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# Extreme Winds in Kuwait Including the Effect of Climate Change

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## 1. Introduction

Wind turbines need to convert the kinetic energy of normal wind speed into electric power but the structure needs to withstand the wind loads exerted by the extreme wind speed on the mast and blades. Also high rise buildings around the world are designed for a wind speed whose probability of exceedence is 2% (Gomes and Vickery (1977), Milne (1992), Kristensen et al., (2000), Sacré (2002) and Miller (2003)). Recently, the State of Kuwait has approved construction of multistory buildings up to about 70 floors. For safe and optimal design of these high rise buildings, extreme wind speeds for different return periods and from different directions are essential. Wind data, measured at 10 m above the ground level at different locations can be used for the prediction of extreme wind speeds at that elevation. These unexpected high wind speed from different directions dictates the design of many structures like towers, high rise buildings, power transmission lines, devices for controlling the sand movements in desert areas, ship anchoring systems in ports and harbors, wind power plants on land and sea, chimneys etc. Also normal and extreme wind data is required for ground control and operation of aircrafts, planning for mitigating measures of life and properties during extreme winds, movements of dust etc. One of the factors for fixing the insurance premium for buildings, aircrafts, ships and tall towers by insurance companies is based on the safety and stability of these structures for extreme winds. The extreme wind speed, whose probability of occurrence is very rare, is also responsible for generating high waves in the seas, which dictates the design, operation and maintenance of all types of marine structures. How does one know the maximum wind speed which is expected at a specified location on the earth for a return period of 50 years or 100 years? This is a billion dollar question. The down to earth answer is "Install anemometers and measure the wind speed for 50 years or 100 years." One cannot wait for 50 to 100 years to obtain the maximum wind speed for that such a large period. The procedure is to use the available and reliable past data and apply the extreme value statistical models to predict the expected wind speeds for certain return periods (Gumbel (1958), Miller (2003)). Most of the countries around the world have the code for design wind speed and wind zoning systems. As on today, Kuwait does not have a code for design wind speed. Wind speed and its directions have been measured in many places in Kuwait for certain projects (for example, Abdal et al., (1986), Ayyash and Al-Tukhaim (1986)). It is also reported that the hinterland areas of Kuwait has wind power potential of about 250 W/m<sup>2</sup> which is appreciable (Ayyash and Al-

Tukhaim (1986)). Al-Nassar et al. (2005) has reported that wind power density of the order of  $555 \text{ W/m}^2$  is available in Al-Wafra, South of Kuwait, especially during summer, when the electricity demand is at its peak. The Kuwait International Airport has been collecting the wind data at different locations in Kuwait. These data, measured at 10 m elevation from the ground is used for the extreme value prediction from different directions in this project. Measured wind data were purchased from the Kuwait International Airport for different spatial locations for the past as many years as is available with them. The measured data from locations 1. Kuwait International Airport, 2. Kuwait Institute for Scientific Research (KISR), 3. Ras Al-Ardh (Salmiya), 4. Failaka Island and 5. Al-Wafra as shown in Fig.1 was used for the present study.

This book chapter contains the extreme wind speed at different directions and at 10 m elevation in Kuwait for all these five different locations. These five locations cover to a certain extent, the important land areas, Coastal and Island areas in Kuwait. Also the effect of climate change on extreme wind and gust speed is also studied for Kuwait International Airport location, where the measured data is available for 54 years. The results of this study can be used by public and private organizations/companies for analysis, design, construction and maintenance of tall engineering structures, where the extreme wind is one of the essential inputs.

The Gumbel extreme value distribution is widely used by the wind engineering community around the world, since the method is simple and robust. In Kuwait, wind data have been collected at many stations for many years, e.g. at Kuwait International Airport since 1957. The following studies are relevant for this book chapter with reference to wind studies in Kuwait:

- Analysis of wind speed and direction at different locations (Ayyash and Al-Tukhaim (1986), Abdal et.al. (1986))
- Assessment of wind energy potential (Ayyash et.al. (1985) and Al-Nassar et. al. (2005))
- Statistical aspect of wind speed (Ayyash et.al. (1984))
- Estimation of wind over sea from land measurement (Al-Madani et.al. (1989))
- Analysis of wind effect in the Arabian Gulf water flow field model (Gopalakrishnan (1988))
- Height variations of wind (Ayyash and Al-Ammar (1984))
- Extreme wind wave prediction in Kuwaiti territorial waters from hind casted wind data (Neelamani et. al. (2006))

Wind direction and speed are critical features in Kuwait because they are associated with dust and sand storms, especially during summer. In Kuwait, NW winds are dominant. The average wind speed in summer is about 30 to 50% higher than in fall-winter. Kuwait airport has recorded a maximum wind speed of 66 mph and maximum gust speed of 84 mph during 1968 (Climatological Summaries, Kuwait International Airport (1983)). Neelamani and Al-Awadi (2004) have carried out the extreme wind analysis by using the Kuwait International Airport data from 1962 to 1997 without considering the wind direction effect. Reliable data for a very long period is the main input for successful prediction of extreme wind speed. Simiu et al. (1978) found that the sampling error in estimating a wind speed with a 50 year return period from 25 years of data, with a 68% confident level is about  $\pm 7\%$ . The error in estimating the 1000 year return period value from 25 years of data is calculated to be  $\pm 9\%$ .





Fig. 1. Locations selected in Kuwait for extreme wind speed predictions.

2. Anemometer, calibration and maintenance schedules

The wind data is collected by KIA using MET ONE 034A-L WINDSET supplied by Campbell Scientific, INC, UK. The wind measuring station location, distance to the nearest obstructions, type of ground cover etc follows the Guidelines of the standards prescribed by WMO (1983), American Association of State Climatologists (1986) and the norms of EPA (1987 and 1989). The MET ONE 034A-L WINDSET anemometer instrument has operating

range of 0 to 49 m/s, threshold of 0.4 m/s, and accuracy of  $\pm 0.12$  m/s for wind speed of  $< 10.1$  m/s and  $\pm 1.1\%$  of the reading for wind speed  $> 10.1$  m/s. The wind direction range is 0 to  $360^\circ$  with threshold of 0.4 m/s, accuracy of  $\pm 4^\circ$  and resolution of  $0.5^\circ$ . The operating temperature range is  $-30^\circ$  to  $+70^\circ$  C. In Kuwait, the minimum temperature in winter is about  $2^\circ$  C and maximum temperature in the open desert in summer is about  $52^\circ$  C. Maintenance engineers specialized in operating and maintaining the above instrument are available to take care of the maintenance of the sensors. Every month, a visual/audio inspection of the anemometer at low wind speed is carried out. It was made sure that the rotations of the cup assembly and wind vane rotations were free. The cups and vanes were verified for its tightness. Every once in 6 month, the bearings of the anemometers are replaced. Once in every year the instrument is calibrated in the calibration facility of Ministry of Defense, Kuwait. The instrument is completely replaced once in two years. In case of any problem, which is not possible to solve locally, the instruments are sent back to Campbell Scientific, INC for refurbishment. Moreover, the wind data is measured by KIA for the air navigation purpose and special attention is provided for accurate data collection and proper routine maintenance of the anemometers.

For the present work, about 53 years of measured data at KIA location and about 12 years of data for other locations are available. The chapter is divided into two parts. The first part deals with extreme wind analysis for five deferent locations and different directions. The second part deals with the effect of climate change on the extreme 10 minute average wind speed and gust speed for the KIA location only, since wind data for 53 years is available only at KIA location.

### **3. Part 1: Extreme 10 minute average wind speed analysis for different locations and different directions**

#### **3.1 Details of wind data collected at different locations in Kuwait**

The measured wind data for five different spatial locations (Table 1), measured at 10 m elevation from the ground level were purchased from the Meteorology office, Kuwait International Airport. The name of location, latitude, longitude, land elevation from mean sea level (m) at each location, period of wind data available, the directions of wind measurements are provided in table 1. The raw data obtained from Meteorology office of KIA for the present study is the maximum wind speed and the corresponding direction for every day for all the locations referred in table 1. The maximum wind speed for a day is defined as the maximum value among the average of the 10 minute wind speed recorded for the whole day from a number of 10 minute data records.

The wind direction is divided into different segments as shown in table 1. For KIA, KISR and Al-Wafra location, the segment of the directional window is 22.5 degrees, whereas for Ras Al-Ardh and Failaka Island the segment of the directional window is 45 degrees. In table 1, fourth column, the direction 'N' means that wind is blowing from North. For KIA, data for a period of 45 years (1962 to 2006) is obtained, whereas for the other 4 locations (KISR, Ras Al-Ardh, Failaka Island and Al-Wafra) data for about 12 years is available. Hence we have adopted two different options of data preparation for the extreme wind analysis:-

- a. For KIA, the maximum value of the wind speed for each direction and for every year is selected as input for extreme wind analysis. Hence a total of 45 data for each direction is available for this location.

- b. For the other four locations, the maximum wind speed for every month and for each direction is used for extreme wind analysis. If yearly maximum wind speed value is used (like the one for KIA), then it will result in only 12 Nos. of data, which may not be sufficient for the extreme value analysis.

S.No.	Location	Latitude (North)	Longitude (East)	Land Elevation from Mean sea level (m)	Period of data used	Direction of measurement
1	Kuwait International Airport (KIA)	29° 13' 18"	47° 57' 57"	45.46	Jan 1962 – July 2006	N, NNW, NW, WNW, W, WSW, SW, SSW, S, SSE,SE, ESE, E, ENE, NE and NNE
2	Kuwait Institute for Scientific Research (KISR)	29° 20' 21.2 "	47° 54' 17"	4.58	June 1995 – March 2006	N, NNW, NW, WNW, W, WSW, SW, SSW, S, SSE,SE, ESE, E, ENE, NE and NNE
3	Ras Al-Ardh (Salmiya)	29° 21' 05.4"	48° 05' 58.7"	5.41	November 1992 – December 2004	N, NW, W, SW, S, SE, E and NE
4	Failaka Island	29° 26' 55"	48° 19' 58"	5.12	June 1996 – May 2004	N, NW, W, SW, S, SE, E and NE
5	Al-Wafra	28° 37' 09.5"	47° 56' 17.1"	164.0	June 1995 – March 2006	N, NNW, NW, WNW, W, WSW, SW, SSW, S, SSE,SE, ESE, E, ENE, NE and NNE

Table 1. Location, Period of Wind Data and Direction of Wind Measurements Available in Kuwait (Source: Kuwait International Airport)

3.2 Steps adopted for extreme wind prediction

Gumbel's extreme value distribution technique is widely used around the world for extreme wind prediction and hence the same is used for the present work. The following are the steps adopted for the prediction of extreme wind speed for different return periods:-

- a. The input data set for extreme wind analysis (yearly maximum wind speed for KIA location and monthly maximum wind speed for KISR, Ras Al-Ardh, Failaka Island and Al-Wafra respectively for different wind directions) is prepared by using the measured



- hourly maximum wind speed and direction at different locations in Kuwait by the Meteorology office, KIA.
- b. Extreme wind analysis (Step c to h) is carried out for data for a typical wind direction.
  - c. The wind speed data for the selected direction is arranged in descending order.
  - d. The Gumbel's plotting formula  $Q = (i-c_1)/(N+c_2)$  is used to reduce the wind speed data to a set of points describing the probability of exceedence of wind speed,  $Q$ , where 'i' is the rank order and 'N' is the total number of values ( $N = 45, 101, 122, 63$  and  $108$  for KIA, KISR, Ras Al-Ardh, Failaka Island and Al-Wafra respectively,  $c_1 = 0.44$  and  $c_2 = 0.12$  for Gumbel distribution).
  - e. The wind speed is then plotted against a reduced variate of  $Q$ . The reduced variate of  $Q$  for Gumbel distribution is  $y = -\ln [-\ln (1-Q)]$ .
  - f. A straight line is fitted by using least square principles through the points to represent a trend.
  - g. The slope and intercept of the straight line fit is obtained.
  - h. The wind speed for different return period,  $U_{TR}$  is then obtained using the formula  $U_{TR} = \gamma - \beta \ln[-\ln\{(\lambda T_R-1)/(\lambda T_R)\}]$ , where  $\beta$  is called as scale factor and  $\gamma$  is called as location factor.  
The value of  $\beta$  is calculated as  $\beta = (1/\text{slope of the line})$   
The value of  $\gamma$  is calculated as  $\gamma = (-\text{intercept} / \text{slope of the line})$ .  
Here  $T_R$  is the return period in years and  $\lambda$  is the number of events per year. For the present analysis,  $\lambda=1$  for the data measured in KIA .and is  $1/12$  for the data measured in KISR, Ras Al-Ardh, Failaka Island and Al-Wafra respectively.
  - i. The steps c to h is repeated for data from different wind directions and for different locations in Kuwait.
- A sample table of extreme wind analysis for KIA data for the NW direction is shown in Table 2.

Year	Max. Wind speed (m/s)	Max. Wind speed in descending order (m/s)	Rank, i	$Q=(i-0.44)/(N+0.12)$	$P=1-Q$	$T_R=1/(\lambda Q)$	$-\ln [-\ln (P)]$
1962	13.9	20.6	1	0.01241	0.9875	80.571	4.382
1963	15.6	20.1	2	0.03457	0.9654	28.923	3.347
1964	16.1	20.1	3	0.05673	0.9432	17.625	2.840
1965	12.5	20.1	4	0.07890	0.9210	12.674	2.498
1966	13	19.7	5	0.1010	0.8989	9.894	2.239
1967	15.6	18.8	6	0.1232	0.8767	8.115	2.028
1968	17.9	17.9	7	0.1453	0.8546	6.878	1.850
1969	18.8	17.9	8	0.1675	0.8324	5.968	1.696
1970	20.1	17.9	9	0.1897	0.8102	5.271	1.558
1971	20.1	17.4	10	0.2118	0.7881	4.719	1.435
1972	13.4	17	11	0.2340	0.7659	4.272	1.321
1973	20.1	16.7	12	0.2562	0.7437	3.903	1.217

1974	19.7	16.1	13	0.2783	0.7216	3.592	1.120
1975	20.6	16	14	0.3005	0.6994	3.327	1.028
1976	17	15.6	15	0.3226	0.6773	3.098	0.942
1977	17.9	15.6	16	0.3448	0.6551	2.899	0.860
1978	16.7	15	17	0.3670	0.6329	2.724	0.782
1979	17.9	15	18	0.3891	0.6108	2.569	0.707
1980	17.4	15	19	0.4113	0.5886	2.431	0.635
1981	14.7	14.7	20	0.4335	0.5664	2.306	0.565
1982	13.4	14.3	21	0.4556	0.5443	2.194	0.497
1983	13	14.3	22	0.4778	0.5221	2.092	0.431
1984	14.3	14	23	0.5	0.5	2	0.366
1985	13.4	14	24	0.5221	0.4778	1.915	0.303
1986	14.3	14	25	0.5443	0.4556	1.837	0.240
1987	14	14	26	0.5664	0.4335	1.765	0.179
1988	15	14	27	0.5886	0.4113	1.698	0.118
1989	15	13.9	28	0.6108	0.3891	1.637	0.057
1990	12	13.4	29	0.6329	0.3670	1.579	-0.002
1991	10	13.4	30	0.6551	0.3448	1.526	-0.062
1992	10	13.4	31	0.6773	0.3226	1.476	-0.123
1993	15	13	32	0.6994	0.3005	1.429	-0.184
1994	13	13	33	0.7216	0.2783	1.385	-0.245
1995	14	13	34	0.7437	0.2562	1.344	-0.308
1996	16	13	35	0.7659	0.2340	1.305	-0.373
1997	14	13	36	0.7881	0.2118	1.268	-0.439
1998	12	13	37	0.8102	0.1897	1.234	-0.508
1999	13	12.5	38	0.8324	0.1675	1.201	-0.580
2000	12	12	39	0.8546	0.1453	1.170	-0.656
2001	12	12	40	0.8767	0.1232	1.140	-0.738
2002	14	12	41	0.8989	0.1010	1.112	-0.829
2003	13	12	42	0.9210	0.0789	1.085	-0.931
2004	12	12	43	0.9432	0.0567	1.060	-1.054
2005	13	10	44	0.9654	0.0345	1.035	-1.213
2006	14	10	45	0.9875	0.0124	1.012	-1.479

Table 2. A Sample Table for the Extreme Wind Speed Analysis for the Wind Data from NW Direction Collected in Kuwait International Airport.

Similar tables are prepared for all different wind directions and different locations.



3.3 Results and discussions

A typical Gumbel distribution plot for the Direction NW for KIA location is given in Fig.2. The equation of the best line fit and the correlation coefficient,  $R^2$  are provided. The value of  $\gamma$  is 13.628 and  $\beta$  is 2.238 and  $R^2$  is 0.9531.

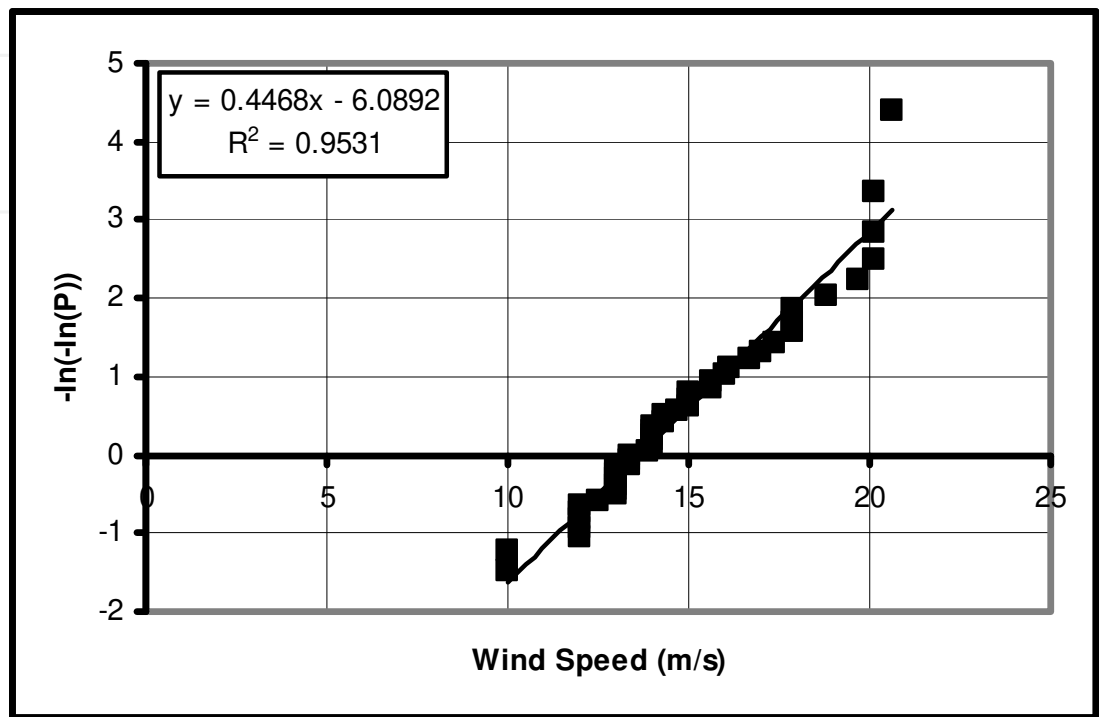


Fig. 2. Gumbel distribution plot for KIA wind data for the Direction NW

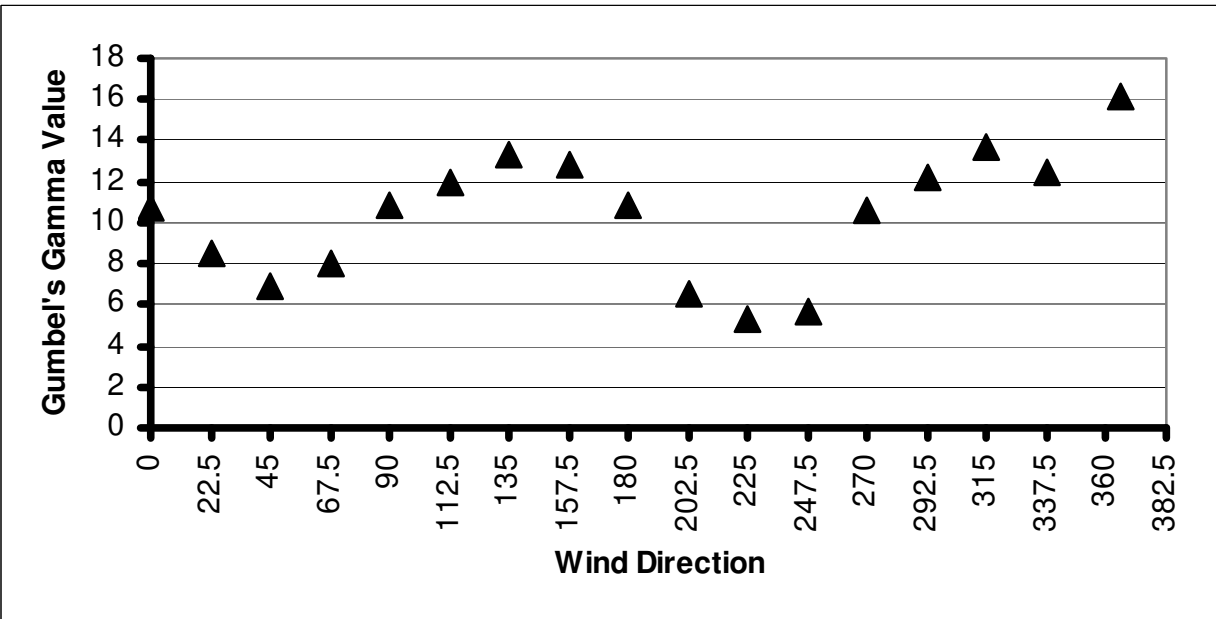


Fig. 3. Gumbel's  $\gamma$  value for all 16 directions and for the data without considering the effect of wind direction for KIA location

The value of  $\gamma$ ,  $\beta$  and  $R^2$  for all 16 different directions and for the combined data of all directions for KIA location is provided in Fig.3, 4 and 5 respectively.

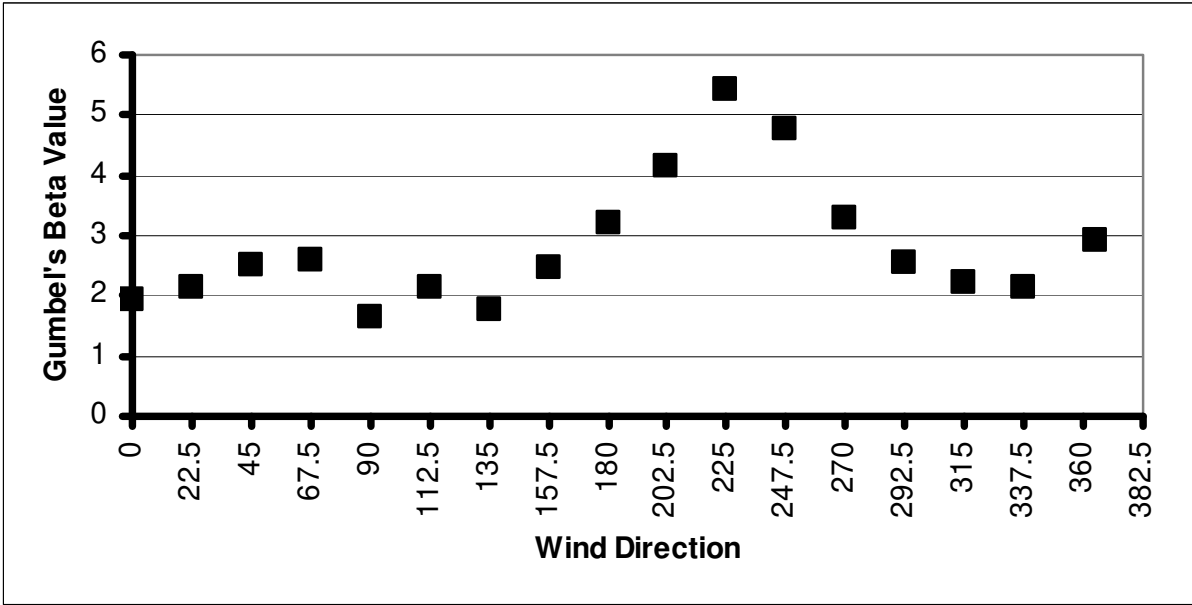


Fig. 4. Gumbel's  $\beta$  value for all 16 directions and for the data without considering the effect of wind direction for KIA location

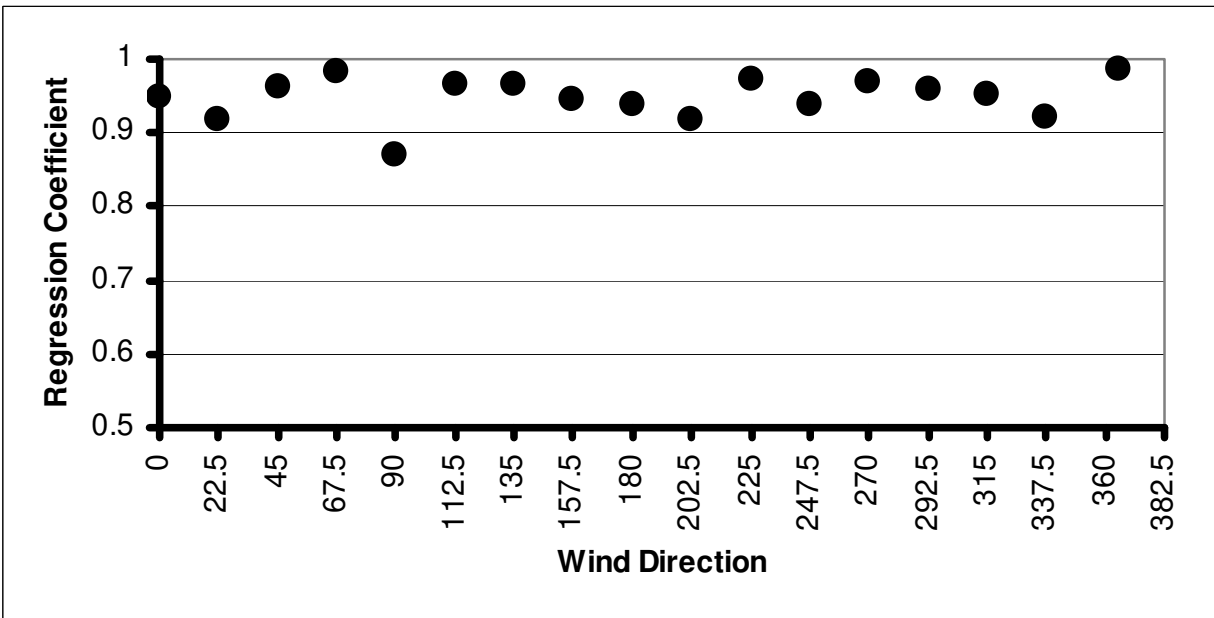


Fig. 5. Regression coefficient,  $R^2$  for wind data from all 16 directions and for the data without considering the effect of wind direction for KIA location.

In the above three figures, the wind direction of 0, 22.5, 45, 67.5, 90, 112.5, 135, 157.5, 180, 202.5, 225, 247.5, 270, 292.5, 315 and 337.5 corresponds to wind blowing from N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW respectively. The  $\gamma$ ,  $\beta$

and  $R^2$  values for the combined data, without considering the direction effect is provided for x axis at 365 degree (Though there is no 365 degree in reality), mainly for the sake of information and comparison. The  $\gamma$  value is found to be fluctuating from 5.3 to 16.2,  $\beta$  value is found to fluctuate from 1.65 to 5.4 and the value of  $R^2$  is found fluctuating from 0.87 to 0.99. The value of  $\gamma$  and  $\beta$  can now be substituted in the formula  $U_{TR} = \gamma - \beta \ln [-\ln\{(\lambda T_R - 1)/(\lambda T_R)\}]$  in order to estimate the extreme wind speed for different return periods and for different directions. It can be seen that most of the values of regression coefficients are more than 0.9, which provides enough confidence in using the value of  $\gamma$  and  $\beta$  for the prediction of extreme wind speed.

The values of  $\gamma$ ,  $\beta$  and  $R^2$  for all the five locations in Kuwait can be obtained from Neelamani et al (2007). The wind speed for different return period,  $U_{TR}$  and for different locations and directions can then be estimated using the formula  $U_{TR} = \gamma - \beta \ln [-\ln\{(\lambda T_R - 1)/(\lambda T_R)\}]$ . The predicted maximum wind speed for return periods of 10, 25, 50, 100 and 200 years from different directions for KIA location is given in Fig. 6.

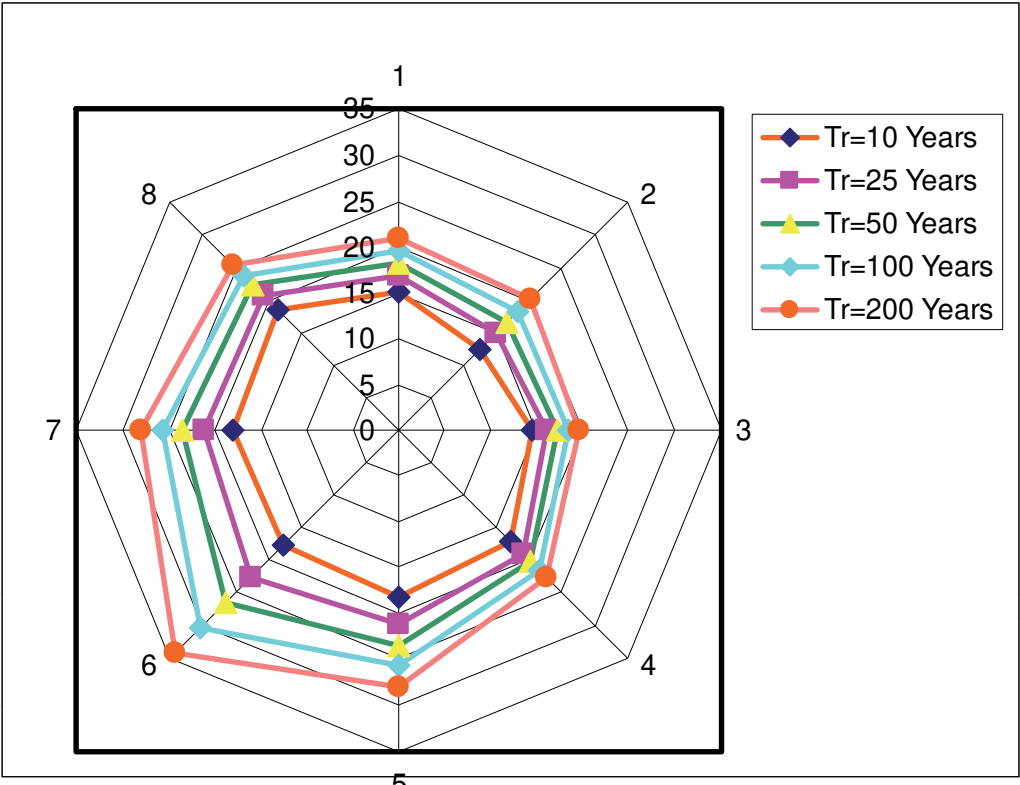


Fig. 6. The predicted maximum wind speed for different return periods and from different directions in KIA location in Kuwait

The following important information will be useful for the selection of suitable wind turbine, designing wind power plants and other tall structures in Kuwait:-

- a. The maximum wind speed for 100 year return period is expected to be of the order of 32.5 m/s and 30.5 m/s from SW direction and WSW directions respectively.

- b. The maximum wind speed from NW and SE direction (Most predominant wind direction in Kuwait) for a return period of 100 years is expected to be about 25 m/s and 22.3 m/s respectively.
- c. The smallest value of maximum wind speed for 100 year return period is expected to be about 19 m/s and is expected from the first quarter of the whole direction band (i.e. from N to E).
- d. From the present study it is found that the maximum wind speed without considering the directional effect is expected to be of the order of 31.24 m/s for a return period of 100 years in KIA location. Similarly, from Fig. 7, one can see that the highest wind speed is from NW for any return period for the KISR location.

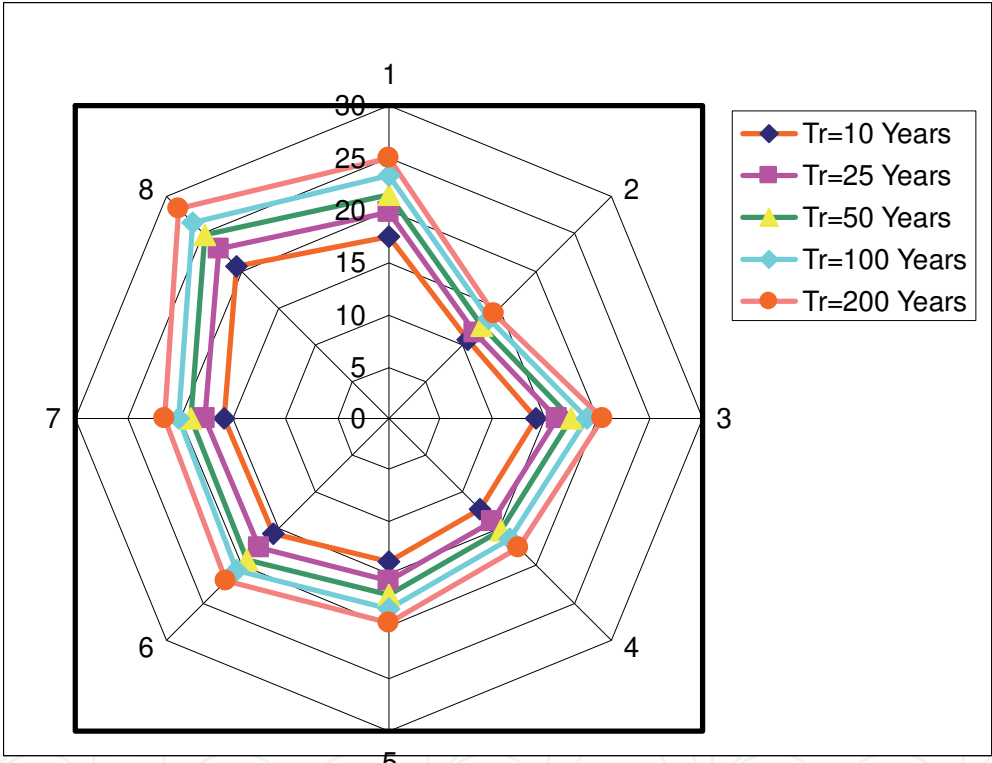


Fig. 7. The predicted maximum wind speed for different return periods and from different directions in KISR location in Kuwait

For Ras Al-Ardh location (Fig. 8), the highest wind speed for any return period is from N. For Failaka island (Fig.9), the highest wind speed for any return period is from N, NW and SW. Finally, for Al-Wafra (Fig.10), the highest wind speed for any return period is both from N and S.

In order to see the effect of change in spatial locations on the predicted 100 year return period wind speed, Fig.11 is provided. It can be seen that the change in spatial location to an extent of about 50 km from the main station (KIA) has reflected significant change in the predicted 100 year probable extreme wind speed.



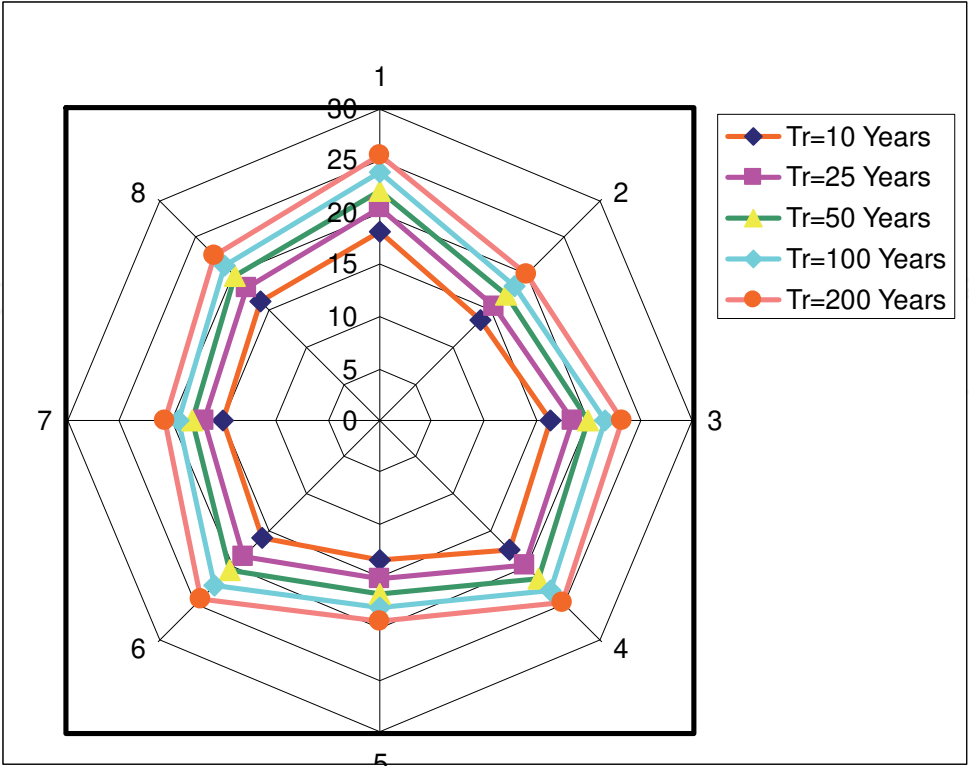


Fig. 8. The predicted maximum wind speed for different return periods and from different directions in Ras Al-Ardh location in Kuwait

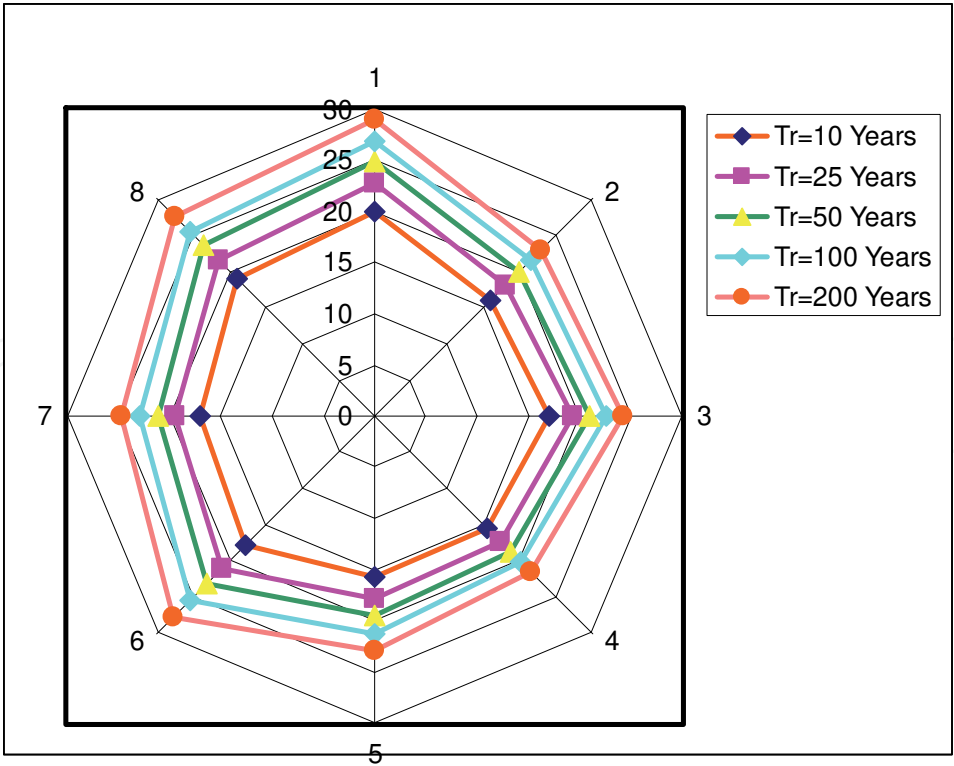


Fig. 9. The predicted maximum wind speed for different return periods and from different directions in Failaka Island location in Kuwait

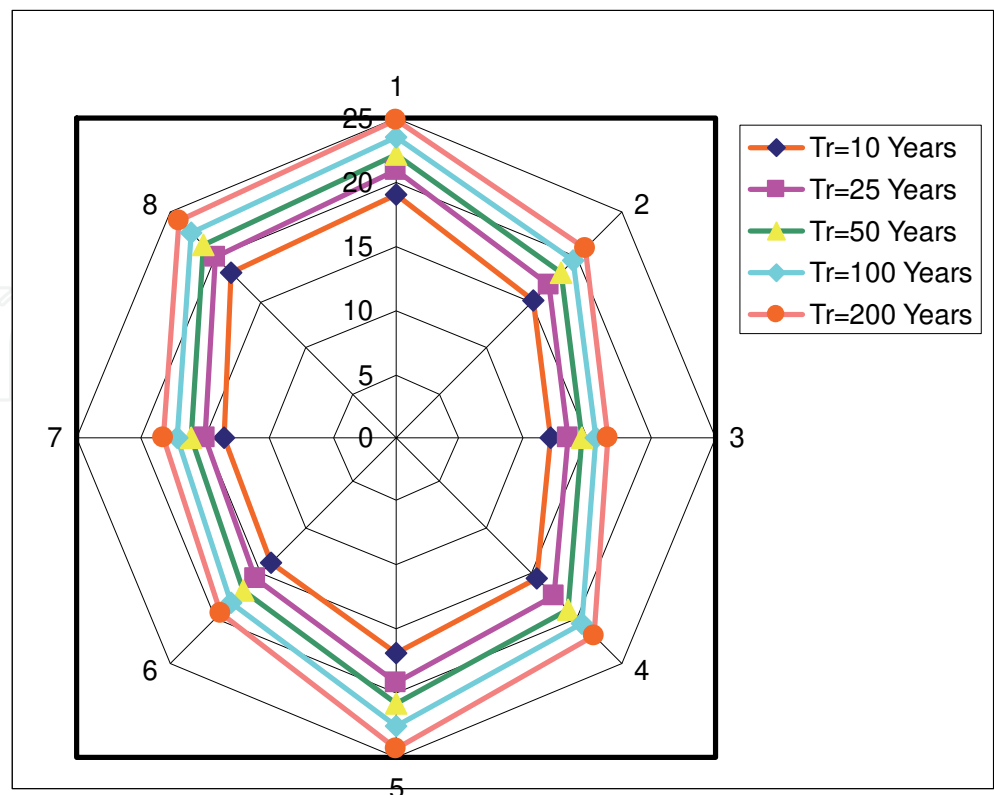


Fig. 10. The predicted maximum wind speed for different return periods and from different directions in Al-Wafra location in Kuwait

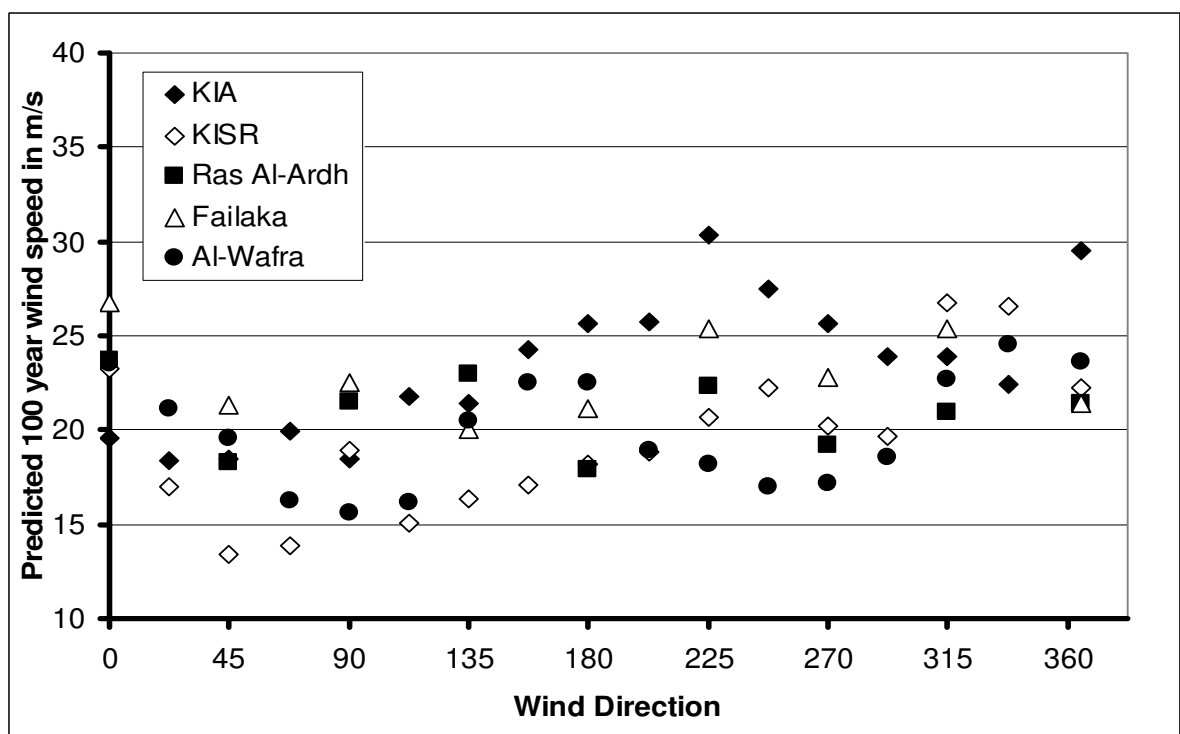


Fig. 11. Comparison of the predicted maximum wind speed for 100 year return periods and from different directions in KIA, KISR, Ras Al-Ardh, Failaka Island and Al-Wafra area

For example, the wind speed for 100 year return period from SW direction at KIA is about 30.3 m/s, whereas it is only about 18 m/s in Al-Wafra area. Al-Wafra area is located at the Southern boundary of Kuwait and is the main farming area in Kuwait. The plants and trees in the farm houses may dissipate significant amount of wind energy blowing from SW. Fig.11 can be used to select the appropriate expected extreme wind speed for 100 year return period at these 5 different locations and from different directions in Kuwait. This will help in appropriate design orientation of tall buildings in order to reduce the wind loading.

The extreme wind speed value and the associated direction will also be useful for the estimation of extreme sand and dust movements in Kuwait. This is because the extreme wind blowing from Iraq (North and North-West) and from Saudi Arabia (South and South-West) brings a large quantity of sand from the desert whereas the wind blowing from the Arabian Gulf side (North-East, East and South-East) moves significant amount of sand from Kuwait to the bordering countries.

#### **4. Part 2: The effect of climate change on the extreme 10 minute average wind and gust speed**

Climate change is already beginning to transform the life on Earth (<http://www.nature.org/initiatives/climatechange/issues>). Around the globe, seasons are shifting, temperatures are increasing and sea levels are rising. If proper actions are not taken now, the climate change will permanently alter the lands and waters we all depend upon for our survival. Some of the most dangerous consequences of climate change are Higher temperatures, changing landscapes, wildlife at risk, rising seas, increased risk of drought, fire and floods, stronger storms and increased storm damage, more heat-related illness and disease and significant global economic losses. In general, it is believed that global warming and climate change has more negative impacts than positive impacts. There are no proven findings on the effect of climate change on the extreme wind speeds at different locations on the earth. However an attempt can be made to visualize the impact, if measured wind data is available for the past many years, say at least for the past 50 years. How does one know the effect of global warming and climate change on the extreme winds and gusts. The only way is to get measured quality data for the past many years, divide them into few data segments (like 20 years of oldest data, 20 years of intermediate years and the latest 20 years), carry out the analysis on these data segments and analyze the trend of the predicted extreme values. For the present work, 45 years of measured data at KIA location (From 1957 to 2009) are available. The measured yearly maximum 10 minute average wind speed and the yearly maximum gust speed are as shown in Fig.12. It is seen that the gust speed has reached to 38 m/s during the past 53 years and the 10 minute average wind speed has reached to 30 m/s. The raw data obtained from Meteorology office of KIA for the present study is the maximum value of the 10 minute average wind speed and the gust speed for every day. Gumbel's extreme value distribution, as discussed in part I is adopted for obtaining the extreme 10 minute average wind and gust speed. The input data for extreme wind analysis (yearly maximum 10 minute average wind speed and the yearly maximum gust speed) is updated and extracted from the measured daily maximum 10 minute average wind and the gust speed data for the period 1957 to 2009. These data are separated into three sets of data groups covering the year 1957-1974, 1975-1992, 1993-2009, each of 18 years duration. Extreme wind analysis is carried out on each data group for both 10 minute average wind speed and the gust speed.

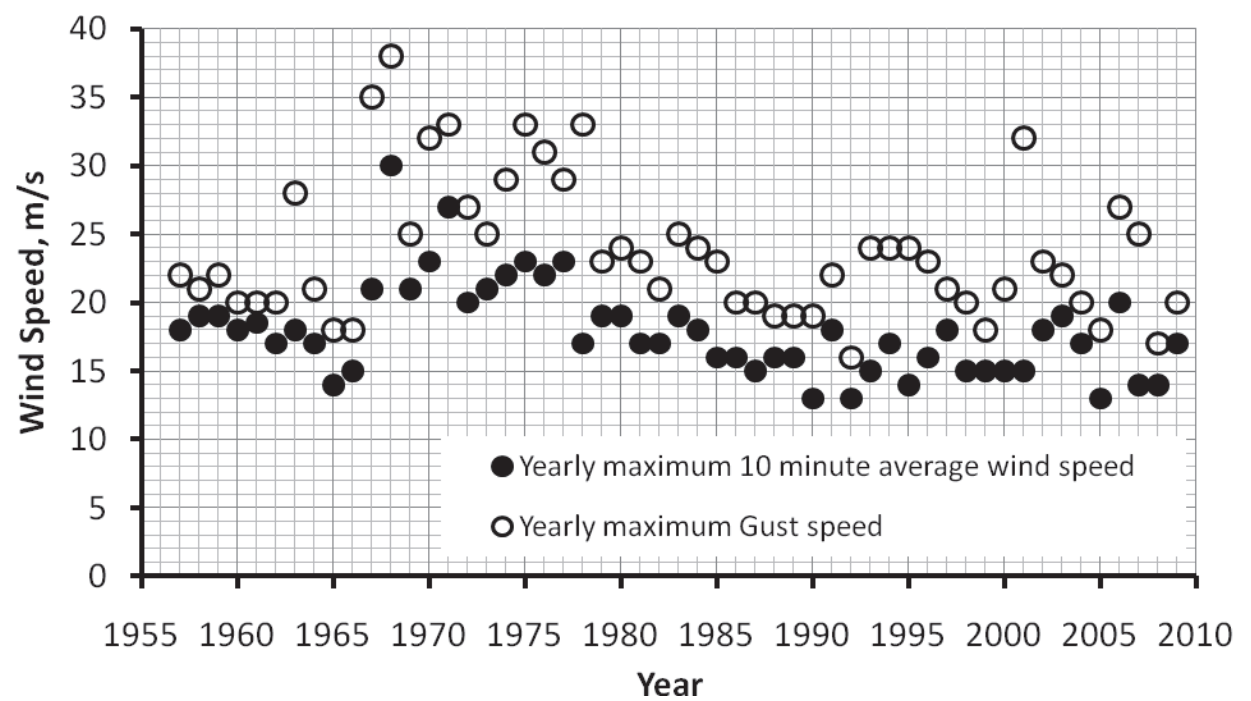


Fig. 12. The measured yearly maximum 10 minute average wind speed and the yearly maximum gust speed in Kuwait International Airport

Year	Max. Wind speed (m/s)	Max. Wind speed in descending order (m/s)	Rank, i	$Q=(i-0.44) / (N+0.12)$	$P=1-Q$	$T_R =1/ (\lambda Q)$	$-\ln [-\ln (P)]$
1993	24	32	1	0.012411348	0.987589	80.57143	4.3829061
1994	24	27	2	0.034574468	0.965426	28.92308	3.34709822
1995	24	25	3	0.056737589	0.943262	17.625	2.84025512
1996	23	24	4	0.078900709	0.921099	12.67416	2.49875277
1997	21	24	5	0.10106383	0.898936	9.894737	2.23920429
1998	20	24	6	0.12322695	0.876773	8.115108	2.02869443
1999	18	23	7	0.145390071	0.85461	6.878049	1.85080821
2000	21	23	8	0.167553191	0.832447	5.968254	1.69616232
2001	32	22	9	0.189716312	0.810284	5.271028	1.5588833
2002	23	21	10	0.211879433	0.788121	4.719665	1.4350469
2003	22	21	11	0.234042553	0.765957	4.272727	1.32189836
2004	20	20	12	0.256205674	0.743794	3.903114	1.21742716
2005	18	20	13	0.278368794	0.721631	3.592357	1.1201187
2006	27	20	14	0.300531915	0.699468	3.327434	1.02880144
2007	25	18	15	0.322695035	0.677305	3.098901	0.94254836
2008	17	18	16	0.344858156	0.655142	2.899743	0.86061123
2009	20	17	17	0.367021277	0.632979	2.724638	0.78237526

Table 3. A Sample Table for the Extreme Gust Speed Analysis for the Wind Data during the year 1993 to 2009



A sample table of extreme wind analysis for the gust data during the year 1993 to 2009 is shown in Table 3.

Similar tables are prepared for all the other 5 data sets.

Gumbel distribution plot for the three data sets of 10 minute average wind speed and three data sets of gust speed is given in Fig.13 to 18. The equation of the best line fit and the correlation coefficient,  $R^2$  are also provided in each figures.

The value of  $\gamma$ ,  $\beta$  and  $R^2$  for all the six different data sets is provided in table 4.

Type of data	Year range	$\gamma$	$\beta$	$R^2$
10 minute average wind speed data	1957-1974	4.047	12.754	0.960
	1975-1992	3.123	12.086	0.895
	1993-2009	2.087	12.176	0.885
Gust speed data	1957-1974	6.325	14.033	0.960
	1975-1992	5.244	14.274	0.895
	1993-2009	3.858	15.227	0.885

Table 4. The value of  $\gamma$ ,  $\beta$  and  $R^2$  for all the six different data sets

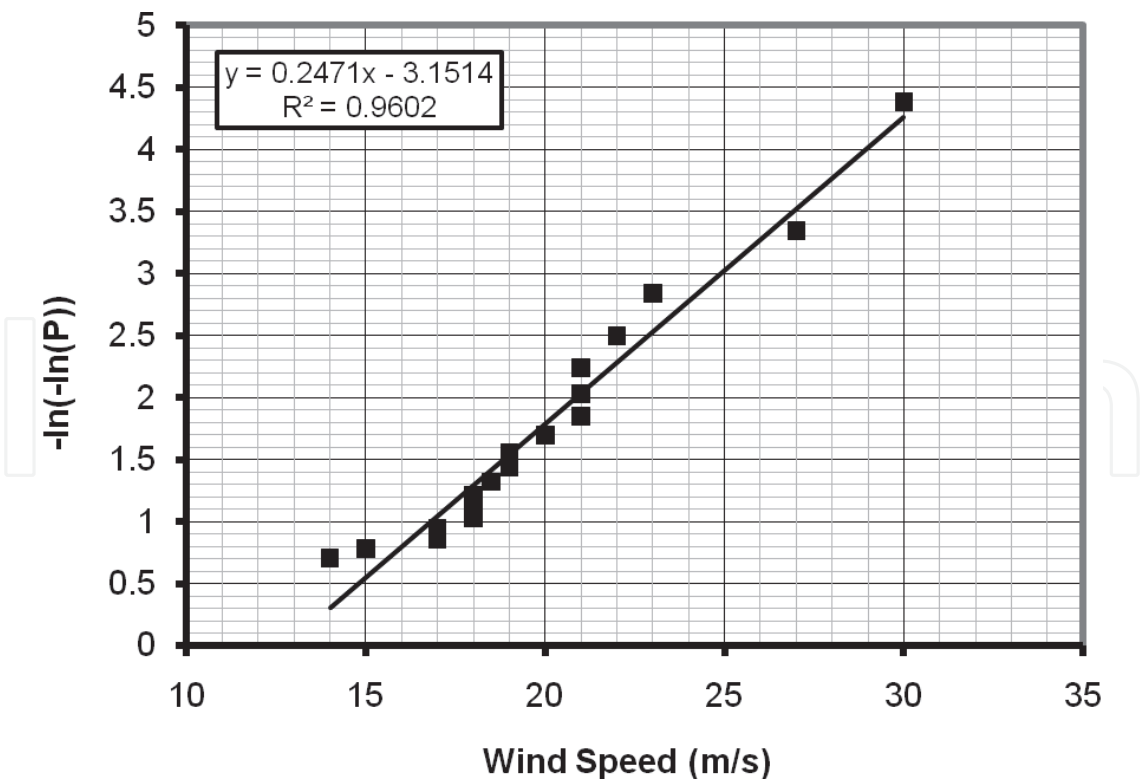


Fig. 13. Gumbel distribution plot for the maximum yearly 10 minute average wind speed data for the year 1957-1974

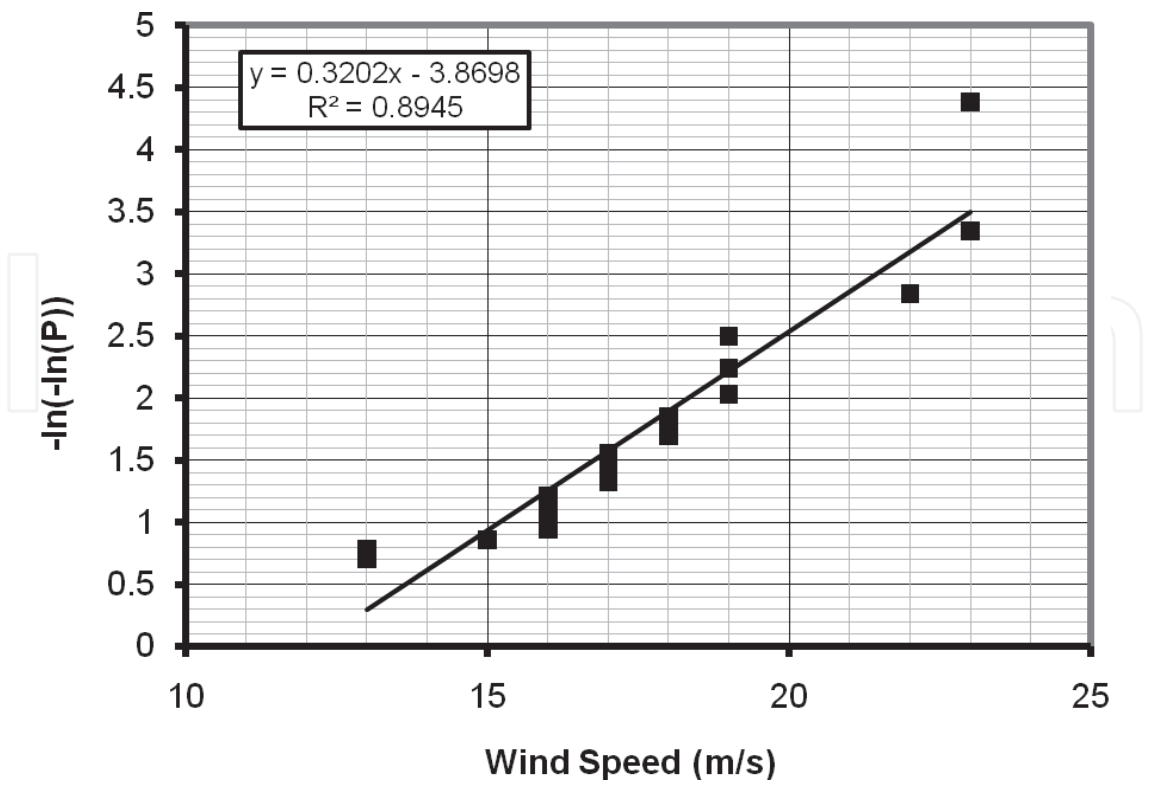


Fig. 14. Gumbel distribution plot for the maximum yearly 10 minute average wind speed data for the year 1975-1992

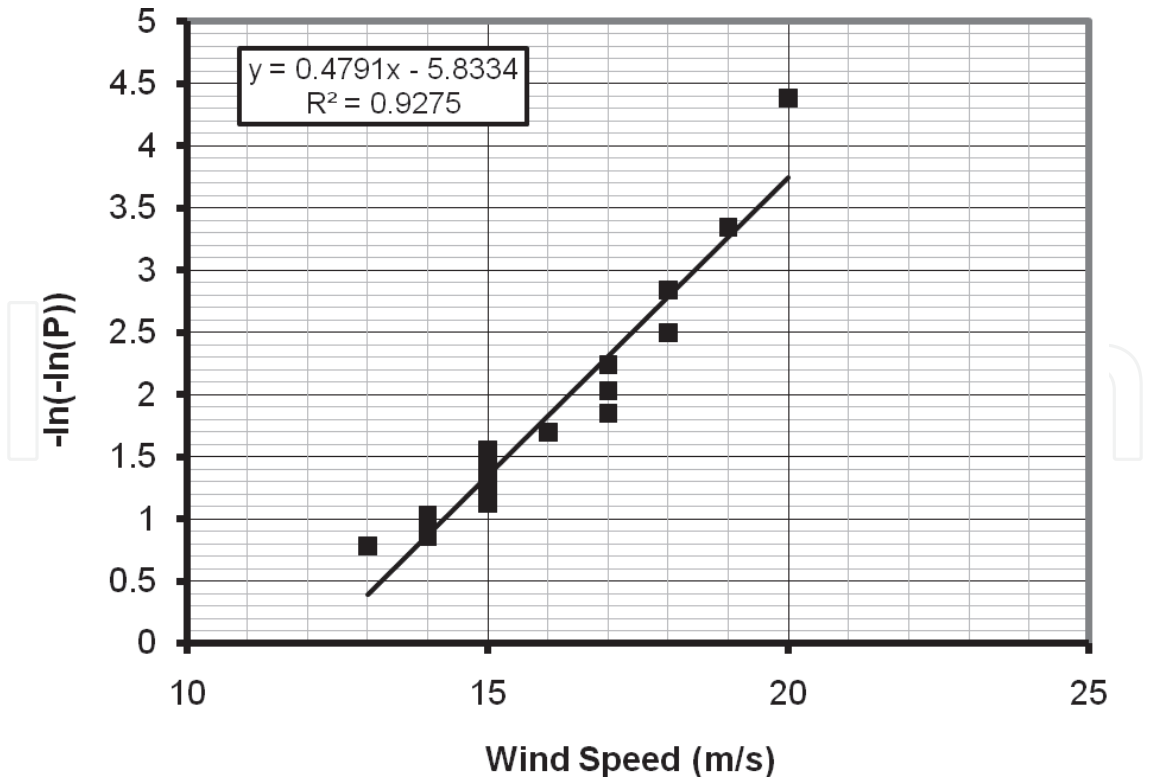


Fig. 15. Gumbel distribution plot for the maximum yearly 10 minute average wind speed data for the year 1993-2009

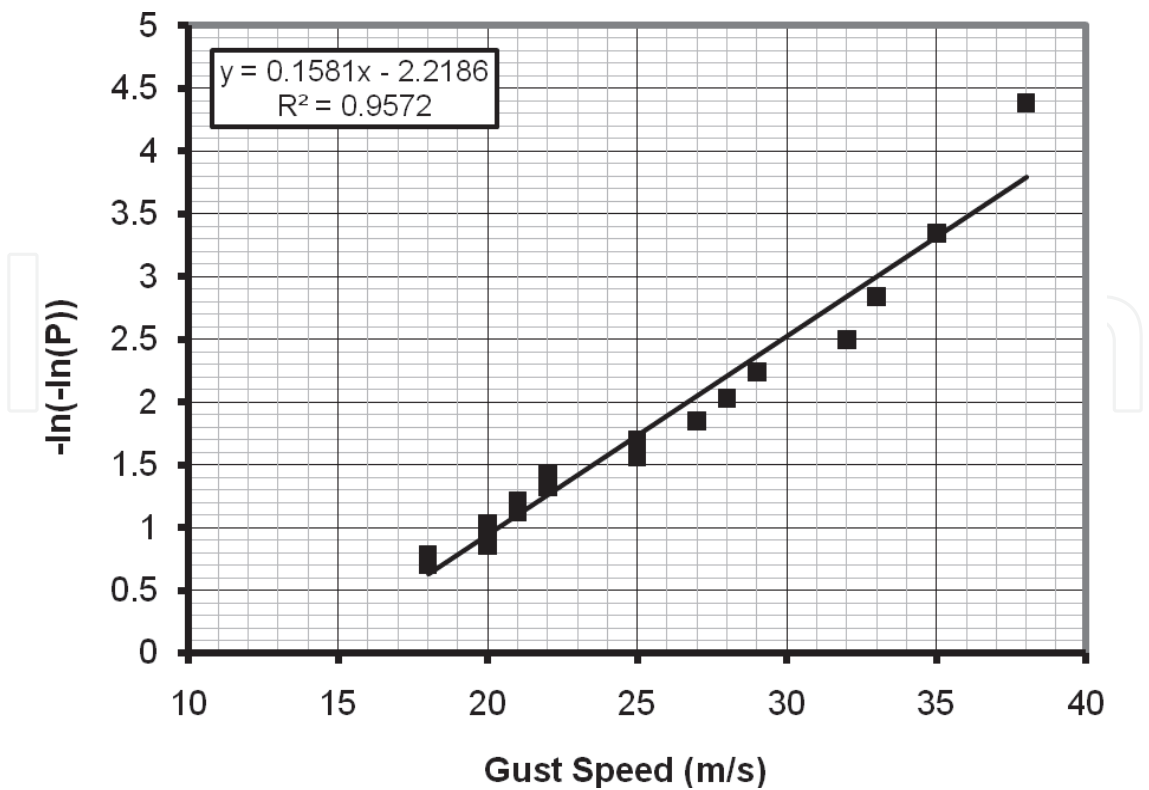


Fig. 16. Gumbel distribution plot for the maximum yearly gust speed data for the year 1957-1974

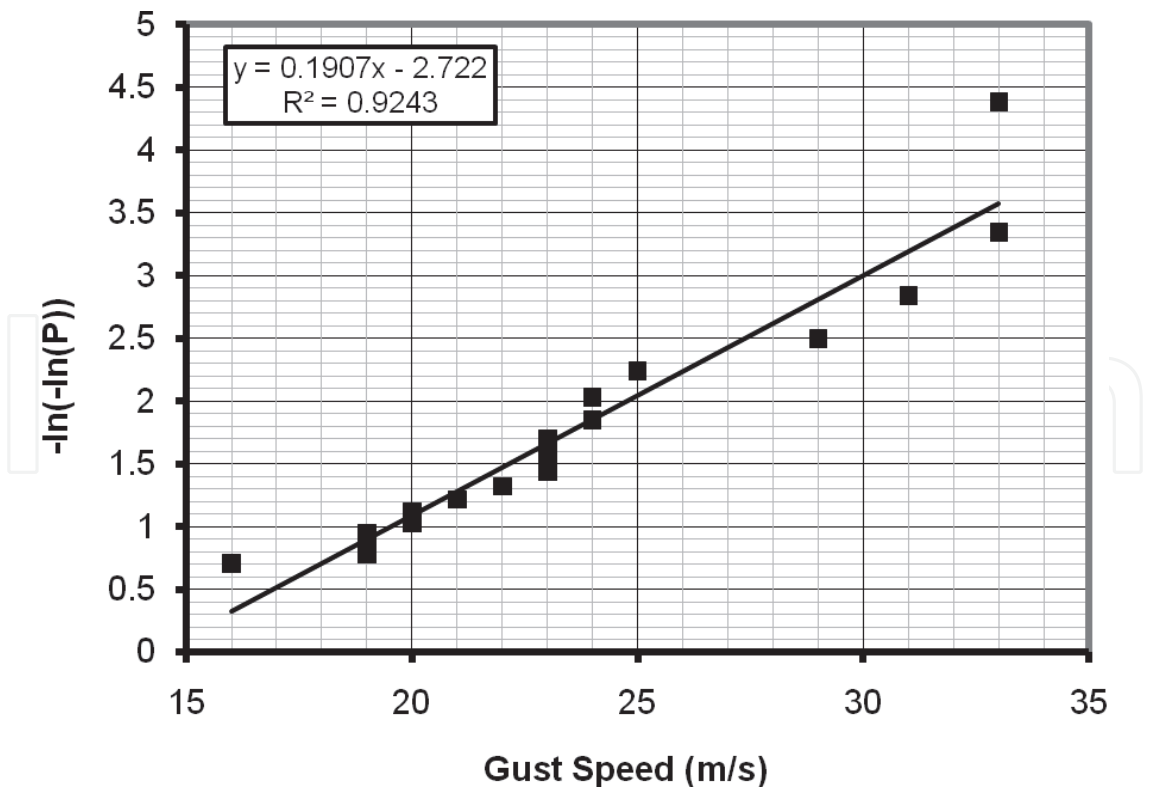


Fig. 17. Gumbel distribution plot for the maximum yearly gust speed data for the year 1975-1992

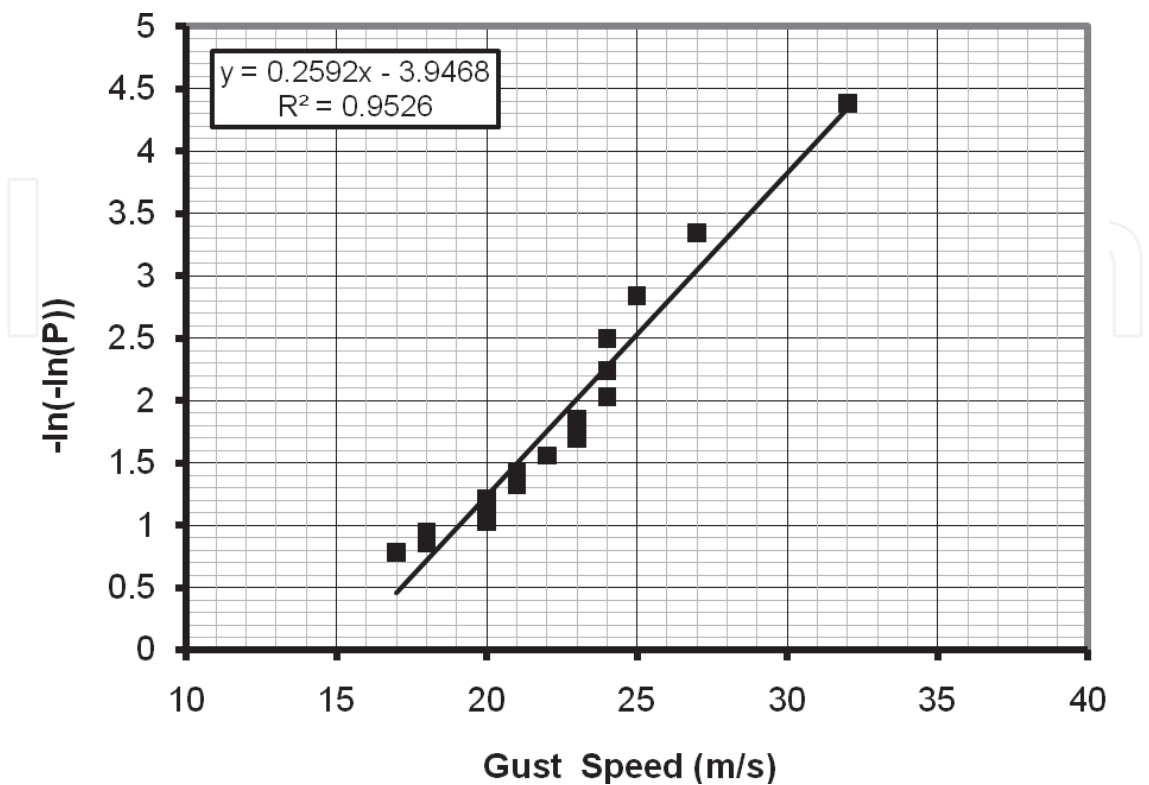


Fig. 18. Gumbel distribution plot for the maximum yearly gust speed data for the year 1993-2009

The plot showing the predicted extreme 10 minute average wind speed for return periods up to 200 years from the extreme value analysis using the three different data groups for the year range 1957-1974, 1975-1992 and 1993-2009 are given in Fig. 19.

It is clear from the following figure that for any return period, the extreme 10 minute average wind speed is the highest for the data in the year range of 1957-1974 and minimum for the latest data set i.e. for the year ranged from 1993-2009. The probable reason for this trend can be as follows:

The temperatures are rising but the temperature gradients, which is mainly responsible for the atmospheric pressure difference may not be increasing. There may be other reasons, which is not clear at this stage. Similarly the plot showing the predicted extreme gust speed for return periods up to 200 years from the extreme value analysis using the three different data groups for the year range 1957-1974, 1975-1992 and 1993-2009 are given in Fig. 20. This figure also indicated that the extreme gust speed for any return period is the highest for the data set 1957-1974 and minimum for the latest data set 1993-2009.

From the following two figures, it is found that the extreme 10 minute average wind speed for 100 year return period is 31.4, 26.5 and 21.8 m/s based on the data set for 1957-1974, 1975-1992, 1993-2009 and the extreme gust speed for 100 year return period is 43.1, 38.4 and 33.0 m/s for the same data sets respectively. This information can be used while designing tall structures and other engineering applications, where the extreme wind data is an essential input for safe and economic design.



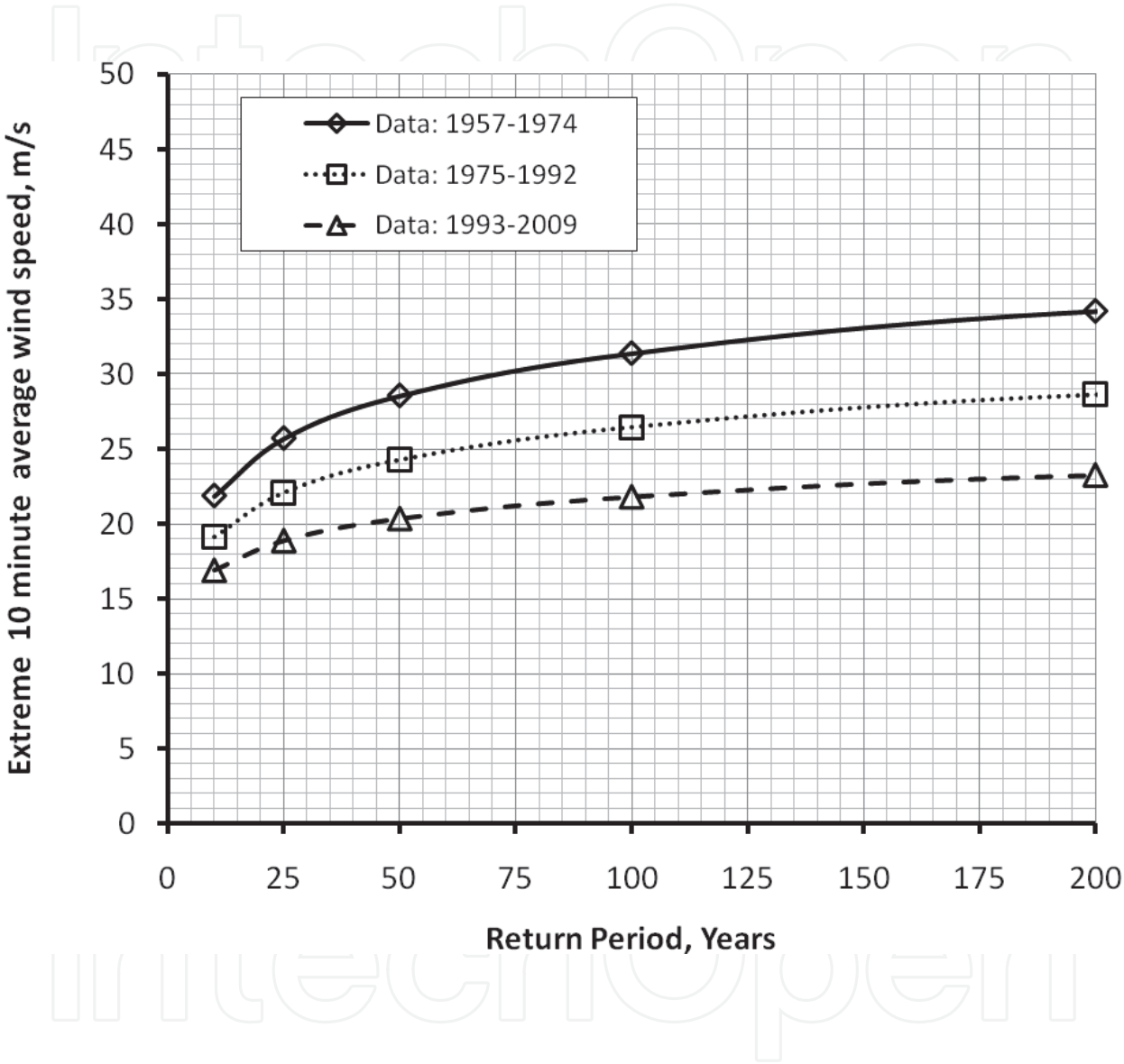


Fig. 19. The predicted extreme 10 minute average wind speed for different return periods from the three different data groups for the year range 1957-1974, 1975-1992 and 1993-2009.

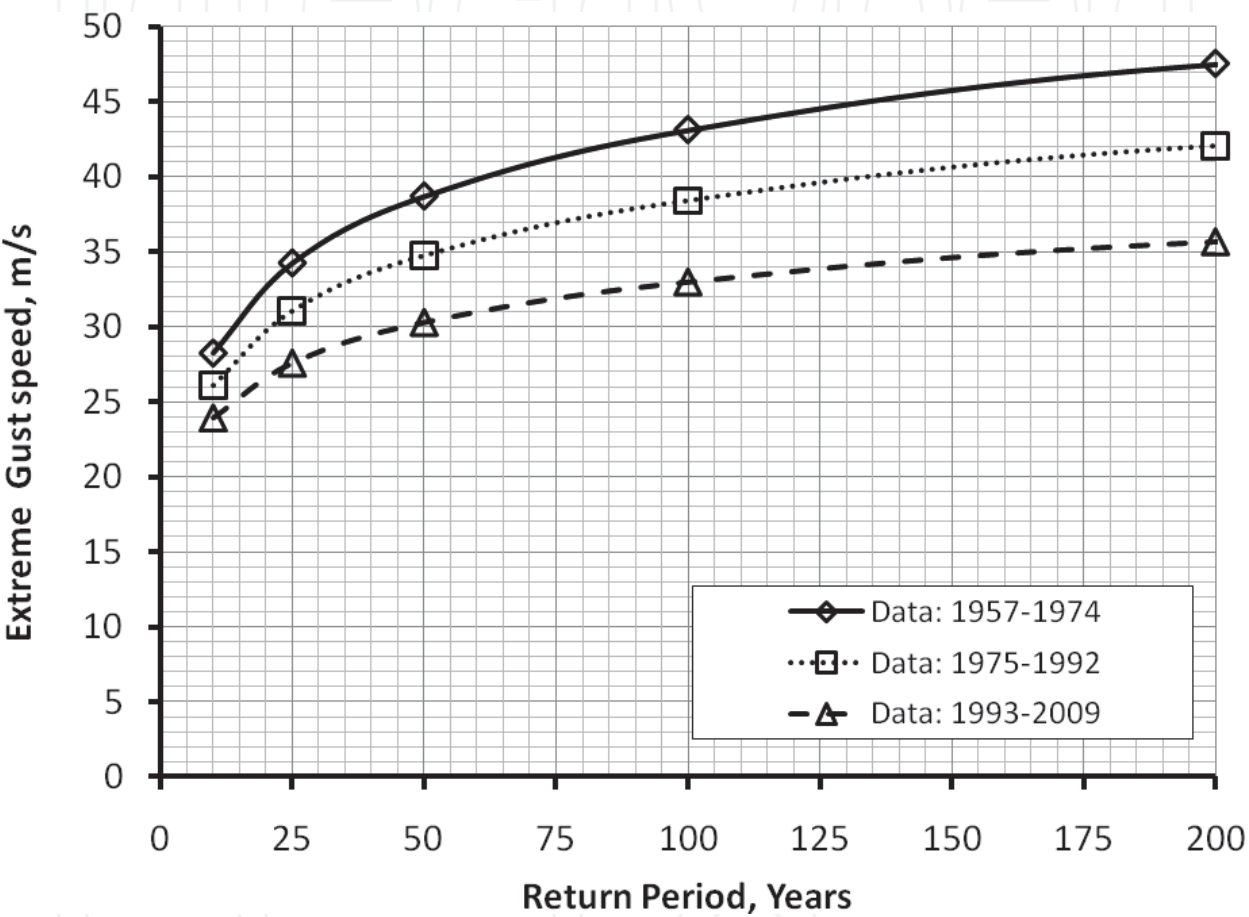


Fig. 20. The predicted extreme gust speed for different return periods from the three different data groups for the year range 1957-1974, 1975-1992 and 1993-2009.

## 5. Conclusions

Extreme wind speed from different directions and for return periods of 10, 25, 50, 100 and 200 years were predicted for five different locations in Kuwait Viz. Kuwait International Airport (KIA), Kuwait Institute for Scientific Research (KISR), Ras Al-Ardh, Failaka Island and Al-Wafra. Measured wind speed by the Meteorological office of KIA is used for this analysis. The wind speeds are measured at 10 m elevation from the ground and the data value is the average of 10 minutes duration. For KIA location, data is available for 45 years (From 1962 to 2006). For other locations, measured data is available for about 12 years. The annual maximum measured wind speed data at KIA location is used as input for the extreme value analysis for KIA location, whereas the monthly maximum measured wind speed data is used for other locations. The extreme 10 minute average wind speeds are predicted based on Gumbel distribution. The wind speed on the earth is dictated by the spatial gradient of the atmospheric pressure which in turn is governed by the temperature gradient. The long term climate change affects the temperature gradients and hence the wind speed. Extreme wind and Gust speed for different return periods is an important input for safe and economic design of tall structures, power transmission towers, extreme sand movement in desert and its effects on farm land and related infrastructures. The updated wind and Gust speed data from Kuwait International Airport (measured data for 54 years from 1957 to 2009) is divided into 3 equal periods, i.e. 1957-1974, 1975-1992, 1993-2009, each of 18 years duration. Extreme value analysis is also carried out on these three sets of data to understand the climate change effect on the extreme wind speed. The following important conclusions are obtained based on the study:-

- a. Among the five locations selected for the study,
  - KIA area is expected to experience the highest wind speed from ENE, ESE, SSE, S, SSW, SW, WSW, W, and WNW directions.
  - KISR area is expected to experience the highest wind speed from NW and NNW.
  - Ras Al-Ardh area is expected to experience the highest wind speed from SE.
  - Failaka Island is expected to experience the highest wind speed from N, NE and E.
  - Al-Wafra Island is expected to experience the highest wind speed from NNE.
- b. Even though the total land area of Kuwait is about 17,818 km<sup>2</sup>, the variation of space has very significant effect on the predicted extreme wind speeds in Kuwait. For example, the 100 year return period wind speed from NW direction varies from 21 m/s to 27 m/s, when the location is changed from Ras Al-Ardh to KISR. Similarly, the 100 year return period wind speed from SW direction varies from 18 m/s to 31 m/s, when the location is changed from Al-Wafra to KIA. Similarly, the 100 year return period wind speed from SE direction varies from 16 m/s to 23 m/s, when the location is changed from KISR to Ras Al-Ardh.
- c. Hence it is strongly recommended that both the effect of wind direction as well as the location need to be considered, while selecting the probable extreme wind speed for different return periods for any engineering or scientific applications. The results of the present study can be useful for the design of tall structures, wind power farms, the extreme sand transport etc in Kuwait.
- d. It is found that the extreme 10 minute average wind speed for 100 year return period is 31.4, 26.5 and 21.8 m/s based on the data set for 1957-1974, 1975-1992, 1993-2009.
- e. The extreme gust speed for 100 year return period is 43.1, 38.4 and 33.0 m/s for the same data sets.

- f. It is clear from the study that long term climate change has reduced the extreme wind speeds in Kuwait.
- g. This information will be useful for various engineering works in Kuwait. Further investigation is needed to understand why the extreme wind speed for any return period is reducing when the latest data set is used compared to the oldest data set.

## 6. Acknowledgements

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