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Quantifying the contributions of different time-scales to wind speed using wavelets

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ABSTRACT
Wind data analysis and accurate wind energy assessment are critical for proper and efficient development of wind power application and is highly site-dependent. The wind power is intermittently available due to the fluctuating nature of the wind and hence needs to be understood well. The present work exploits daily mean values of wind speed from different meteorological stations spread over the Kingdom of Saudi Arabia to understand the dynamic nature of the wind using wavelet transform and fast Fourier transform power spectrum. It is found that wind speed changes by ±0.6 to ±1.6 knots over a long period of about 10 years depending on the locations. The long-term mean wind speed of 5.6, 8.9, 6.25, 8.1, 6.0, 7.1, 6.0, 8.6 and 7.3 knots were obtained at Abha, Dhahran, Gizan, Guriat, Hail, Jeddah, Riyadh, Turaif and Yanbu, respectively.

Keywords: wind energy, wind speed, wavelet, fast Fourier transform, power spectrum.

1. Introduction

The variability of wind speed covers a wide spectrum of time-scales from seconds to several years, say, random variation at very short interval (turbulence scale), synoptic scale, seasonal variation, annual cycle variation, etc. This statistical information is required not only for a feasibility study of the wind farm to be installed but also for wind power prediction at different years/seasons/months/day as well as wind turbine control. Without analytical prediction, the statistical information on variations of past wind at different at time-scales can give us a rough idea about how the wind will behave in the near future [1-2]. Usually, most of the signals contain numerous non-stationary or transitory characteristics such as drift, trends, abrupt changes, and beginnings and ends of events. These characteristics are often the most important part of the signal and are needed to be analyzed to understand physical phenomena hidden behind the signal. Wavelet analysis allows the use of long time intervals where we want more precise low-frequency information, and shorter regions where we want high-frequency information.

To investigate the timescale structure of natural wind, the wavelet transform is employed to the time history of measured wind velocity data [3]. Ref. [4] applied the wavelet transform to the time data of roof-corner pressures with extreme local loads and obtained the PDFs on the time-dependent characteristics of the pressure transients. Based on these PDFs, a method to generate synthetic signals was developed, and time histories similar to the original roof-corner pressure data were composed. A new wind speed data generation scheme was introduced in Ref. [5], based on wavelet transform and compared this scheme with existing wind speed generation methods. Their results proved that the proposed wavelet-based method was found to be the best for wind speed data generation compared with existing methods. Wavelet transform as a time-frequency analysis to meteorological data for the region of Adrar, Algeria was exercised in Ref. [6] to investigate the power spectra behaviors of wind speed and its variations with time. The results showed significant synoptic oscillations for periods of 2 to 16 days in the cold weather. The wavelet power spectrum also revealed the presence of intra-seasonal oscillations for periods of 30 to 60 days.

When the wind has salient periodic features only over limited intervals of times, a global Fourier analysis is theoretically possible; but it may not be practical or efficient. The Fourier transform is limited because an analysis with single window cannot detect features in the signal that are either much longer or much shorter than the window size. Therefore, to have better representation of the wind spectrum for such case, we should seek a representation that is capable of following the wind spectrum as it varies with time [7]. Such representation is known by Time–Frequency Representation [8].

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The signals of meteorological parameters of the Kingdom of Saudi Arabia have so much noise that their overall shape is not apparent upon visual inspection. Thus, wavelet analysis is useful in revealing signal trends, a goal that is complementary to the one of revealing a signal hidden in the noise. If the signal itself includes sharp changes, then successive approximations look less and less similar to the original signal. A repeating pattern in the wavelet coefficient plots is characteristic of a signal that looks similar on many scales.

The main objective of the present work is to understand the fluctuating nature of the wind using wavelet and fast Fourier transform power spectrum techniques which are very useful to quantify the highly fluctuating natural phenomenon. The daily mean values of wind speed time series data over a period of 1990 - 2005 at Abha, Dhahran, Gizan, Guryat, Hail, Jeddah, Riyadh, Turaif and Yanbo, all in Saudi Arabia, are analyzed.

2. Steady nature of wind speeds

Wind speed data are obtained from the nine weather stations in Saudi Arabia, showing great potential for application in verifying the current criteria used for design practices. Illuminations are shed on FFT analysis results of wind speed data. Here data analysis of daily average wind-speed time series data is done for 1990 to 2005. The data was scanned every three seconds and 10-minute average values were recorded. Finally, the daily average values were obtained using 144 10-minute average values recorded during 24 hours. The total number of daily average data points in the time series for 1990 to 2005 is 5960. The power spectra of daily average wind speed time series data at the nine locations are shown in Fig. 1. While the horizontal axis represents the frequency f (1/day = D^{-1}), the vertical axis shows energy at the frequency. Abha is a station with many hills around. As seen in Fig. 1(a) for Abha, power spectral energy mostly concentrates on a low frequency range 0.002 – 0.006 D^{-1} with a peak at f = 0.0027 D^{-1}. The peak corresponds to a period of about $T = 1/f \approx 370$ days ≈ one year, implying that wind speed variation in a year is similar to that in another at least qualitatively. One should not be confused with the 370 days; the deviation from exactly 365 days arises from the frequency resolution in the FFT analysis. The f = 0.006 D^{-1} over which energy decays corresponds to about half a year. That is the half-year repetition in wind speed also exists.

Dhahran is a coastal site 3 km inland from the Arabian Gulf. There is a small single-storey airport building in the vicinity of the meteorological station. The station is

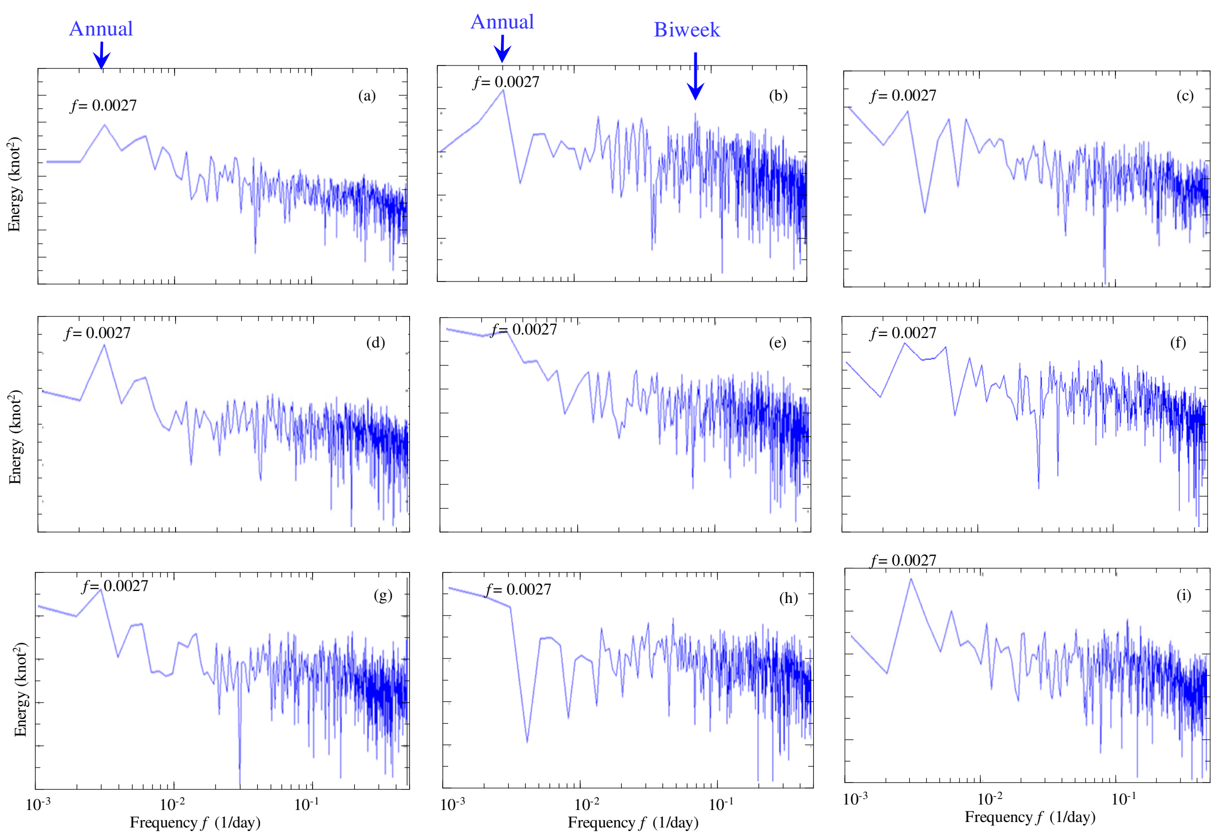

Fig. 1 FFT power spectrum of wind speed data for (a) Abha, (b) Dhahran, (c) Gizan, (d) Guryat, (e) Hail, (f) Jeddah, (g) Riyadh, (h) Turaif, and (i) Yanbo.

17 m above the mean sea level and the wind direction is mostly from the sea to the station. Here the peak corresponding to annual repetition (f = 0.0027 D^{-1}) is more clear (Fig. 1b). However, the half-year recurrence that appeared at Abha is not explicit. The high-frequency energies (f > 0.02 D^{-1}) at Dhahran (Fig. 1b) are larger than those at Abha (Fig. 1a). A small peak emerges at f = 0.074 D^{-1} at Dahran, which communicates to biweekly repetition of wind speed. The biweekly change in wind speed may be a unique feature for a coastal area as it is observed in other coastal area, namely Yanbo, which will be presented later.

Gizan is a coastal station on the west coast of Saudi Arabia, some 100 meters inland. There are one small single-storey airport building and some trees around. This station is only 5 m above the mean sea level. The Red Sea is a bit more turbulent than the Arabian Gulf on the east coast (Dhahran) and is wide open. Therefore, the annual and biweekly peaks are not as dominant as those in Abha or Dhahran (Fig. 1c). Another cause may be that the site is only 5 m above the sea level. Guryat is an inland station with high land and small hills with gentle topographical features. Since the station is high, the annual recurrence (f = 0.0027 D^{-1}) is more dominant than that at Abha and Dhahran (Fig. 1d). Hail is a highland plateau in the north central area of Saudi Arabia. As seen in Fig. 1(e), speed varies not only annually (f = 0.0027 D^{-1}) but also at further low frequencies (f < 0.0027 D^{-1}), e.g. two- and three-year repetitions which will be further clarified through wavelet analysis results later.

Jeddah station is around 10 km inland from the Red Sea. The FFT power spectrum for this station is presented in Fig. 1(f). There are many buildings around and it is situated in an urban area. The wind blows from the sea inwards and is intercepted by high-rise buildings and structures such as bridges and other industrial installations. Due to this confrontation of wind with structures, the annual maximum wind speed is smaller compared with that in Abha, Dahran, Guryat and Hail. Gizan also has similar power spectra because of wind obstructed by trees. The presence of high-rise buildings and/or trees makes the flow boundary layer wider, resulting in a smaller speed. The FFT power spectrum obtained using long-term mean wind speed data for Riyadh is shown in Fig. 1(g). Riyadh station is on the mainland and is around 450 m above the mean sea level. Riyadh is the capital of Saudi Arabia, hence it is a very developed region and surrounded by high-rise buildings, bridges and various industrial installations. The winds are prevalent from the northern and northwestern direction in this region. Since the site is quite high above sea level, the annual variation is evident.

Turaif is a small city in the northernmost part of Saudi Arabia and is a hilly inland area. The wind blows mostly from the north onto this area and accelerates due to topographical features. The power spectrum displays low-frequencies variation (f < 0.0027 D^{-1}), having similar characteristics to that at Hail. Yanbo is a coastal site on the Red Sea in the north-west of Saudi Arabia. It is an industrial area and is surrounded by a range of hills on the northern side and exposed to the sea on its western side. The station is 10 m above the mean sea level. The peak at f = 0.0027 D^{-1} is sharp, indicating the annual variation in wind speed is very regular (see Fig. 1i). A biweekly variation also exists. A scrupulous observation of all the FFT figures reveals that Abha, Dhahran, Guryat and Yanbo having a sharp peak at f = 0.0027 D^{-1} retain a more regular annual repetition of wind speed than Gizan, Hail, Jeddah, Riyad and Turaif.

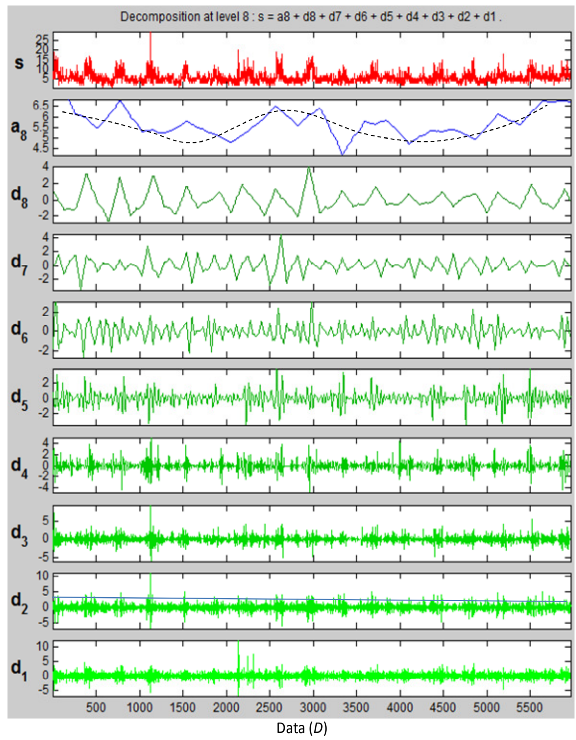

Fig. 2 Decomposition of wind speed time series data for Abha using DB8.

3. Unsteady nature of wind speeds

The daily mean values of wind speed time series data are analyzed, using Wavelet, over a period of 1990 - 2005 at the nine locations using db8. Naturally the daily mean signal captures information for a period of longer than 2 days following the Nyquist frequency criterion. The decomposition analysis results of wind speed data for Abha, Dhahran, Gizan, are shown in Figs. 2， 3 and 4, respectively, while those for Guryat, Hail, Jeddah, Riyadh, Turaif and Yanbo are not shown here. In these figures, the x-axis presents the number of days (D) of the entire data period (1990 to 2005) used in this study. Each of these figures has 10 parts. The first part 'S' represents the signal or raw data and the second part 'a_8' corresponds to the amplitude of the signal for wavelet Daubechies (db) at level 8 corresponding to a period of longer than 512 days. Note that that the dashed line in a_8 signal is not an output of the analysis, but just a hand sketch showing the low-frequency trend. The last eight parts, i.e. d_1, d_2, d_3, d_4, d_5, d_6, d_7 and d_8 of these figures represent details of decomposed signals of the raw data at eight different levels corresponding to a period range of 2 to 4, 4 to 8, 8 to 16, 16 to 32, 32 to 64, 64 to 128, 128 to 256 and 256 to 512 days, respectively. The raw signal S in Fig. 2 (Abha) displays a sharp spike at D = 1200 and a nearly regular variation of speed. The nearly regular variation is evident in the d_8 signal with a periodicity of approximately 365 days (one year), forming a peak between June and August of each year. The minimum speed occurs sometime in December to January. The fluctuation of the speed is relatively high, -2.5 to 2.5 knots for D < 3300 (<1998) and -2 to 2 knots for D > 5000 (> 2003) and small, -1 to 1 knots for D = 3300 to 5000 corresponding to year 1998 to 2003. On an average, the fluctuation occurs from -1.7 to 1.7 knots. That is, an annual fluctuation can contribute a speed of ±1.7 knots. Further low-frequency (longer than 512 days) variation is evident in signal a_8. This signal can also be considered as the signal of yearly (exactly 256 days) average wind speed. The duration for the average is long enough. The signal, however, contains approximately two-year undulations with small amplitudes. If the two-year undulation is ignored, the mean speed indicated by the dashed line is initially about 7 knots, slowing down to 4.7 knots at D =1700 (1995), followed by augmentation to 6.5 at D = 2800 (1998). This variation constitutes a period of about 8.5 years as evidenced by the dashed line.

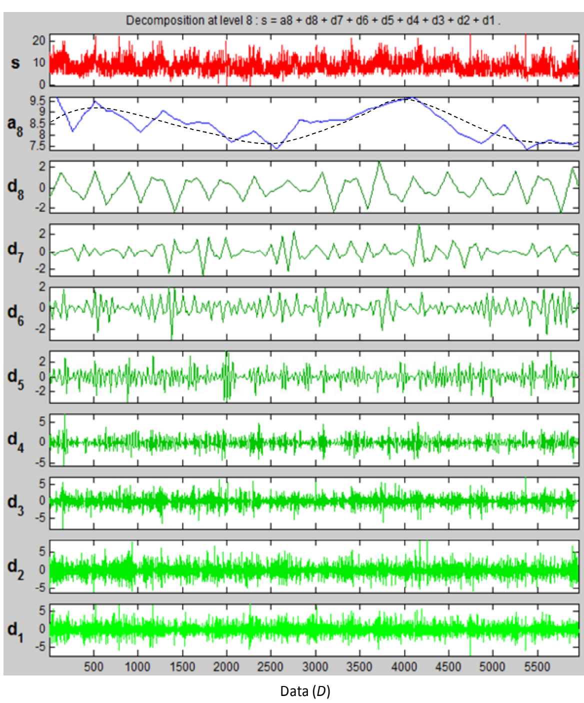

Fig. 3 Decomposition of wind speed time series data for Dhahran using DB8.

This information is very useful for a long-term wind prediction and power production. The observation also explains why a long-term wind speed trend at a location should be known to run a wind farm productively. Signals d_7 and d_6 display oscillation with a period of about a half and a quarter year, respectively. The oscillation is, however, small (±2 knots). The d_5 and d_4 signals have some large amplitude variations in the ranges of peaks in d_8 signal. The amplitude is greater in d_4 (±2.0 knots) than d_5 (±1.5 knots). The observation insinuates that the monthly variation in wind speed is stronger than the bimonthly variation and it occurs in the peak season (June to August) of wind speed. The d_3 and d_2 signals display a spike at D = 1200; the spike is nevertheless larger at d_2 than d_3. It has been mentioned that in signal S there is a spike at D = 1200 where the magnitude of speed is about 27 knots, which can now be explained with a view on d_2 signal that around D =1200 (1993) there was a persistent wind gust or storm in a period of 4 to 8 days. Similarly, another wind gust is observed in d_1 signal at D = 2200 (1996) for a shorter period of 2 to 4 days. Overall, wind speed variation is stronger for a period of one year (d_8), half a year (d_7), one month (d_4) and less than 8 days (d_1 and d_2) but weaker for a period of a quarter year (d_6), bimonthly (d_5), and bi-weekly (d_3).

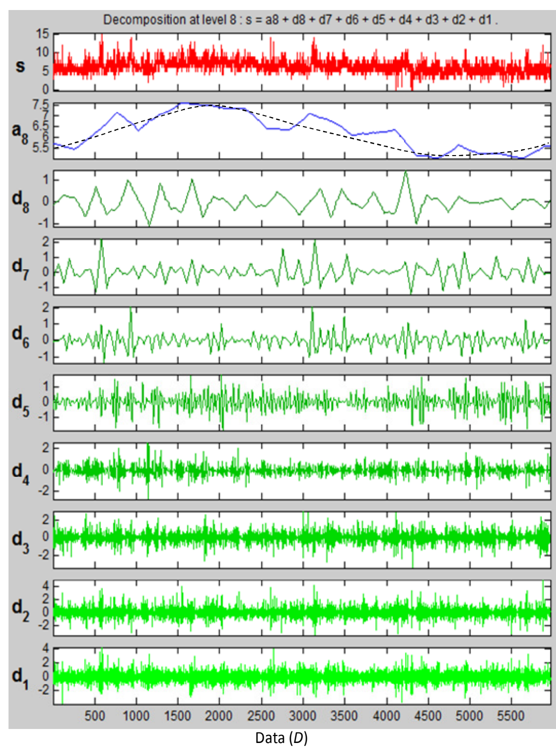

Fig. 4 Decomposition of wind speed time series data for Gizan using DB8.

The raw signal ‘S’ at Dhahran (Fig. 3) displays sharp spikes at D = 500, 800, 2000, 3400, 4150, 4750, 5400. Gusty winds were afoot more frequently. Here the long-term variation shown by the dashed line in a_8 represents a period of about 9 years. This long-term variation period is almost the same for both Abha and Dhahran.

Table 1. Intrinsic features of wind speed at different locations. June to August is the wind peak season.

Site	a_8			d_8	d_4	d_1
	Long-term mean speed (knots)	Long-term period (years)	Long-term fluctuation (knots)	Annual fluctuation (knots)	Monthly fluctuation, June – August (knots)	Half-weekly fluctuation (knots)
Abha	5.6	8.5	±0.9	±1.7	±2.6	±2.5
Dhahran	8.9	9	±0.6	±1.3	±2.9	±3.3
Gizan	6.25	12	±0.9	±0.7	±1.5	±1.6
Guryat	8.1	9	±0.9	±3.0	±3.0	±3.8
Hail	6.0	9	±1.5	±1.0	±2.4	±3.0
Jeddah	7.1	10.5	±0.9	±1.1	±2.4	±2.5
Riyadh	6.0	9.5	±0.65	±1.1	±2.8	±2.9
Turaif	8.6	10	±1.4	±0.9	±2.5	±3.5
Yanbo	7.3	10.5	±1.6	±1.7	±2.5	±3.0

The speed fluctuates from 8.3 to 9.5 knots (dashed line), while that for Abha oscillates from 4.7 to 6.5 knots. Therefore, the mean speed over the whole duration can be considered as 8.9 knots for Dhahran and 5.6 knots for Abha. The contribution of the long-term variation to the speed is about ±0.6 and ±0.9 knots for Dhahran and Abha, respectively. The annual variation of speed (d_8 signal) is more regular for Dhahran than for Abha, forming a peak in the months of April to June of each year. This regularity was also reflected in the power spectrum results with a peak at f = 0.0027 appearing sharper at Dhahran than at Abha. While the mean variation in amplitudes at Dhahran (d_8 signal) is about ±1.3 knots, that at Abha is about ±1.7 knots, i.e. slightly larger in the latter. The $d_7 - d_3$ signals display almost the same characteristics as those for Abha. The d_2 and d_1 signals, however, have larger amplitudes at Dhahran than Abha. The larger amplitudes at Dhahran result from the fact that Dhahran is 17 m above the sea level and very close (3 km) to the sea.

At Gizan (Fig. 4), which is located on the south-west coast of Saudi Arabia, the long-term variation period (dashed line) is slightly longer, about 12 years with a change in speed from 5.0 to 7.5 knots. The entire duration average is about 6.25 knots. The annual variation in amplitude is very small here, about ±0.7 knots (d_8 signal). Because of the small amplitude, the corresponding peak at f = 0.0027 in the FFT power spectrum was not distinguished enough (Fig. 1c). Wavelet analysis results for Guryat, Hail, Jeddah, Riyadh, Turaif and Yanbo are not shown here. Table 1 extracts important intrinsic features of wind speed analysis results in Figs. 2-4 and in the other figures not shown. The long-term (16 years) mean speed (second column), long-term period (third column) and long-term fluctuation (fourth column) are extracted from a_8 signals. On the other hand, annual fluctuation (fifth column), monthly fluctuation (sixth column) and half-weekly fluctuation in speed are obtained from d_8, d_4 and d_1 signals, respectively. Having smaller fluctuations, other data are not included in Table 1. The data in Table 1 are plotted in Figs. 5 and 6 for the sake of a better perceptibility of comparison between different locations. The long-term mean speed is a minimum of 5.6 knots at Abha (Table 1, Fig. 5). Dhahran, Guryat and Turaif undergo a higher speed of 8.9, 8.1 and 8.6 knots, respectively (Table 1, Fig. 6). It is interesting that the wind speed has a long period of about 10 (8.5 to 1.2) years (third column of Table 1) which contributes to a change in speed by ±0.6 to ±1.6 knots (fourth column) depending on the location.

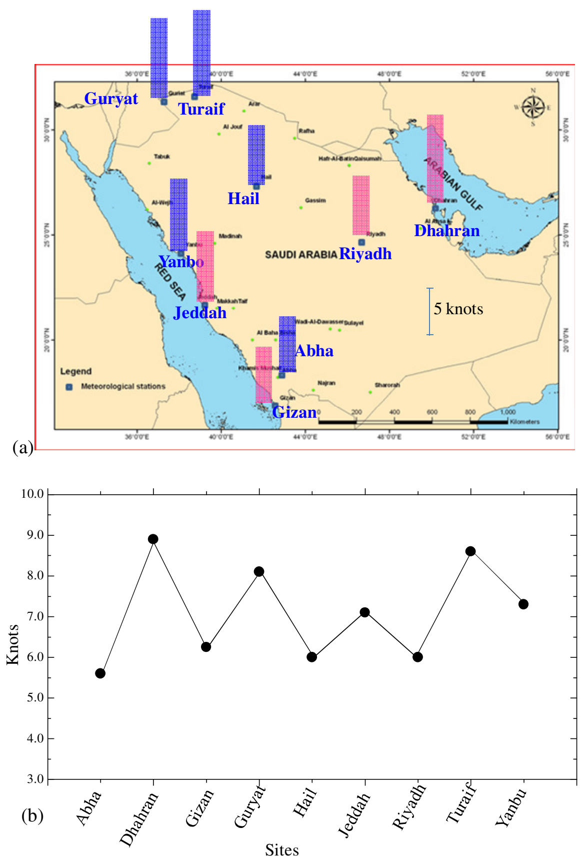

Fig. 5 Long-term (16 years) mean wind speed at different sites, shown in (a) bar diagram, and (b) Cartesian coordinate.

The long-term contribution is, however, maximum at Yanbo (±1.6 knots) and Hail (±1.5 knots). It was found in the FFT analysis results that Abha, Dhahran, Guryat and Yanbo showing a sharp peak at f = 0.0027 preserved a more regular annual repetition than Gizan, Hail, Jeddah, Riyad and Turaif. The data in the fifth column agree with the observation in the FFT analysis results, displaying larger fluctuations (±1.3 to ±3.0 knots) at the former locations and smaller (±0.7 to ±1.1 knots) at the latter locations. The annual variation is, however, the largest (±3.0 knots) at Guryat and the smallest (±0.7 knots) at Gizan. Except for the small value (1.5 knots) at Gizan, the monthly fluctuation is less dependent on location, nestling between ±2.4 and ±3.0 knots. Among the long-term, annual, monthly and half-weekly fluctuations (Table 1 and Fig. 6), the half-weekly fluctuation is the largest at all locations, varying from ±1.6 to ±3.8 knots. This observation points to the fact that the daily fluctuation should also to be investigated. Overall, the annual, monthly, and half-weekly fluctuations are the largest at Guryat and the smallest at Gizan. The most possible cause behind the largest and smallest fluctuations at Guryat and Gizan, respectively, is that while Guryat is a high land with low and high hills, Gizan is a coastal area only 5 m above the sea level. The information in Table 1 will be very useful for short- and long-term wind forecasts, hence to distinguish idle and running periods of a wind turbine. Using wavelet transform, Chellali *et al.* [6] made a time-period analysis of wind speed data recorded at Adrar, Algeria for four years (2005 to 2009). Their analyzing period ranged from 2 to 64 days only, which is rather small compared with our range of 2 to 512 days investigated. They observed the dominant oscillation of periods between 2 and 16 days including intra-seasonal oscillations of periods between 30 and 60 days.

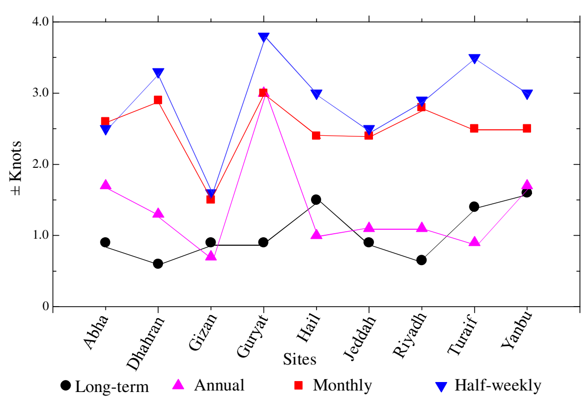

Fig. 6 Contributions of different time-scales to wind speed fluctuation.

4. Conclusions

Wavelet analysis extracted the intrinsic features of wind speed, including long-term, annual, half-yearly, quarter-yearly, monthly, biweekly, weekly and half-weekly fluctuations. The information on speed fluctuations at different periods is very useful for meteorological purposes, including wind and weather forecasting. The wind speed over Saudi Arabia has a long period of about 10 years, contributing to change in speed by ±0.6 to ±1.6 knots depending on the locations. The long-term contribution is maximum (±1.6 knots) at Yanbo and minimum (±0.6 knots) at Dhahran. The long-term mean wind speed is 5.6, 8.9, 6.25, 8.1, 6.0, 7.1, 6.0, 8.6 and 7.3 knots at Abha, Dhahran, Gizan, Guryat, Hail, Jeddah, Riyadh, Turaif and Yanbo, respectively. The annual fluctuation in wind speed is larger (±1.3 to ±3.0 knots) and more regular at Abha, Dhahran, Guryat and Yanbo, while smaller (±0.7 to ±1.1 knots) and less regular at Gizan, Hail, Jeddah, Riyad and Turaif, with the greatest (±3.0) and smallest (±0.7) at Guryat and Gizan, respectively. Among long-term, annual, half-yearly, quarter-yearly, monthly, biweekly, weekly and half-weekly fluctuations, the largest change in wind speed occurs half-weekly, by about ±1.6 to ±3.8 knots depending on location. The highland and coastal sites, Dhahran, Guryat and Yanbo, correspond to larger annual, monthly and half-weekly fluctuations of wind speed.

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