon season by using the Least Square Method. In view of the small data sample on monthly scale, β was not obtained for each of the monsoon months.

As in the preceding sub-section, values of the regression constant (denoted by β') have also been computed for each of the stations by considering all the data except those of 1971, for the purpose of verifying the relationships on independent data of 1971.

Table 6 also gives the values of β and β'. As will be seen, the differences are generally very small, bringing out the stability of the constants.

Fig. 2 gives a plot of β and, $\bar{V}_s$ where $\bar{V}_s$ is the mean wind for the monsoon season based on the whole record of hourly wind speed values for the season. The relationship is seen to be linear. This linear relationship can be used for estimating β for a station from $\bar{V}_s$.

It is seen from Fig. 2 that the value of β for Gopalpur is not fitting. It may be mentioned that Gopalpur is a station periodically under the influence of monsoon depressions moving westwards across north Orissa. It appears to be quite a different wind regime as compared to the wind regimes at the remaining places.

6. Verification of the estimates of the wind power density obtained from the regression equations

The regression equations between the mean daily wind power density and the cube of the mean daily wind speed and between mean monthly wind power density and the cube of the mean monthly wind speed as obtained in section 3 on the basis of all the hourly wind data have been utilised to obtain for 1971 estimates of mean daily power density for each day of the monsoon months and for each month of the monsoon season respectively, for each of the stations considered From the daily estimates, the mean power density $(\bar{P}_{Ed})_s$, is estimated for the monsoon season of 1971. Using the hourly wind data for the monsoon season of 1971 actual mean wind power density $(\bar{p}_A)_s$ for the monsoon season has been computed by using Eqn. (3). The percentage error for the season, 100 $[(\bar{P}_{Ed})_s - (\bar{P}_A)_s]/(\bar{P}_A)_s$, of estimation of the mean monsoon seasonal wind power density from the daily relationship, is obtained. Likewise, from the monthly estimates of the mean wind power density for each of the monsoon months, mean wind power density $(\bar{P}_{Em})_s$, is obtained for the monsoon season of 1971. The percentage error for the season, 100 $[(\bar{P}_{Em})_s - (\bar{P}_A)_s] / (\bar{P}_A)_s$ of the estimation of the mean wind power density for the season from the monthly relationship has also been obtained for each of stations. The percentage errors of estimation of the mean wind power for the monsoon season of 1971 by the daily and the monthly regression relationships are given in Table 7. It is seen from this table that the error of seasonal estimates based on the daily relationship is smaller for Gopalpur, Bombay (Colaba), Bhopal and New Kandla than that of the estimates based on the monthly relationship, and for Ahmedabad, Hyderabad, Madras, Tiruchirapalli and Tuticorin, the errors of the two estimates are almost equal. Only in one case, *viz*., that of Mormugao, is the error of estimation by the monthly relationship lower than that of the estimation by the daily relationship. We thus find that the estimation of the mean wind power for the monsoon season by the use of the daily relationship is slightly better than that by the monthly relationship. The error is generally less than 15 per cent. Both the relationships generally underestimate the mean power.

7. Discussion of results

Stations within the tropics are characterised by marked diurnal variation and the pattern of diurnal variation generally shows small variation from one day to another in a month. In view of this, a fairly stable ratio of $E(V^3)/\bar{V}_d^3$ and a high correlation between $E(V^3)$ and $\bar{V}_d^3$ can be expected to exist. The symbol V stands for hourly wind speed, E for expected value, $\bar{V}_d$ for mean hourly wind speed for the day.

$$E(V^3) = 1/24 \sum_{h=1}^{24} V_h^3$$

where V_h is hourly wind speed, h varying from 1 to 24.

It may be noted that $E(V^3)$ is proportional to $\bar{P}_d$, the mean daily power density.

The hourly wind speed is generally distributed symmetrically around the day's maximum speed, and as such the skewness would be negligible. According to Hennessey (1977), when skewness is negligible :

$$E(V^3) = 3\,\bar{V}_d\,\sigma_d^2 + \bar{V}_d^3$$

Hence, $E(V^3)/\bar{V}_d^3 = 3\,(\sigma_d/\bar{V}_d)^2 + 1$

where σ_d is standard deviation of 24 hourly wind speeds. Now $(\sigma_d/\bar{V}_d)^2$, *i.e.*, square of the coefficient of variation is expected to show small variations from day to day within a month in view of the small variation from day to day. Hence the ratio $E(V^3)/\bar{V}_d^3$ would show small variation from day to day, and since $\bar{P}_d$ is proportional to $E(V^3)$, $\bar{P}_d$ should be highly correlated with $\bar{V}_d^3$, the cube of 24-hour mean wind speed.

The high linear relationship would permit application of the relationship to the mean daily wind speeds obtained from the 24-hour run of the wind as measure on the cup anemometer to estimate the mean power density.

8. Conclusions

(*i*) The relationships between mean daily wind power density and cube of mean daily wind speed, and also between mean monthly wind power density and cube of mean monthly wind speed are very close, linear and stable, and the regression equations between these can be used for estimation of mean power density for the monsoon season.

(*ii*) The constants in these regression equations are quite stable, and show a linear relationship with mean wind.

(*iii*) The regression equations could provide a basis for utilising the mean daily wind and the mean monthly wind speed obtained from the cup-anemometer data from a large number of observatories in India for estimation of mean wind power density during the monsoon season. Some studies on this aspect are, however, necessary before attempting an application of these relationships.

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