# ESTIMATION OF THE DESIGN WIND SPEEDS FOR THE KINGDOM OF SAUDI ARABIA BASED ON SHORT-TERM RECORDS

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## ABSTRACT

The methods of order statistics and that of moments are examined for estimation of the extreme wind speeds from short-term records of the largest monthly winds taken at the six stations in the Kingdom of Saudi Arabia. Basic design wind speeds derived from the largest annual winds taken at the twenty stations of the long-term record, from an earlier study, are employed as the bench mark speeds to assess the reliability of the analyses based on the largest monthly records in the Kingdom. It was found that the method of moments is an appropriate procedure for dealing with short term monthly records and that, in general, it underestimates the design speeds. However, association of probability of 10% of being exceeded with the design speeds so estimated circumvents the situation. A simple procedure for effecting this modification of the design speed is also proposed. The estimated design speeds at the six short-term stations enhance the previous work.

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## INTRODUCTION

The theory of extreme values has been successfully used in civil engineering applications. Floods, winds, earthquakes and floor loadings are all variables whose largest value in a sequence may be critical to a civil engineering system. Wind speeds with various mean recurrence intervals can generally be estimated by extreme value analysis of the largest yearly winds. In this method yearly winds are assumed to be independent, stationary and well presented by Type I or II distribution function. The method gives reliable values of design wind speed for long term mean recurrence interval when based on wind records of at least 15 years. For short-term records (e.g. 3 to 5 years), it is well established in literature that the basic design wind speed can be estimated from monthly winds [1,2].

In order to enhance the previous work [3], which presented design speeds based upon analysis of the largest annual wind (LAW) speed data taken at twenty stations of the long-term (LT) record in the Kingdom, this study employs the largest monthly wind (LMW) speed data taken at the remaining six stations of the short-term (ST) record.

Among the various statistical estimation methods, the distribution parameters of the extreme value probability functions can be determined by the method of order statistics (MOS) and the method of moments (MOM). The main effort of this paper is focused on assessing suitability of these methods in evaluation of design winds from LMW speeds at ST-stations in the Kingdom of Saudi Arabia (KSA). This is necessary in view of the fact that the method proposed in Refs. [1 and 2] for dealing with the ST-record assumes that LMW speeds are independent, stationary and that they follow type I distribution.

The wind data details, and a concise development of the probability distribution functions and that of MOS and MOM for determination of their distribution parameters are presented in what follows. The wind speeds of 50-year mean recurrence interval obtained from MOS applied to LAW speeds taken at LT-stations [3] are employed as the bench mark speeds for assessment of the results from analyses performed on LAW- and LMW-speeds at LT-stations. The study also determines the distribution that best fits the LMW-speeds, evaluates the reliability of design speeds from LMW-records and proposes the possible post-analysis treatment required to enhance the confidence level of such an analysis.

## WIND SPEED DATA

The data comprising the largest annual and monthly wind speeds available with the Meteorological and Environmental Protection Agency (MEPA) include records varying over periods of three to twenty seven years measured at twenty six stations well distributed over the Kingdom. A profile of the wind monitoring stations in the Kingdom, the anemometer heights and the duration of continuous record at the stations are listed in Table 1. Twenty of the stations have records over a continuous duration of fifteen or more years which is desirable for the annual extreme value analysis while six stations have records of less than fifteen years.

In an earlier study [3], the LAW speeds were utilized to estimate design wind speed according to ASCE code [4] procedure at the LT-stations where the records exceed 15 year duration. A sample size of 15 or more is considered to be sufficient to develop representative probabilistic models for the variability in LAW speeds.

## BASIC DESIGN WIND SPEED

Basic design wind (BDW) speed is defined as the wind speed at the standard height of 10 meters above ground in open country and associated with an annual probability of 0.02 of being exceeded, i.e. having 50 year mean recurrence interval. ASCE [4] employs fastest mile wind (FMW) speed as the BDW speed. FMW speed is the maximum annual wind speed at which a one mile long column of wind passes by an anemometer. The BDW speeds, $\upsilon_{50}$, of twenty LT-stations, obtained by extreme value analysis are produced in Table 2, along with the distribution type and their parameters.

## RELIABILITY AND HOMOGENEITY OF DATA

In order for the wind speed data to provide useful information it must be reliable and form a homogeneous set.

Measured data are considered reliable if the recording instruments are adequately calibrated and are not exposed to local effects due to proximity of obstructions. However, if at any time in future the calibration is found to be inadequate, it is possible to evaluate the corrections and adjust the data.

Measured data form a homogeneous set when they are obtained under identical conditions of averaging time and height above ground .

### Averaging Time

The measured annual and monthly wind speeds at all the stations are averaged over ten-minute duration. The ten-minute speed in knots is converted to ten-minute speed in miles per hour. The averaging time for conversion of this speed to FMW speed is obtained by an iterative procedure, which is used to derive the required fastest mile [5].

### Anemometer Height above Ground

Height of 10 m above ground is considered to be the standard instrument height. Wind data measured at any other height are adjusted to the standard height by power law. The values of exponent in the power law for different "exposures" are available in literature [5]. Specifically for meteorological stations, which are invariably located in open country, the exponent is one-seventh.

## PROBABILITY FUNCTIONS OF THE LARGEST VALUES

In the case of well behaved climates (i.e. ones in which infrequent strong winds are not expected to occur) it is reasonable to assume that each of the data in a series of the LAW-speeds contributes to the probabilistic behavior of the extreme winds. Generally two types of extreme value distributions are used in literature for modeling the behaviour of extreme wind speeds [6,7,8]. The Type I (Gumbel) extreme-value probability distribution function, $F_{Iv}(\upsilon)$ , which provides the probability of not exceeding the wind speed $\upsilon$ is defined as,

$$F_{Iv}(\upsilon) = \exp\left[ - \exp\left( - \text{خطأ!} \right) \right] , \qquad (1)$$

where, $\alpha$ and u are the scale and location parameters, respectively, and are estimated from the observed data at each station. The parameter u is also called as the characteristic largest value.

The Type II (Frechet) extreme-value distribution function, $F_{IIv}(\upsilon)$ , is,

$F_{IIv}(\upsilon)$ = exp [ - ( خطأ! ) خطأ! ] , (2)

where the parameters $\omega$ and $\gamma$ are estimated from the observed data at each station. The parameter, $\gamma$, is known as the tail length (shape) parameter and $\omega$ as the largest characteristic value [9].

## ESTIMATION OF THE DISTRIBUTION PARAMETERS

There are two methods that are generally employed to estimate the distribution parameters of Eqs. 1 and 2, whichever is applicable to a given set of data. These methods are, the method of order statistics (MOS) and method of moments (MOM). A brief description of these two methods is presented herein.

### Method of Order Statistics

The method of order statistics was developed by Lieblein [10] in which the values of cumulative distribution function (CDF), $F_V(\upsilon)$, corresponding to a series of LAW-speeds can be estimated as follows,

$\hat{F}_v(\upsilon)$ = خطأ! (3)

where, n is the number of years of record and $m(\upsilon)$ is rank of the event, $\upsilon$, in the ascending order of the magnitudes.

The inverse of CDF known as the percentage point function (PPF), $\upsilon(F)$, which gives the value of wind speed

$\upsilon$ at a selected value of CDF. For Type I distribution the PPF is linearly related to an intermediate variate y(F), as,

$$\upsilon(F) = u + \alpha\, y(F) \qquad (4)$$

where,

$$y(F) = -\ln\left(-\ln F\right) \qquad (5)$$

In MOS, the determination of distribution parameters is based on least squares fitting of a straight line to the data on probability paper. In case V has Type II distribution function, then the parameter Z = ln V can be shown to have Type I distribution with $u = \ln \omega$ and $\alpha = 1/\gamma$. This relationship enables use of Type I probability paper for Type II distribution also.

Step-wise procedure of analysis was presented in [3] where the method was used to select an appropriate distribution (i.e. Type I or Type II) function from LAW-record at each LT-stations. The BDW speeds were then estimated by extrapolating the corresponding distribution functions to 50 years mean recurrence interval.

**Method of Moments**

In the method of moments (MOM), the distribution parameters are obtained by replacing the expectation and the standard deviation of wind speed records by the corresponding statistics of the sample. In the case of the Type I distribution, it can be shown that using the principles of expectations of the continuous random variable, V (the LAW-speed), the mean value, $\overline{V}$ , and standard deviation, $s(\upsilon)$, of the LAW-speed,respectively, are [8,11],

$$\bar{V} = u + 0.5772\ \alpha \qquad (6)$$

$$s(\upsilon) = \text{خطأ!}\alpha \qquad (7)$$

so that, $\alpha = (\sqrt{6}\ /\pi)s(\upsilon)$ and $u = \bar{V} - 0.5772\ \alpha$.

Employing α and u values from Eqs. 6 and 7, and the fact that y(F) at mean recurrence interval, $\bar{N}$ , is approximately equal to $\ln(\bar{N})$, Eq. 4 yields,

$$\upsilon'_{,\bar{N}} = \bar{V} - 0.45\ s(\upsilon) + 0.78\ s(\upsilon)\ \ln(\bar{N}) \qquad (8)$$

where, $\upsilon'_{,}$ is the estimated extreme wind in mean recurrence interval of $\bar{N}$ years.

Under the assumption that the random variables $\bar{V}$ and s are, asymptotically normally distributed, it can be shown that for large sample of size n the standard deviation of the estimated wind speed is as follows [11],

$$s[\upsilon'_{,\bar{N}}] = 0.78\ [\ 1.64 + 1.469(\ln \bar{N} - 0.577) + 1.1(\ln \bar{N} - 0.577)^2\ ]^{1/2}\ \text{خطأ!}\ (9)$$

For $\bar{N}$=50, the Eq. 8 and 9 become,

$$\upsilon'_{,50} = \bar{V} + 2.6\ s \qquad (10)$$

$$s[\upsilon'_{,50}] = 3.377\ \text{خطأ!} \qquad (11)$$

It is shown in [1] and [2], that Eq. 8 can be used to estimate the extreme wind speeds with mean recurrence interval $\bar{M}$ , in months, provided that $\bar{V}_m$ and $s_m$ are defined, respectively, as the sample mean and the sample standard deviation of the LMW speeds. The estimated extreme wind speed with 600 month mean recurrence interval, $\upsilon_{50m}$, and its standard deviation are,

$$\upsilon'_{,50m} = \overline{V}_m + 4.54\ s_m \quad (12)$$

$$S\ [\upsilon'_{,50m}] = 5.37 \text{ خطأ!} \quad (13)$$

**CONFIDENCE IN LMW-ANALYSIS**

Simiu et al. [2] studied the reliability of estimated wind speeds derived from LMW-data of short records of 3 to 5 years. They employed 67 sets of records from 36 stations. It was found that the differences $\upsilon_{50m}$ - $\upsilon_{50}$ were less than $\pm s(\upsilon_{50m})$ in 66% and less than $\pm 2s(\upsilon_{50m})$ in 96% of the cases. They concluded that a sample of 36 consecutive largest monthly speeds is usually sufficient to obtain respectable estimates of the extreme wind speed with a mean recurrence interval N=600 months (50 years). This finding for the extreme wind speeds in regions with a well-behaved wind climate is also confirmed by additional calculations reported in [1].

**SUITABILITY OF ANALYTICAL PROCEDURES**

Several analyses by MOS and MOM which employ LAW- and LMW-speeds at LT-stations are done to assess the extent of their applicability to KSA wind data. Table 3 presents the overall scheme and the parameters involved in these analyses numbered A-1 through A-5. Analysis A-6 is made after critical evaluation of the first five.

## DISCUSSION OF RESULTS

The results from the analysis listed in Table 3 are discused below.

**Analysis A-1:**

The analysis employed MOS on LAW speeds taken at LT-stations. The results of this analysis are reproduced from [3] in Table 2. These BWD speeds are considered as the bench mark (BM) speeds.

Results indicated that LAW-speed data were well presented by Type I distribution function at all the LT-stations. However, the goodness-of-fit tests, i.e. the Chi-Square and Kolmogorov-Smirnov goodness-of-fit tests at 5 percent significance level, indicated that Type II was more appropriate for the data from Hail, Najran, Riyadh, Sulayel and Tabuk stations and as such was adopted at these stations. However, it should be pointed out that the estimated values of BDW speeds using Type II distribution are higher than those calculated by Type I distribution. Also Type II distribution tends to overestimate the values of BDW speeds at recurrence intervals of 100 or more years. The magnitude of error increases with lower values of the tail length parameter, $\gamma$, of Type II distribution.

**Analysis A-2:**

The analysis employed MOM on LAW speeds taken at LT-stations and the results are presented in Table 4 and Fig. 1. The purpose is to examine the accuracy of analysis by MOM as it involves assumptions and approximations in its formulation mentioned earlier. It is noted that the deviation of $\upsilon'_{,50}$ from the bench mark (BM) is less than $\pm s(\upsilon'_{,50})$ at all the stations except Hail, Najran, Riyadh, Sulayal and Tabuk. At these stations the BM speeds of Table 2 were calculated from type II distribution which normally yields higher values. MOM in general, underestimates the design speeds slightly as shown in Fig. 1. This trend is attributable to approximations inherent in its formulations [11].

**Analysis A-3:**

This analysis employed MOS on LMW speeds taken at LT-stations and the results are presented in Table 5 and Fig. 2. The purpose here was to check the suitability of Type I distribution for LMW speeds and compare the design speeds obtained from largest monthly record, $\upsilon_{50m}$, with those from largest annual record, $\upsilon_{50}$. In general, the analysis indicates that type I distribution best fits the LMW-speeds. The errors in $\upsilon_{50m}$ are within ±10% of the BM speeds at all the stations excepting at Al-Jouf and Dhahran. However, this analysis overestimates the design speeds at eight stations with Dhahran and Al-Jouf being 19.3% and 16.4% higher than the BM, respectively as shown in Fig. 2. This trend is attributable to lower values of LMW speeds which control the slope of the regression line as is indicated by the regression of Al-Jouf data shown in Fig. 3. The analysis also reveals that the LMW-speeds at Madina and Gizan stations may as well fit type II distribution. This distribution yields a design speed of 103.4 MPH at Madina, which is 22% higher than the BM speed. This reinforces the basic assumption that type I is the most suited distribution for estimation of design speeds from LMW record.

**Analysis A-4:**

This analysis employed MOM on LMW speeds taken at LT-stations and the results are presented in Table 6 and Fig. 2. Design speeds from this analysis are close to those from A-3. MOM, therefore, can be confidently applied to long-term LMW-speeds.

**Analysis A-5**

This analysis employs MOM on randomly chosen three-year subsets of LMW speeds taken at LT-stations and the results are presented in Table 7 and Fig. 4. The purpose here is to calibrate the MOM results, $\upsilon^{",50m}$, obtained from the short data with the results from A-4. Sixty percent of the design speeds are within ±s ($\upsilon^{",50m}$) and 90% within ±2s($\upsilon^{",50m}$). However, 70% of the design speeds, $\upsilon^{",50m}$, are less than the corresponding bench mark speeds as shown in Fig. 4. This indicates that there is a high probability of underestimating design speeds from the Saudi Arabian short-term LMW-data. A modification to analysis by MOM, therefore, is desirable to furnish a simple and practical procedure for estimating design speeds from these records.

## MODIFICATION OF MOM RESULTS FROM ST-RECORD

Assigning a probability to wind speed of 90% of not being exceeded, the modified BDW speed, $\upsilon^{*,50m}$, can be calculated at a station under the assumption that the random variable, the MOM design speed from the LMW record taken at ST-stations, $\upsilon^{",50m}$, is asymptotically normally distributed as,

$$\upsilon^{*,50m} = \upsilon^{",50m} + k_z\, s(\upsilon_{50m}) \quad (14)$$

where, factor $k_z$ = 1.282.

The modified design speed, $\upsilon^{*,50m}$ , from the subsets of LT-record are obtained by employing $\upsilon^{",50m}$ in Eq.(14) and produced in Table 7 and Fig. 4. The modification effectively reduces the trend of underestimating, and in general, it is recommended to employ modified MOM procedure for finding estimated design speed from ST-speeds.

Nevertheless, the proposed modification overestimates the design speed at some stations as shown in Fig. 4. It is, therefore, proposed that in such a situation a detailed cost and reliability study of the structural system at hand be carried out to justify a lower value of the factor $k_z$.

## ESTIMATION OF BDW SPEEDS FROM LMW-SPEEDS OF ST-RECORD

The analysis A-6 employes MOM on LMW record taken at the six ST-stations in KSA, as shown in Fig. 5, and the results are presented in Table 8. Both the design speeds, $\upsilon^{",50m}$ and $\upsilon^{*,50m}$ are listed in the table. The $\upsilon^{*,50m}$ values may confidently be employed as the design speed at these stations.

## SUMMARY AND CONCLUSIONS

The study investigated the question whether design wind speeds can be estimated confidently from short terms of three to eight years available in the Kingdom. The study referred to basic design wind speeds from an earlier study of long-term records as the bench mark speeds, employed the methods of order statistics and moments on the largest annual and monthly speeds of the long-term records to assess the results derived from the largest monthly records.

The method of order statistics indicated that the largest monthly speeds are well modeled by type I distribution function. However, this function highly overestimated the design speeds at five out of twenty long-term stations as compared to the bench mark speeds. Type II distribution function was also found to overestimate the design speeds from the largest monthly records.

The method of moments using the largest monthly winds provides a good estimate of the design speeds when continuous monthly records of fifteen or more years are employed.

The design speeds from method of moments derived from randomly selected three-year subsets of the largest monthly speeds taken at the long-term stations, were underestimated at 70% of the stations. Therefore, in order to rectify this situation, it is proposed to modify the design speeds from short-term records to reflect a desired probability of not being exceeded. This approach is employed to estimate the design speedsfor probability of 90% of not being exceeded at the six stations of short-term records in the Kingdom.

The proposed modification, however, tends to overestimate the actual values at some stations and as such can not be employed as a blanket procedure. Therefore, a detailed cost and reliability analysis of the structural system needs to be conducted at the design stage. Lower values of modification factor can be evaluated to attain minimum total cost of the structural system.

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**Table 1.** Profile of Wind Monitoring Stations in the Kingdom [3].

| Record Type | Station Code | Station Name | Anemometer Height (m) | Years of Continuous Record |
|---|---|---|---|---|
| Long-term | BA | Badanah | 6 | 15 |
| | BI | Bisha | 6 | 19 |
| | DH | Dhahran | 10 | 24 |
| | GS | Gassim | 7 | 21 |
| | GZ | Gizan | 8 | 24 |
| | HL | Hail | 8 | 25 |
| | JD | Jeddah | 10 | 22 |
| | JF | Jouf | 7 | 15 |
| | KM | Kh-Mushiat | 9 | 21 |
| | MD | Madina | 10 | 27 |
| | NJ | Najran | 8 | 15 |
| | QS | Qaisumah | 8 | 18 |
| | RF | Riyadh | 10 | 23 |
| | RF | Rafah | 12 | 15 |
| | SU | Sulayel | 10 | 18 |
| | TB | Tabuk | 9 | 27 |
| | TF | Taif | 8 | 25 |
| | TR | Turaif | 8 | 15 |
| | WJ | Wajeh | 10 | 24 |
| | YB | Yanbu | 10 | 22 |
| Short-term | AB | Abha | 10 | 4 |
| | BH | Baha | 10 | 4 |
| | GT | Gurayat | 10 | 3 |
| | MK | Makkah | 10 | 8 |
| | RK | Riyadh(KKIA) | 10 | 3 |
| | SH | Sharurah | 10 | 3 |

**Table 2** Extreme Value Models and BDW speeds (MPH) Derived from LAW speeds Taken at the LT-Stations in the Kingdom of Saudi Arabia [3 ].

| Station (1) | Type (2) | u (ω) (2) | α (γ) (3) | $\upsilon_{50}$ |
|---|---|---|---|---|
| Badana | I | 59.54 | 11.37 | 103.9 |
| Bisha | I | 51.16 | 8.73 | 85.2 |
| Dhahran | I | 45.95 | 4.90 | 65.1 |
| Gassim | I | 63.19 | 11.59 | 107.2 |
| Gizan | I | 53.48 | 11.59 | 98.6 |
| Hail | II | 53.52 | 7.99 | 87.2 |
| Jeddah | I | 48.59 | 6.44 | 73.7 |
| Jouf | I | 56.88 | 7.09 | 84.5 |
| Khamis-Mushiat | I | 42.05 | 7.58 | 71.6 |
| Madina | I | 45.34 | 9.87 | 83.8 |
| Najran | II | 47.94 | 8.03 | 77.9 |
| Qaisumah | I | 57.46 | 6.66 | 83.4 |
| Riyadh | II | 51.98 | 7.57 | 87.0 |
| Rafah | I | 55.26 | 7.27 | 83.6 |
| Sulayel | II | 51.22 | 6.55 | 92.9 |
| Tabuk | II | 54.54 | 8.05 | 88.5 |
| Taif | I | 51.36 | 8.68 | 85.2 |
| Turaif | I | 56.53 | 8.19 | 88.8 |
| Wajh | I | 47.17 | 8.21 | 79.7 |
| Yanbu | I | 46.58 | 6.68 | 72.6 |

(1) Extreme value distribution type.
(2) In case of the Type II distribution, the values listed belong to the parameters within the parentheses in the column heading.
(3) Basic design wind speed for 50 year mean recurrence interval derived by MOS from the largest annual winds of LT-records.

**Table 4** BDW Speed (MPH) from LAW-Record at LT-Stations by Method of Moments.

| Station | $\bar{V}$ | s | $\upsilon'_{,50}$ | $s(\upsilon'_{,50})$ | خطأ! |
|---|---|---|---|---|---|
| Badana | 65.5 | 12.5 | 98.2 | 9.68 | -0.59 |
| Bisha | 55.6 | 9.6 | 80.7 | 7.25 | -0.62 |
| Dhahran | 48.6 | 5.7 | 63.2 | 3.78 | -0.50 |
| Gassim | 69.2 | 12.9 | 103.0 | 9.08 | -0.46 |
| Gizan | 59.6 | 12.9 | 93.3 | 9.29 | -0.57 |
| Hail | 57.8 | 8.7 | 80.5 | 5.76 | -1.16 |
| Jeddah | 52.0 | 7.2 | 70.7 | 5.58 | -0.54 |
| Jouf | 60.6 | 8.1 | 81.6 | 6.28 | -0.46 |
| Kh-Mushiat | 46.1 | 8.7 | 68.8 | 6.13 | -0.46 |
| Madina | 50.6 | 11.3 | 79.9 | 7.48 | -0.52 |
| Najran | 51.5 | 7.3 | 70.6 | 6.37 | -1.15 |
| Qaisumah | 60.9 | 7.7 | 80.9 | 5.97 | -0.42 |
| Riyadh | 56.4 | 9.4 | 80.8 | 6.23 | -1.00 |
| Rafah | 59.0 | 8.0 | 79.7 | 6.37 | -0.61 |
| Sulayel | 56.3 | 9.9 | 81.9 | 7.48 | -1.47 |
| Tabuk | 58.8 | 8.7 | 81.5 | 5.76 | -1.22 |
| Taif | 56.0 | 9.9 | 81.6 | 6.56 | -0.55 |
| Turaif | 60.8 | 9.0 | 84.2 | 7.37 | -0.63 |
| Wajh | 52.0 | 9.3 | 76.4 | 6.16 | -0.54 |
| Yanbu | 50.1 | 7.7 | 70.1 | 5.42 | -0.46 |

**Table 5.** Type I Extreme Value Models and BDW Speeds (MPH) Derived from LMW-Speeds Taken at the LT-Stations.

| Station | u | α | $\upsilon_{50m}$ | Error% [1] |
|---|---|---|---|---|
| Badana | 37.74 | 9.27 | 97.1 | -6.7 |
| Bisha | 31.80 | 8.27 | 84.7 | -0.6 |
| Dhahran | 33.60 | 6.89 | 77.6 | 19.3 |
| Gassim | 33.82 | 11.52 | 107.5 | 0.4 |
| Gizan | 31.62 | 9.49 | 92.3 | -6.8 |
| Hail | 33.15 | 8.64 | 88.4 | -1.4 |
| Jeddah | 30.82 | 6.68 | 73.5 | -0.2 |
| Jouf | 35.40 | 9.85 | 98.4 | 16.4 |
| Kh-Mushiat | 30.54 | 6.44 | 71.7 | 0.2 |
| Madina | 29.50 | 7.45 | 77.1 | -8.0 |
| Najran | 30.25 | 8.08 | 81.6 | 5.0 |
| Qaisumah | 39.60 | 8.03 | 91.0 | 8.5 |
| Riyadh | 32.83 | 7.85 | 83.0 | -4.6 |
| Rafah | 36.17 | 8.30 | 89.2 | 6.7 |
| Sulayel | 33.48 | 8.27 | 86.4 | -7.0 |
| Tabuk | 34.70 | 8.62 | 89.9 | 1.6 |
| Taif | 34.14 | 7.66 | 83.1 | -2.5 |
| Turaif | 39.39 | 9.03 | 97.1 | 9.3 |
| Wajh | 31.89 | 6.95 | 76.3 | -4.3 |
| Yanbu | 34.48 | 5.67 | 70.7 | -2.6 |

(1) Referred to BM speed of Table 2.

**Table 6** BDW Speed (MPH) from LMW-Record at LT-Stations by Method of Moments.

| Station | $\bar{V}_m$ | $s_m$ | $\upsilon'_{,50m}$ |
|---|---|---|---|
| Badana | 43.0 | 11.5 | 95.2 |
| Bisha | 36.5 | 10.3 | 83.1 |
| Dhahran | 37.5 | 8.6 | 78.0 |
| Gassim | 40.4 | 14.6 | 107.0 |
| Gizan | 37.0 | 11.9 | 91.0 |
| Hail | 38.1 | 10.9 | 87.6 |
| Jeddah | 34.6 | 8.4 | 73.0 |
| Jouf | 41.0 | 12.3 | 96.9 |
| Kh-Mushiat | 34.2 | 8.1 | 71.0 |
| Madina | 33.7 | 9.5 | 76.7 |
| Najran | 34.6 | 9.7 | 78.6 |
| Qaisumah | 44.1 | 10.0 | 89.5 |
| Riyadh | 37.3 | 9.9 | 82.2 |
| Rafah | 40.9 | 10.3 | 87.6 |
| Sulayel | 38.2 | 10.4 | 85.3 |
| Tabuk | 39.6 | 10.8 | 88.4 |
| Taif | 38.5 | 9.6 | 82.2 |
| Turaif | 44.5 | 11.2 | 95.2 |
| Wajh | 35.9 | 8.7 | 75.5 |
| Yanbu | 37.7 | 7.1 | 69.7 |

**Table 8** BDW Speed (MPH) from LMW-Record at ST-Stations by Method of Moments

| Station | $\bar{V}_m$ | $s_m$ | $\upsilon''_{,50m}$ | $s(\upsilon''_{,50m})$ | $\upsilon^*_{,50m}$ |
|---|---|---|---|---|---|
| Abha | 36.9 | 6.0 | 64.1 | 4.65 | 70.0 |
| Baha | 34.2 | 6.8 | 65.1 | 5.27 | 71.8 |
| Gurayat | 43.3 | 10.1 | 89.3 | 9.04 | 100.9 |
| Makkah | 24.4 | 6.7 | 54.7 | 3.67 | 59.4 |
| Riyadh (KKIA) | 40.0 | 9.0 | 80.8 | 8.06 | 91.1 |
| Sharurah | 28.7 | 7.6 | 63.0 | 6.80 | 71.7 |