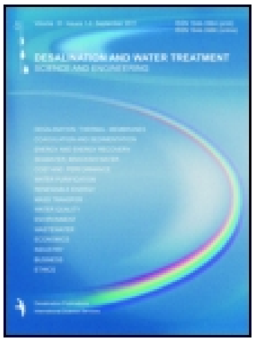

Desalination and Water Treatment

ISSN: 1944-3994 (Print) 1944-3986 (Online) Journal homepage: http://www.tandfonline.com/loi/tdwt20

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To cite this article: Mohammad Nabeel ElNesr, Abdulrahman Ali Alazba & Muhammad Tahir Amin (2016) Estimation of shortwave solar radiations in the Arabian Peninsula: a new approach, Desalination and Water Treatment, 57:1, 37-50, DOI: 10.1080/19443994.2015.1006821

To link to this article: http://dx.doi.org/10.1080/19443994.2015.1006821

Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1006821

57 (2016) 37–50
January

Taylor & Francis
Taylor & Francis Group

Estimation of shortwave solar radiations in the Arabian Peninsula: a new approach

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Received 5 October 2014; Accepted 16 November 2014

ABSTRACT

Identifying the shortwave solar radiation, R_s, is very important in various fields of science which is calculated by mathematical models if not measured experimentally. These models depend on the coastality factor, k_r. Several equations are developed to calculate k_r but with errors of estimation. The aim of this paper was to develop a local formula to calculate k_r from temperature range. Based on the 30-year climate data for 29 weather stations throughout the Kingdom of Saudi Arabia (KSA), monthly temperature ranges were calculated. The hyperbolic equation was derived based on the best-fit analysis and the resulted errors of four statistical parameters were compared with any other established formula. The average of the absolute percent error was estimated as 2.1% as compared with 6–11% of the various published models. Results show that k_r is inversely proportional to the distance from the coast and the altitude. In addition, it was found that urbanization has a considerable effect on k_r and the noncoastal but high-population cities behaved similar as coastal cities. It is recommended to use the proposed equation due to its accuracy for the KSA instead of using other models. More research is needed to further investigate the effects of urbanization on the k_r.

Keywords: Short wave radiation; Coastality value; Proposed model; Urbanization; KSA

1. Introduction

Of the huge amount of energy emitted by the sun into space, our earth receives a small fraction in the form of the spectrum of light, namely solar radiation (R_s). Measuring the amount of solar radiation is very important for environmental, meteorological, and agricultural studies. Usually, R_s is measured directly using pyranometers, actinometers, or pyrheliometers, or indirectly using other devices and methods. In many cases, direct measuring devices are not available, so mathematical methods remain the only alternatives to estimate the R_s using the climate data. One of the earlier published works is that of Prescott [1], who correlated and revised the Angstrom formula using Eq. (1).

$$R_s = \left(a + b\frac{n}{N}\right)R_a \tag{1}$$

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Presented at the International Conference on Business, Economics, Energy and Environmental Sciences (ICBEEES) 19–21 September 2014, Kuala Lumpur, Malaysia

where R_s is the solar or shortwave radiation (MJ m^{-2} d^{-1}), a is the regression constant representing the fraction of extraterrestrial radiation reaching the earth on overcast days, b is the regression constant, $(a + b)$ is the fraction of extraterrestrial radiation reaching the earth on clear days, n is the actual sunshine duration (h), N is the maximum possible sunshine hours (h), n/N is the relative sunshine duration, and R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}). The calculation procedure of R_a is presented in the Appendix.

The values of a and b, as derived from the literature, lie in the range of 0.1–0.3 and 0.4–0.7, respectively. If not measured experimentally, a value of 0.25 and 0.50 for a and b, respectively, is the recommended value to be used [2,3].

To measure the relative sunshine duration, two parameters i.e. n (measured) and N (calculated) are to be acquired, at first. The N is calculated using Eq. (A2), as described in the Appendix. The values of n were not recorded at some of the weather stations used in this study, so cloud cover was measured to determine n using the conversion formula as proposed by Doorenbos and Pruitt [4], using Eq. (2).

$$\frac{n}{N} = 0.9659 - 0.0083 \cdot C_c \tag{2}$$

where C_c is the percent of the cloud cover and is calculated as: $C_c = \text{Oktas}/8 \times 100$ with Oktas being the number of parts appear as cloud covered of a mirror divided by eight equal parts facing the sky, i.e. Oktas = 0 if the sky is totally clear, while Oktas = 8 in full-covered cloudy sky.

Hargreaves [5] concluded that R_s can be computed between R_a and n/N, similar to the Angstom's approach using the Eq. (3).

$$R_s = 0.075 R_a \sqrt{\frac{n}{N} \times 100} \tag{3}$$

The accurate calculation of R_s, however, was region-specific with limited rather invalid application at other places. Hargreaves and Samani [6] proposed an improved formula for calculating the R_s based on the global climate database. The modified formula depends on the temperature range and is given by Eq. (4).

$$R_s = k_r \times \text{TR}^{0.5} \times R_a \tag{4}$$

where TR is the temperature range (℃, $T_{\max}$–$T_{\min}$) with $T_{\max}$ and $T_{\min}$ being the mean daily maximum and minimum dry-bulb temperatures, respectively, and k_r is the empirical coefficient for the curve-fit of R_s/R_a vs. TR. For instance, the k_r coefficient's value was 0.16 for Senegal River Basin as reported by Hargreaves [7]. Later, Hargreaves concluded that the values of k_r can be estimated globally as 0.190 for any coastal region (excluding island region), and as 0.162 for noncoastal (interior) regions [8]. Because of that the variable k_r was termed as the coastality value and several attempts were made to find its appropriate values. Allen [9] relates k_r to the atmospheric pressure at the site using the following equation.

$$k_r = k_{\text{ro}} \sqrt{\frac{P}{P_o}} \tag{5}$$

where k_{ro} is the empirical coefficient having a value of 0.17 for interior regions, and 0.20 for coastal regions, P is the atmospheric pressure at station level (kPa), and P_o is the mean atmospheric pressure at sea level. This formula was not found functioning well at elevations >1,500 m, and therefore, was no longer recommended at such elevations [10]. However, Samani estimated an error up to 54% for the k_r based on the above formula and recommended an interpolated formula from real data of 25 years for 65 stations in the United States which can reduce the error to as low as 15% [11]. The Samani's proposed equation can be written as:

$$k_r = 0.00185 \times \text{TR}^2 - 0.0433 \times \text{TR} + 0.4023 \tag{6}$$

However, Samani recommend localizing the above relationship for each region/country especially for regions with extreme altitudes and/or arid and hyper-arid regions [11]. Several attempts were made to estimate R_s, k_r, and other empirical parameters by many researchers [12–14].

In the Arabian Peninsula, most of the regions suffer extreme aridity especially in the Kingdom of Saudi Arabia (KSA) which occupies about 86% of the peninsula's area [15]. Additionally, direct radiation measurement is not common in the KSA except at some agricultural weather stations. The oldest recorded weather data were available only at weather stations located at airports for measuring the aviation related properties, such as temperature, humidity, air pressure, wind speed, wind direction, and cloud cover. Hence, no direct measurement of solar radiation was available and R_s has to be calculated by indirect measurements. In the agricultural and industrial community, it is rare to find weather data save the temperature records. Thus, it is essential to develop a

Table 1
Geographical information of the meteorological stations included in this study

Station		Station location						Radiation variables	
ID	Name	Latitude *deg. N.*	Longitude *deg. East*	Altitude *m*	Coastal /Interior	Logged years	Average temperature ℃	*a*	*b*
St:01	A'Dhahran	26.16	50.1	17	Coastal	30	26.48 ± 7.49	0.26	0.30
St:02	Abha	18.4	42.39	2,093	Interior	30	18.60 ± 3.72	0.31	0.41
St:03	Ad Dammam	26.42	50.12	1	Coastal	10	26.72 ± 7.86	0.26	0.30
St:04	Al Ahsa	25.3	49.48	179	Interior	25	27.26 ± 8.27	0.26	0.30
St:05	Al Baha	20.3	41.63	1,652	Interior	25	22.83 ± 4.92	0.16	0.56
St:06	Aljouf	29.47	40.06	671	Interior	30	22.03 ± 8.61	0.35	0.32
St:07	Al Madina	24.33	39.42	636	Interior	30	28.45 ± 7.00	0.29	0.44
St:08	Al Qaisumah	28.32	46.13	358	Interior	30	25.23 ± 9.28	0.29	0.45
St:09	Al Qassim	26.18	43.46	650	Interior	30	24.94 ± 8.26	0.30	0.38
St:10	Al Quuraiat	31.5	37.5	560	Interior	5	20.04 ± 7.91	0.27	0.47
St:11	Al Wajh	26.12	36.28	21	Coastal	30	25.00 ± 3.98	0.29	0.45
St:12	Arar	31	41	600	Interior	30	22.01 ± 9.17	0.35	0.32
St:13	ArRiyadh Middle	24.63	46.77	624	Interior	30	26.66 ± 8.10	0.23	0.45
St:14	ArRiyadh North	24.42	46.44	611	Interior	25	25.80 ± 8.12	0.29	0.41
St:15	AtTa'if	21.29	40.33	1,454	Interior	30	22.92 ± 5.12	0.21	0.45
St:16	Bisha	19.59	42.37	1,163	Interior	30	25.69 ± 5.40	0.30	0.42
St:17	Gizan	16.54	42.35	3	Coastal	30	30.22 ± 2.80	0.31	0.40
St:18	Hafr El-Batin	28.2	46.07	360	Interior	20	25.26 ± 9.21	0.29	0.45
St:19	Hail	27.26	41.41	1,013	Interior	30	22.47 ± 8.20	0.30	0.35
St:20	Jeddah	21.3	39.12	17	Coastal	30	28.23 ± 3.50	0.30	0.43
St:21	Khamis Mushait	18.18	42.48	2,057	Interior	30	19.49 ± 3.75	0.31	0.41
St:22	Makkah	21.4	39.85	213	Interior	25	30.78 ± 4.57	0.30	0.42
St:23	Najran	17.37	44.26	1,210	Interior	30	25.51 ± 5.54	0.36	0.50
St:24	Rafha	29.38	43.29	447	Interior	30	23.33 ± 9.05	0.27	0.47
St:25	Sharurrah	17.47	47.11	725	Interior	25	28.57 ± 5.81	0.36	0.50
St:26	Tabuk	28.22	36.38	776	Interior	30	21.99 ± 7.53	0.28	0.46
St:27	Turaif	31.41	38.4	818	Interior	30	19.06 ± 8.27	0.27	0.47
St:28	Wadi Al Dawasir	20.5	45.16	652	Interior	25	28.15 ± 7.01	0.30	0.42
St:29	Yenbo	24.09	38.04	6	Coastal	30	27.56 ± 4.72	0.28	0.45

formula for calculating R_s using the available weather data. The aim of this work is to develop an empirical formula for the KSA to calculate the solar radiation from temperature data and to compare the accuracy with that of the already developed R_s calculation methods.

2. Methodology

2.1. Data collection and types

In this study, weather data were obtained from the Presidency of Meteorology and Environment (PME) in the KSA. Data represent 29 weather stations covering the entire KSA. The records represent 30 years of weather data on daily basis for 20 stations, 25 years of similar data for six stations, and remaining three stations with daily weather data of less than 20 years, as summarized in Table 1.

The weather data were recorded on daily basis and the average monthly values for each parameter were calculated. The collected data are regarded as the most reliable one in the KSA and are used by most of the governmental and academic groups for climate research and prediction. These weather stations were located at domestic and international airports and were equipped with the most advanced monitoring devices subjected to regular inspection and replacement of defected devices (personal communication with the PME).

Each data-set includes daily values of climatic records comprising maximum, average, and minimum of each dry- and wet-bulb temperatures, relative humidity (maximum, average, and minimum), wind

Table 2a
Average monthly radiation data (R_a in MJ $m^{-2}\,d^{-2}$) of the studied stations

Months	St:1	St:2	St:3	St:4	St:5	St:6	St:7	St:8	St:9	St:10	St:11	St:12	St:13	St:14	St:15	St:16	St:17	St:18	St:19	St:20	St:21	St:22	St:23	St:24	St:25	St:26	St:27	St:28	St:29	Avg.
1	23.6	28	23.4	24.1	26.8	21.6	24.6	22.3	23.5	20.4	23.6	20.7	24.4	25.4	26.3	27.2	28.8	22.4	22.9	26.3	27.9	26.2	28.4	21.7	28.3	22.4	20.5	26.7	24.7	24.7
2	27.7	31.4	27.6	28.1	30.4	26.1	28.6	26.7	27.7	25	27.7	25.3	28.5	28.6	30	30.7	32	26.7	27.2	30	31.3	29.9	31.7	26.1	31.6	26.7	25.1	30.3	28.7	28.6
3	33	35.2	32.9	33.2	34.7	31.8	33.5	32.2	32.9	31.1	33	31.3	33.4	33.5	34.4	34.9	35.6	32.3	32.6	34.4	35.2	34.4	35.4	31.9	35.4	32.3	31.1	34.6	33.6	33.5
4	37.4	38	37.4	37.5	37.9	36.9	37.6	37.1	37.4	36.6	37.4	36.7	37.6	37.6	37.8	37.9	38	37.1	37.2	37.8	38	37.8	38	36.9	38	37.1	36.6	37.9	37.6	37.5
5	3,609	36	39.9	39.8	39.3	40	39.7	40	39.8	40	39.8	40	39.7	39.7	39.4	39.2	38.8	39.9	39.9	37.4	39	39.4	38.9	40	38.9	39.9	40	39.3	39.7	39.6
6	40.6	38.9	40.6	40.5	39.6	41	40.3	40.9	40.6	41.2	40.6	41.2	40.4	40.3	39.8	39.4	38.7	40.9	40.8	39.8	39.1	39.8	38.9	41	39	40.9	41.2	39.6	40.3	40.2
7	40.1	38.1	40.1	40	39.3	40.4	39.9	40.3	40.1	40.5	40.1	40.5	39.9	39.9	39.4	39.2	38.6	40.3	40.2	39.5	38.9	39.5	38.8	40.4	38.8	40.3	40.5	39.3	39.8	39.7
8	38.1	35.9	38	38.1	38.2	37.8	38.1	37.9	38.1	37.6	38.1	37.7	38.1	38.1	38.2	38.2	38.1	37.9	38	38.2	38.1	38.2	38.1	37.8	38.1	37.9	37.7	38.2	38.1	38
9	34.2	32.3	34.2	34.4	35.5	33.3	34.7	33.6	34.2	32.7	34.2	32.9	34.6	34.7	35.3	35.7	36.2	33.7	33.9	35.3	35.9	35.3	36.1	33.3	36	33.7	32.7	35.5	34.7	34.6
10	29.1	28.6	28.9	29.4	31.5	27.6	29.8	28.1	29	26.6	29.1	26.8	29.7	29.8	31.1	31.7	32.9	28.1	28.6	31.1	32.3	31	32.6	27.6	32.5	28.1	26.6	31.4	29.9	29.9
11	24.4	28.6	24.2	24.8	27.5	22.5	25.4	23.2	24.4	21.7	24.4	21.6	25.2	25.3	27	27.9	29.4	23.2	23.8	27	28.6	26	29	22.6	29	23.3	21.4	27.4	25.5	25.85
12	22.2	26.8	22	22.7	25.6	20.2	23.3	20.9	22.2	19	22.2	19.3	23.1	23.2	25	26	27.7	21	21.5	25	26.8	25	27.2	20.3	27.2	21	19	25.5	23.4	23.4
Avg.	32.5	34.3	32.4	32.7	33.9	31.6	33	31.9	32.5	31	32.5	31.2	32.9	32.9	33.6	37	34.6	32	32.2	33.6	34.3	33.6	34.4	31.6	34.4	32	31	33.8	33	32.9

Table 2b
Average monthly radiation data (R_s in MJ $m^{-2} d^{-2}$) of the studied stations

Months	St:1	St:2	St:3	St:4	St:5	St:6	St:7	St:8	St:9	St:10	St:11	St:12	St:13	St:14	St:15	St:16	St:17	St:18	St:19	St:20	St:21	St:22	St:23	St:24	St:25	St:26	St:27	St:28	St:29	Avg.
1	14.5	17.3	14.7	15.1	16.8	13.5	15.8	13.9	14.5	12.9	15.1	12.8	15.1	15.3	16.6	17.5	18	13.6	14.6	16.9	18.1	16.2	19.1	13.7	19.7	14.2	12.3	17.7	16.3	15.7
2	17.2	19.5	17.7	18.1	20.1	16.6	18.7	17.1	17.6	15.4	18.1	16	18.1	18.3	19.5	20	19.8	17.4	17.5	20.2	30.3	19.4	21.4	16.8	22	17.2	15	20.6	19.2	18.5
3	20	21.9	21.4	20.8	22.4	20.4	21.7	20.1	20.3	20.3	21.8	19.9	20.3	20.6	22	21.8	22.8	21	20.3	23.3	22.3	22.7	23.1	20.3	24	20.8	19.1	22.7	22.6	21.4
4	22.9	23	23.3	23.4	23.6	23.6	23.9	22.8	22.5	23.2	25.1	22.9	22.3	22.6	23.6	23	24.9	23.9	23.8	26.1	23.3	25.2	24	23	25	23.6	22.4	24.9	25.5	23.7
5	26.7	23.8	27.7	27	24.4	26	25.6	25.9	25.1	26.8	26.7	25.7	25.5	25.7	24.6	24.2	25.6	26.7	25.7	27.1	23.8	26.2	25.3	25.5	26.8	24.7	25.4	26.9	26.8	25.7
6	29.4	24.6	29.5	29.4	25.5	29.7	28.3	29.5	29	29.9	29.4	29.8	28.8	28.9	26.5	26.1	24.8	29.5	29.2	28.1	24.7	27.6	26.1	29.6	27	29.4	29.7	28.3	27.7	28.1
7	28.3	23	28.8	28.4	24.1	29.2	27.1	28.9	28.3	29.6	28.8	29.3	27.7	28	25.9	24.2	22.9	29	28.4	27.4	22.9	26.3	23.3	29.1	25.4	28.7	29.2	26.7	27.9	27
8	26.9	21.9	27.3	27.2	22.6	27	25	27.2	26.7	27.3	27.2	27.1	26.3	26.6	23.9	23.1	22.1	27.3	26.4	25.6	22.1	24.5	23.1	27.2	24.7	26.9	27.1	25.7	26.1	25.5
9	24.8	22.8	24.8	25	22.9	23.8	22.8	24.4	24.1	23.6	24.4	23.6	24.7	24.9	22.3	23.8	22.5	24.3	23.7	23.9	23	22.7	24.3	23.9	25	23.9	25.5	25.2	23.8	23.8
10	20.5	21.2	20.7	21.1	21.1	18.4	19.9	19.2	19.6	18.2	20.1	18.1	20.8	21	20.4	21.5	21.4	19.4	19.2	21.8	21.4	21.3	22.6	18.6	23.2	18.9	17.8	22.3	20.6	20.4
11	15.8	18.7	16	16.6	18	14.4	16.4	14.5	15.2	14.8	16.3	13.7	16.3	16.4	17.3	18.5	19.4	14.9	15.3	18.4	18.8	17.8	20.2	14.3	20.8	15.1	13.6	19.1	17.2	16.7
12	13.7	17.2	13.9	14.4	16.6	12.5	14.9	12.8	13.5	12.6	14.3	11.8	14.3	14.5	15.9	16.9	17.9	13	13.7	16.5	17.6	15.6	18.5	12.6	19.1	13.2	11.4	17.2	15.6	15
Avg.	21.7	21.2	22.2	22.2	21.5	21.3	21.7	21.3	21.4	21.2	22.3	20.9	21.7	21.9	21.5	21.7	21.8	21.7	21.5	22.9	21.5	22.1	22.6	21.2	23.6	21.5	20.6	23.1	22.5	21.8

Table 3a
Average monthly temperature difference (TR) for the studied stations

Months	St:1	St:2	St:3	St:4	St:5	St:6	St:7	St:8	St:9	St:10	St:11	St:12	St:13	St:14	St:15	St:16	St:17	St:18	St:19	St:20	St:21	St:22	St:23	St:24	St:25	St:26	St:27	St:28	St:29	Avg.
1	10.9	11.8	11.6	12.8	12.8	12	12.5	11.8	12.9	14	10.8	12.4	11.3	13.3	14.1	16.9	9	12.4	13.6	10.6	13.4	11.7	16.5	12.5	16.6	14.1	11.6	15.1	13.5	12.8
2	11.2	11.4	12.5	13.6	13	12.8	13.1	13	14.1	14.2	10.7	13.2	12.1	14	14.5	17.1	8.6	13.8	14.1	11.3	12.8	12.7	16.5	13.6	17.1	14.7	12.2	15.8	13.8	13.3
3	11.9	11.7	14.9	14.7	12.7	13.7	13.5	13.9	14.4	16.3	10.6	14.3	12.5	14.5	14.5	16.3	8.7	15.2	14.2	12.2	12.7	13.8	15.5	14.6	16.8	15.3	13.4	15.8	14	13.7
4	13.2	12.4	14.6	15.5	12.6	14.5	14	14.8	15	17.1	10.2	14.9	13	15	14.4	15.6	9.4	15.8	14.5	12.7	13.3	14.2	15.1	15.5	16.1	16	14.4	16	13.8	14.1
5	14.4	13.7	15.7	16.6	12.8	14.7	14.1	15.6	15.8	17.7	9.5	15.4	13.5	16.1	14.3	15.9	9.7	16	14.7	13	14.3	14.5	15.5	16.2	16.8	16	15.1	16.3	14.1	14.6
6	14.8	14.3	16.1	16.9	12.8	15.6	14.5	16.6	17.2	18.6	9.4	16.3	14.6	17.4	13.4	16.5	8.8	16.9	16	13.3	14.8	15.2	16.4	17.6	17.8	16.2	16.1	17.7	14.8	15.2
7	14.7	13.5	15.7	16.3	12.5	15.6	13.8	16.4	17.3	18	9.1	16.2	14.3	17.3	11.9	15.1	8.2	16.7	16	12.8	14.2	13.9	14.2	17.9	16.6	15.4	16.3	16.9	13.6	14.7
8	14.1	13.7	15.9	16.6	12.6	15.8	13.9	16.6	17.2	18.1	8.8	16.4	14.4	17.4	12.1	15.2	8.4	17.1	16.2	11.3	14.3	13.3	14.5	18	16	15.6	16.4	16.9	13.1	14.6
9	15	14.6	16.3	17	12.4	15.9	14.4	16.8	17.6	16.9	9.1	16.6	14.5	17.8	13.9	17	9.5	17.1	16.9	11.1	14.7	13.9	16.2	17.9	16.7	16.2	16.2	18	13.7	15.2
10	14.1	14.4	16.4	16.6	13	14.5	14.3	15.7	16.7	16.2	9.9	15.3	14.1	17.3	14.8	17.6	10.4	16.5	16.1	12.6	14.6	14.2	16.6	16.3	16.7	15.7	14.8	17.7	13.2	14.9
11	12.1	14.1	13	14.4	13.3	12.7	12.8	13.2	13.7	15.9	10.8	13.4	12.3	14.9	14.3	17.5	9.9	13.8	13.8	11.1	14.9	12.2	16.2	13.6	16.5	14.4	13	16.5	13.4	13.6
12	11	13.4	11.1	12.9	13	12	12.3	11.9	13	14.5	10.9	12.2	11.4	13.4	14.2	17.3	9.4	12.6	13.5	10.6	14.5	11.6	16.3	12.5	16.4	14.2	11.8	15.5	13.4	13

Table 3b
Average monthly coastality values, k_r, $((R_s/R_a)/T\mathrm{dif}^{0.5})$ for the studied stations

Months	St:1	St:2	St:3	St:4	St:5	St:6	St:7	St:8	St:9	St:10	St:11	St:12	St:13	St:14	St:15	St:16	St:17	St:18	St:19	St:20	St:21	St:22	St:23	St:24	St:25	St:26	St:27	St:28	St:29	Avg.
1	0.187	0.18	0.185	0.176	0.175	0.18	0.182	0.181	0.171	0.169	0.194	0.175	0.183	0.171	0.168	0.157	0.208	0.173	0.173	0.198	0.177	0.181	0.166	0.179	0.171	0.169	0.176	0.17	0.179	0.177
2	0.186	0.184	0.181	0.174	0.184	0.178	0.181	0.178	0.169	0.163	0.2	0.174	0.182	0.171	0.17	0.157	0.211	0.175	0.172	0.2	0.181	0.182	0.167	0.174	0.169	0.168	0.171	0.171	0.18	0.177
3	0.176	0.182	0.169	0.163	0.181	0.173	0.176	0.168	0.162	0.162	0.203	0.169	0.172	0.161	0.168	0.155	0.218	0.167	0.17	0.194	0.177	0.177	0.166	0.167	0.165	0.165	0.168	0.165	0.179	0.173
4	0.169	0.172	0.163	0.158	0.176	0.168	0.17	0.16	0.156	0.153	0.21	0.162	0.164	0.155	0.165	0.154	0.214	0.162	0.167	0.193	0.168	0.177	0.163	0.158	0.164	0.159	0.162	0.164	0.183	0.168
5	0.177	0.165	0.175	0.167	0.173	0.17	0.172	0.165	0.158	0.159	0.217	0.164	0.175	0.161	0.165	0.155	0.212	0.167	0.168	0.191	0.161	0.174	0.165	0.158	0.168	0.161	0.164	0.17	0.18	0.17
6	0.188	0.166	0.181	0.177	0.18	0.183	0.184	0.177	0.172	0.168	0.236	0.179	0.187	0.172	0.182	0.163	0.215	0.176	0.179	0.193	0.164	0.177	0.166	0.172	0.164	0.179	0.179	0.169	0.186	0.179
7	0.184	0.161	0.181	0.176	0.174	0.183	0.183	0.177	0.17	0.172	0.238	0.18	0.184	0.169	0.19	0.159	0.207	0.176	0.177	0.194	0.156	0.179	0.159	0.17	0.16	0.182	0.179	0.165	0.19	0.177
8	0.188	0.155	0.18	0.176	0.167	0.18	0.176	0.176	0.169	0.171	0.241	0.178	0.182	0.167	0.18	0.155	0.201	0.174	0.173	0.2	0.153	0.176	0.159	0.17	0.162	0.18	0.178	0.164	0.189	0.175
9	0.187	0.166	0.18	0.176	0.183	0.179	0.173	0.175	0.168	0.176	0.236	0.176	0.187	0.17	0.169	0.162	0.202	0.174	0.17	0.202	0.167	0.172	0.168	0.169	0.169	0.177	0.179	0.167	0.186	0.177
10	0.188	0.174	0.177	0.176	0.186	0.176	0.177	0.172	0.165	0.17	0.22	0.172	0.186	0.169	0.171	0.162	0.202	0.169	0.167	0.198	0.173	0.182	0.17	0.167	0.175	0.169	0.174	0.169	0.19	0.177
11	0.187	0.174	0.183	0.176	0.18	0.18	0.181	0.173	0.168	0.171	0.204	0.173	0.184	0.168	0.17	0.159	0.21	0.173	0.174	0.205	0.171	0.189	0.173	0.172	0.177	0.171	0.176	0.172	0.184	0.178
12	0.186	0.176	0.189	0.177	0.18	0.179	0.182	0.177	0.169	0.174	0.195	0.175	0.183	0.17	0.169	0.157	0.212	0.175	0.173	0.203	0.173	0.184	0.168	0.176	0.174	0.167	0.174	0.171	0.181	0.178
Avg.	0.171	0.179	0.173	0.178	0.177	0.178	0.173	0.166	0.167	0.216	0.173	0.181	0.167	0.172	0.158	0.209	0.172	0.172	0.197	0.168	0.179	0.166	0.169	0.168	0.17	0.173	0.168	0.184	0.176	0.184

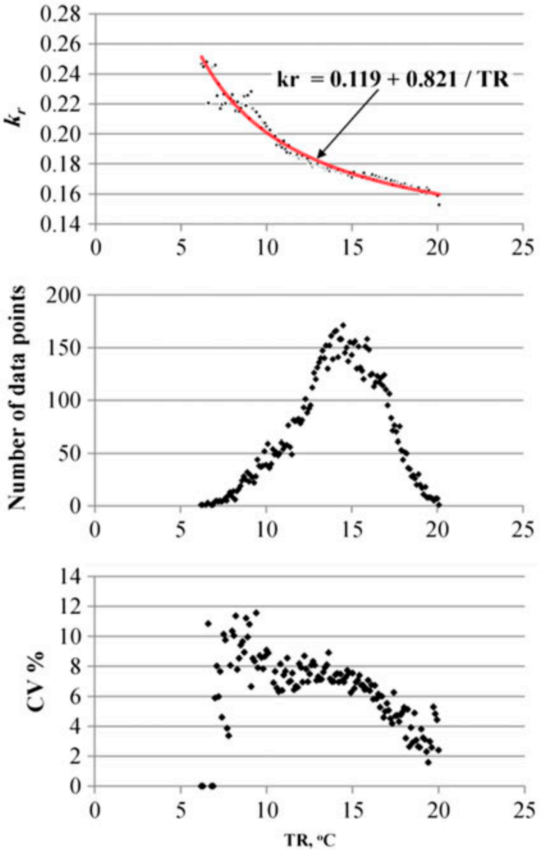

Fig. 1. Fitting k_r values to TR in the studied stations.

speed (maximum and average), sky coverage, air pressure at sea level and at station level (maximum, average, and minimum), mean vapor pressure, rainfall, and wind direction.

2.2. Calculation criteria

Due to the nonavailability of direct radiation data, R_s was estimated from the available data of cloud coverage and extraterrestrial radiation using Eqs. (1), (2), and (A1). Values of a and b were taken from the published literature by Hummeida and Mohammad [16] and Shafiqur-Rehman [17], as listed in Table 1. The monthly average values of R_s for each of the studied stations are shown in Table 2.

The resultant R_s value of each record was substituted to Eq. (4), along with average monthly values of TR and R_a, as shown in Tables 2 and 3. The k_r values were calculated on daily basis using Eq. (7) and were averaged on monthly basis for each station, as shown in Table 3.

$$k_r = \left(\frac{R_s}{R_a}\right)(\mathrm{TR})^{-0.5} \tag{7}$$

Similarly, k_r was calculated on daily basis to get the monthly average values by employing methods developed by Hargreaves [8], Allen [9], and Samani [11]. The average monthly values of TR were related to the measured values of k_r based on the best-fit curve for all the studied climatic stations. One of the simplest and best-fit models was the hyperbolic model (Eq. (8)) with $r^2 = 0.962$. Dataplot and the best-fit curve are shown in Fig. 1.

$$k_r = 0.119 + 0.821/\mathrm{TR} \tag{8}$$

This formula was derived from a set of 9,640 point-pairs representing the monthly averages of each year for the studied stations. For an easier and quicker prediction of the equation, the TR values were normalized to a ceiling number of (0.1); i.e. ceiling numbers 10.3, 6.7, and 15.9 were assigned for TR values of 10.23, 6.69, or 15.85, respectively. These TR values were grouped and the corresponding k_r values were averaged for calculating the coefficient of variation (CV) of each normalized value (Fig. 1). As shown in Fig. 1, most of the datapoints lie between TR values of 11 and 17, whereas the CV ranges from 8 to 4%. The higher values of CV correspond to the lower values of datapoints. This increases the reliability of the normalized data-set as an acceptable representative of the original data-set to be in agreement with Samani [11] (Tables 2a, 2b, 3a, 3b).

$$\mathrm{CV} = \frac{1}{\bar{x}}\sqrt{\frac{\sum_{i=1}^{n}(x-\bar{x})^2}{n-1}} \tag{9}$$

where x is any variable and $\bar{x}$ is the average of that variable.

2.3. Statistical validation

Statistical comparisons were performed among the different formulas expressing k_r which in turn is compared with actual records. The investigated statistical measures, include the absolute prediction error (APE), the standard error of estimate (SEE), the mean percent error (MPE), and the normalized root mean squared deviation (NRMSD), as presented in following equations:

Table 4
Monthly average k_r values using different methods

			Measured k_r			Calculated k_r				Error %			
Station name	Coastality	Altitude	Average	StDv	CV %	A	H	S	C	A	H	S	C
AlWajh	Coastal	21	0.216	0.019	8.247	0.169	0.190	0.154	0.202	25.44	14.23	33.59	7.93
Gizan	Coastal	3	0.209	0.006	2.638	0.170	0.190	0.161	0.209	21.53	10.53	26.34	0.21
Jeddah	Coastal	17	0.197	0.005	2.278	0.170	0.190	0.149	0.188	15.14	4.08	26.40	4.98
Yenbo	Coastal	6	0.184	0.012	2.259	0.170	0.190	0.156	0.179	7.37	3.39	14.92	2.69
A’Dhahran	Coastal	17	0.184	0.007	3.429	0.170	0.190	0.153	0.182	7.41	3.50	16.83	0.64
ArRiyadh Middle	Interior	611	0.181	0.007	3.837	0.159	0.162	0.153	0.182	12.00	10.24	15.16	0.51
Makkah	Interior	213	0.179	0.005	2.537	0.165	0.162	0.155	0.180	7.58	9.36	13.36	0.66
Ad Dammam	Coastal	21	0.179	0.008	3.939	0.170	0.190	0.164	0.177	4.62	6.16	8.09	1.16
Al Baha	Interior	1,652	0.178	0.018	3.022	0.141	0.162	0.151	0.183	19.92	8.75	14.66	2.70
AlMadina	Interior	636	0.178	0.005	2.684	0.160	0.162	0.156	0.179	9.69	8.75	12.19	0.74
AlJouf	Interior	671	0.177	0.005	2.720	0.157	0.162	0.160	0.178	10.90	8.43	9.50	0.04
Turaif	Interior	818	0.173	0.006	3.421	0.154	0.162	0.161	0.177	10.30	6.16	6.57	2.19
AlQaisumah	Interior	650	0.173	0.007	3.568	0.165	0.162	0.166	0.176	4.75	6.14	4.13	1.30
Arar	Interior	600	0.173	0.006	3.324	0.160	0.162	0.166	0.175	7.13	5.96	3.75	1.29
Al Ahsa	Interior	179	0.173	0.006	3.582	0.167	0.162	0.174	0.173	3.21	5.77	0.50	0.24
AtTa’if	Interior	1,454	0.172	0.007	4.519	0.144	0.162	0.157	0.178	15.28	5.59	8.09	3.35
Hail	Interior	1,013	0.172	0.019	2.124	0.152	0.162	0.169	0.174	10.99	5.42	1.58	1.11
Hafr El-Batin	Interior	360	0.172	0.020	2.539	0.163	0.162	0.174	0.173	4.54	5.32	1.00	0.74
Abha	Interior	2,093	0.171	0.010	5.114	0.134	0.162	0.153	0.181	20.47	5.00	9.70	5.49
Tabuk	Interior	776	0.170	0.007	4.332	0.156	0.162	0.173	0.173	7.92	4.62	1.46	1.17
Rafha	Interior	447	0.169	0.007	3.662	0.162	0.162	0.176	0.173	4.16	4.05	3.51	1.82
Khamis Mushait	Interior	2,057	0.168	0.009	5.059	0.134	0.162	0.159	0.177	18.60	3.50	5.10	4.93
Sharurrah	Interior	725	0.168	0.006	3.080	0.166	0.162	0.195	0.168	1.47	3.39	14.40	0.03
Wadi Al Dawasir	Interior	652	0.168	0.004	1.722	0.159	0.162	0.192	0.169	5.08	3.36	13.02	0.30
AlQuraiat	Interior	560	0.167	0.006	3.934	0.161	0.162	0.192	0.169	3.26	2.90	13.58	1.01
ArRiyadh North	Interior	611	0.167	0.006	3.113	0.159	0.162	0.179	0.172	4.63	2.77	6.37	2.54
AlQassim	Interior	358	0.166	0.006	3.066	0.158	0.162	0.175	0.173	4.47	2.40	4.49	3.49
Najran	Interior	1,210	0.166	0.006	2.429	0.148	0.162	0.180	0.171	9.70	2.07	7.59	2.84
Bisha	Interior	1,163	0.158	0.003	2.013	0.149	0.162	0.191	0.169	4.97	2.30	18.26	5.99
Average			0.176	0.008	3.39	0.158	0.168	0.167	0.178	9.74	5.66	10.83	2.14
Maximum			0.216	0.020	8.25	0.170	0.190	0.195	0.209	25.44	14.23	33.59	7.93
Minimum			0.158	0.003	1.72	0.134	0.162	0.149	0.168	1.47	2.07	0.50	0.03

$$\mathrm{APE} = \frac{|F_i - A_i|}{A_i} \times 100 \tag{10}$$

$$\mathrm{SEE} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(F_i - A_i)^2} \tag{11}$$

$$\mathrm{MPE} = \frac{100}{n}\sum_{i=1}^{n}\frac{(F_i - A_i)}{A_i} \tag{12}$$

$$\mathrm{NRMSD} = \sqrt{\frac{1}{n-2}\sum_{i=1}^{n}(F_i - A_i)^2} \Big/ (A_{\max} - A_{\min}) \tag{13}$$

where F and A are the forecasted (estimated) and actual (measured) value, respectively, n is the number of readings, i is the counter, $A_{\max}$ and $A_{\min}$ are the maximum and minimum measured values, and the straight brackets round a variable ($|\cdots|$) refer to its absolute value.

3. Results and discussion

3.1. Analysis of annual means

Table 4 shows the annual average values of k_r calculated by four methods namely A, H, S, and C representing Allen [9], Hargreaves [8], Samani [11], and Eq. (8), respectively. The real value of k_r was also calculated as described above and is presented in Table 4.

The annual means in the KSA tend to be constant and the average k_r value was about 0.176 regardless of

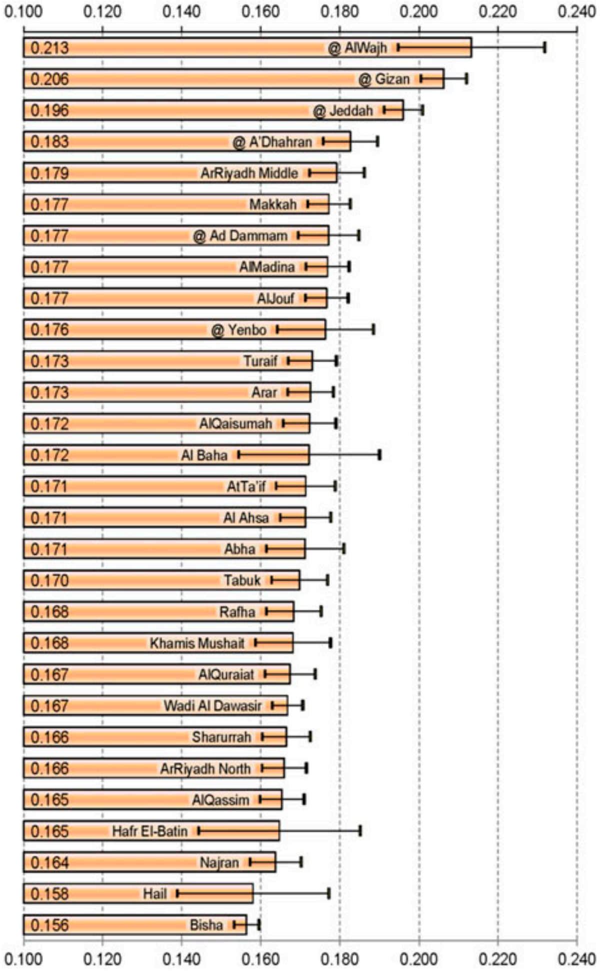

Fig. 2. Average annual values of k_r of the studied stations sorted in ascending order, the I bar shows the deviation range out of average. Stations denoted by @ are considered coastal stations while others as interior.

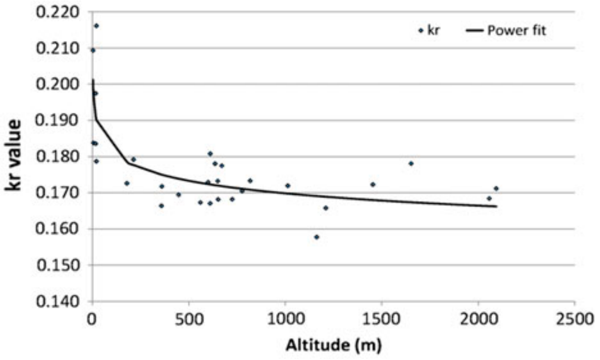

Fig. 3. Average annual values of k_r vs. the altitude of the studied stations.

the coastality conditions. The maximum k_r value of 0.216 was found for AlWajh station (st:11) which is located along the Red Sea's shore in northwest of the KSA. This value reflects the maximum effect of coastal location in the KSA. The next coastal regions according to k_r values (in descending order) were Gizan ($k_r = 0.209$), Jeddah ($k_r = 0.197$), Yenbo and "A'Dhahran" ($k_r = 0.184$). "Ad Dammam" was considered a coastal station although its coastality value was only 0.179 (was a round-average value). This could be due to the distance between the station and the seashore (38 km). As shown in Fig. 2, although "Ar Riyadh-middle" and Makkah are noncoastal stations, but the coastality value of these seems to be as high as 0.181and 0.179 i.e. even higher or equal to the coastality value of "Ad Dammam." This could be attributed due to the urbanization as was evident from the location of these stations i.e. inside the heavily populated cities of the KSA.

The urbanization effect becomes more evident when "Ar Riyadh-middle" was compared with "Ar Riyadh-North." Unlike the former station, which was located in the midst of the high populated city, the later was located at King Khaled International Airport, in the upper North region of Riyadh with less population and urbanization. The k_r of "Ar Riyadh-North" was only 0.167 compared with 0.181 for "Ar Riyadh-middle" station. The minimum value of k_r (0.158) in the KSA was found for Bisha followed by Najran and AlQassim with k_r value of 0.166 for each of these two cities. For AlQassim station in Najd Plateau, one can understand the low coastality value as this region was too arid. But for Bisha and Najran, the situation was different, as both lies at South of the KSA near Yemen. This zone was not arid at all but the aridity of these two stations had a common phenomenon i.e. the altitude value which was more than 1,000 m for both cities. This leads to a conclusion in agreement with Allen [9] that k_r is affected by the atmospheric pressure (or altitude).

Fig. 3 shows the relationship between altitude (Z) and k_r showing that k_r decreases as altitude increases. The best-fit of this relationship can be written as follows:

$$k_r = 0.208 \times Z^{-0.029} \tag{14}$$

Although, the correlation coefficient was not high ($r = 0.734$) but the standard error quite less (SE = 0.0086). The purpose of the above formula was to confirm that k_r was inversely proportional to the

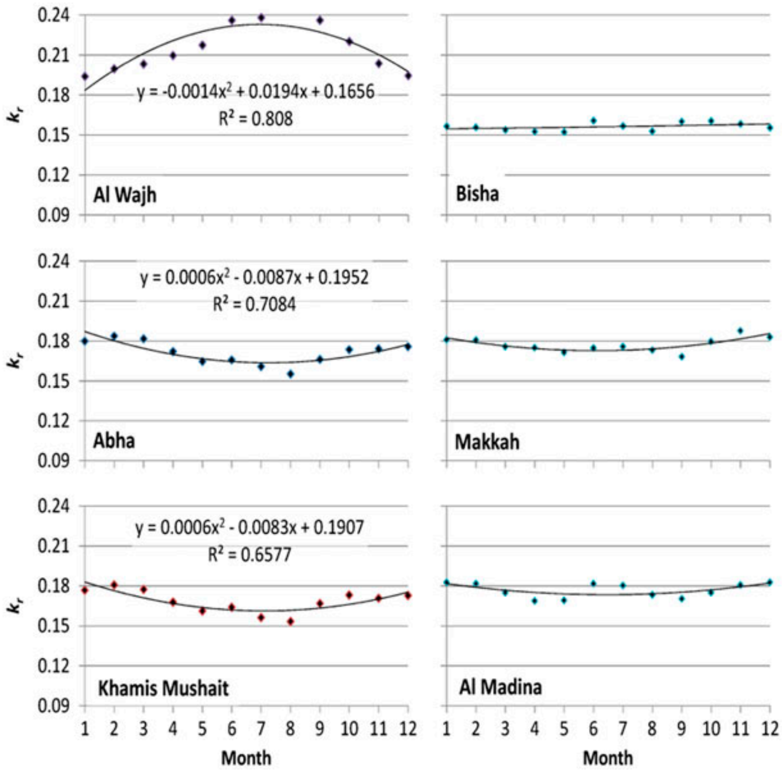

Fig. 4. The k_r values in different months for some of the studied stations.

altitude instead of an exact value of k_r. The monthly deviation of the annual averages, expressed as CV, is illustrated as I bars in Fig. 2. The CV values fall below 5% for most of the stations, which is a reasonable value to let one rely on the annual average as a representative value of the whole year. The exception occurred for three stations, namely "AlWajh", Abha, and "Khamis Mushait," with CV values of 8.24, 5.11, and 5.06, respectively. Fig. 4 shows the k_r values of these three stations with high CV values, along with three other stations, namely Bisha, Makkah, and "Al Madina," with low CV values of 2.0, 2.54, and 2.68%, respectively.

The CV values of three stations (with high CV values) seem to follow a quadratic curve trend with respect to months. The quadratic curve has a positive curvature for "Al Wajh" (the coastal station) and a negative curvature for Abha and "Khamis Mushait" (the interior stations). This leads to conclusion that the coastality value increases during summer for coastal stations while decreases for interior (noncoastal) stations. However, this conclusion cannot be established for rest of the stations, used in the study, with CV less than 5%, which is hard to be observed in quadratic curves for other three stations, as seen in Fig. 4.

3.2. Comparison between models' prediction patterns

Three models were established for prediction of k_r based on temperature range. These were Hargreaves [8], Samani [11], and the current model, Eq. (8), in addition to the model developed by Allen [9] that predicts k_r from the atmospheric pressure. As shown in Fig. 5, the APE ranges from 1.47 to 25.44% for Sharura and "Al Wajh" stations, respectively, when using Allen's model.

There were 10 stations with error less than 5%, 8 stations with error of 5–10%, and 11 stations with error more than 10%. Three of the extreme wrongly estimated stations were coastal cities, while the rest were interior stations with extreme high altitudes. These results were in agreement with Samani [11] who reported that the formula of Allen [9] might not be applicable for high altitudes. The SEE was calculated as 0.022 with MPE = 9.936 and normalized root mean square error (NRMSE) = 0.646. These results are summarized in Table 5.

Fig. 6 shows the results of H model which appear to be a better estimate than the A model with maximum APE of 14.23% compared with 25.44% for the A model. There were only three stations with APE > 10%, two of them were coastal (Al WAjh and Gizan) and the one was interior ("ArRiyadh Middle") station.

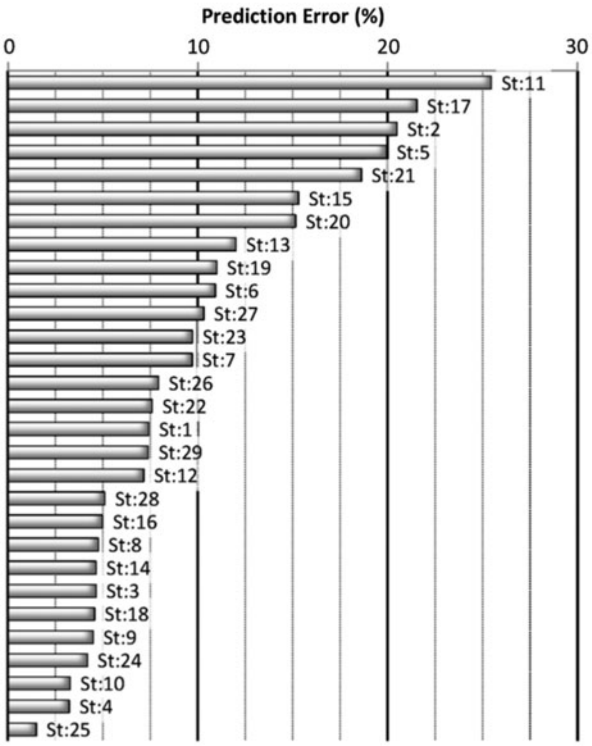

Fig. 5. APE % of the A model, Allen (1995), for the studied stations. Stations were expressed in numbers instead of names to save space. See Table 1 for stations' information.

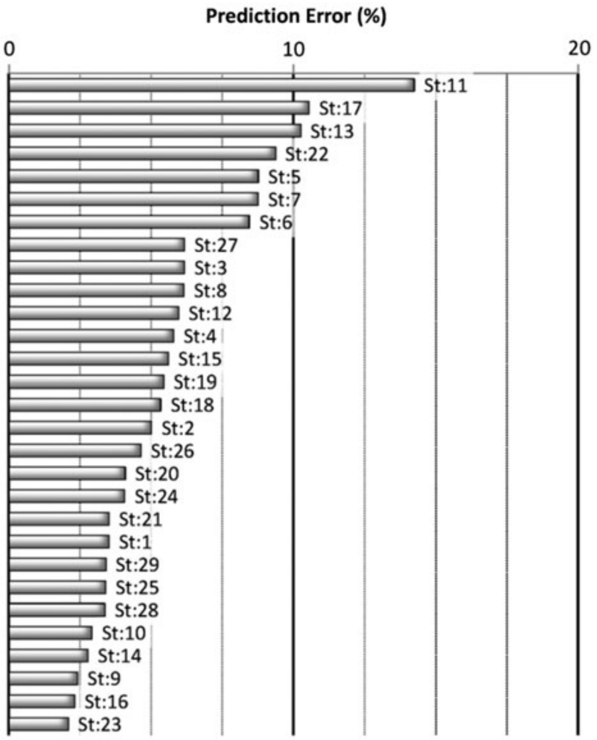

Fig. 6. APE (%) of the H model, Hargreaves (1994), for the studied stations.

Table 5
Summary of the evaluation statistics and measures

Model		Statistic			APE			Num. of stations having APE		
Name	Symbol	SEE	MPE	NRMSD	Avg	Max	Min	<5%	5–10%	>10%
Allen (1995)	A	0.022	9.936	0.646	9.74	25.44	1.47	10	8	11
Hargreaves (1994)	H	0.012	4.689	0.355	5.66	14.23	2.07	14	12	3
Samani (2000)	S	0.025	4.517	0.750	10.83	33.59	0.50	8	8	13
Current, Eq. (8)	C	0.005	−1.111	0.164	2.14	7.93	0.03	26	3	0

For noncoastal stations, the model appears to have large errors when predicting for stations with high population like "Ar Riyadh Middle," Makkah, and AlMadina. On the contrary, the model perfectly represents noncoastal stations with low populations like Bisha, Najran, and "ArRiyadh North." The estimated parameters of H model, including SEE = 0.012, MPE = 4.68, and NRMSD = 0.355, were better than that of the A model. On the other hand, the S model appears to have the largest prediction error, as shown in Fig. 7. A maximum APE value of 33.59% was observed with 13 and 8 stations having APE > 10% and <5%, respectively.

There is no clear conjunction between stations with minimum error or between stations with maximum error. The maximum error appears mostly for coastal stations with an APE of almost more than14% except "Ad Dammam" having APE = 8%, which is the farthest away coastal station and hence, may be regarded as noncoastal. For interior stations, the situation was not clear with respect to the altitude. "Khamis Mushait" with extremely high altitude (2,057 m) resulted APE = 5.1% while both Abha and Albaha (with altitudes of 2,093 and 1,652 m, respectively) resulted APE of 9.7% and 14.66%, respectively. This leads to conclude the unsuitability of the S model in the prediction

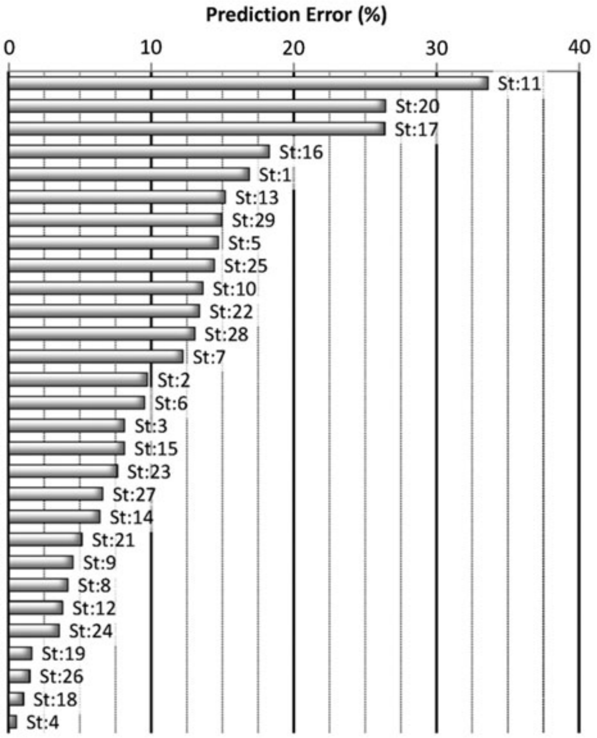

Fig. 7. APE (%) of the S model, Samani (2000), for the studied stations.

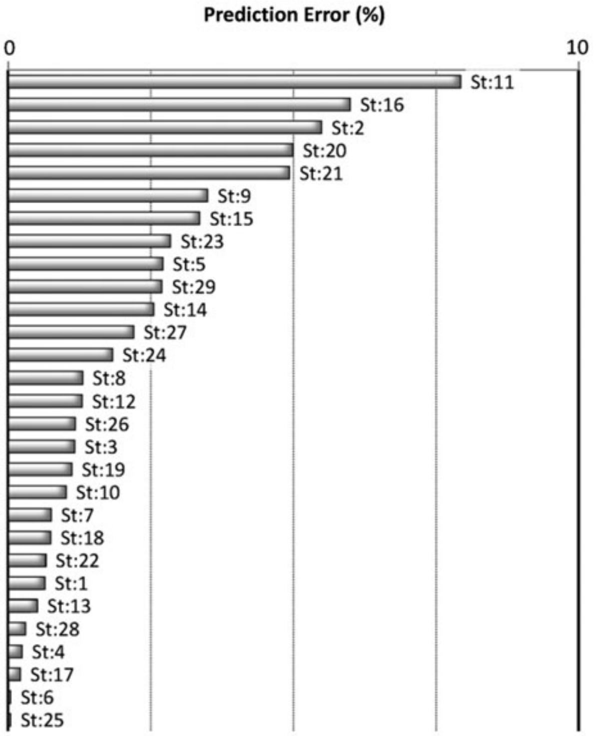

Fig. 8. APE (%) of the C model, Eq. (8), for the studied stations.

of k_r in KSA. Finally, the proposed model, Eq. (8), seems to be the best one for estimating all parameters. The model predicted k_r for 26 stations with less than 5% APE, as seen in Fig. 8.

The overall statistics of the proposed model was the best of all other models with SEE = 0.005, MPE = −1.111, and NRMSE = 0.164. With the exception of "Al Wajh" station, which was the most unpredictable station in all models, the maximum APE error of 5.99% was seen for Bisha station, which, however, was reasonable error if only a single accurate equation for all stations in KSA is to be considered. In Table 5, the MPE statistic shows the amount and direction of over/under estimation. The current model underestimates the actual value by almost 1.11% in most of the cases, while the other three models (S, H, and A) overestimate the actual value by 4.5, 4.6, and 9.9%, respectively. The NRMSD, which expresses the residual variance, was observed to be the minimum for the current model (0.164), and maximum for the S model (0.75). These values were estimated as 0.646 and 0.355 for A and H models, respectively. Moreover, the value of SEE was the least (0.005) when using the current model following the same trend as of NRMSD.

4. Conclusions

As an important parameter to calculate the short-wave solar radiation, the coastality value, k_r, of 29 weather stations in the KSA was determined from the measured data and was compared to the values obtained from three published models, namely Hargreaves [8], Samani [11], and Allen [9]. A new local formula was derived through a 30-year climatic record of 29 weather stations. Comparisons were performed through four statistical measures. The results show that the k_r is inversely proportional to both the distance from the coastline and the altitude of the station. Another interesting finding was regarding the urbanization which had a coast-like effect. In other words, noncoastal but highly populated cities can be regarded as coastal cities. A local hyperbolic equation to estimate the k_r using the monthly average temperature range was derived. The developed relationship yielded the best prediction results compared with other three models followed by Hargreaves, Allen, and Samani models. It is recommended to use the corrected values of k_r as derived from the proposed equation for future investigations of solar-based studies. A detailed investigation is also recommended for the urbanization effect on the k_r.

Acknowledgments

This project was supported by the NSTIP strategic technologies program, grant number (11-WAT1875-02) in the Kingdom of Saudi Arabia.

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Appendix

According to the FAO (1990), the extraterrestrial radiation R_a (MJ m^{-2} d^{-1}) is calculated as follows;

$$R_a = 37.6\ d_r(\omega_s \sin\varphi \sin\delta + \sin\omega_s \cos\varphi \cos\delta) \tag{A1}$$

where d_r relative distance Earth to Sun; $d_r = 1 + 0.033\cos(0.0172J)$, J the Julian day ranges from 1 to 366 in leap year, δ solar declination (rad); $\delta = 0.409\sin(0.0172J - 1.39)$, φ latitude (rad), ω_s sunset hour angle (rad); $\omega_s = \arccos(-\tan\varphi\tan\delta)$.

The maximum allowed daylight hours (N) is calculated as follows [2]

$$N = \frac{24}{\pi}\omega_s \tag{A2}$$