

Temporal and Spatial Variability of Potential Evapotranspiration in Saudi Arabia



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Introduction:

Accurate estimation of evapotranspiration (ET), which is a major process in the hydrologic cycle, is fundamental to the estimation of irrigation water requirements and management of the vital water resource. This is especially true in arid regions where the quality and quantity of water are limited. Under such conditions, underestimating ET leads to applying less irrigation water which results in low crop yield and insufficient leaching and consequently soil salinization. On the other hand, applying more than needed of irrigation water due to overestimating ET results in unwarranted loss of the non-renewable water resource.

Estimation of actual evapotranspiration from a surface with a particular type of vegetation proceeds in two stages. **First**, estimation of potential evapotranspiration (ET_p) is obtained. **Second**, the estimated ET_p is multiplied by the crop coefficient for that particular type of vegetation. Potential evapotranspiration is typically estimated either by multiplying pan-evaporation amounts by pan-coefficients or by empirical or semi-empirical equations that are based on various meteorological data. Pan-based estimates of ET_p require reliable measurements of evaporation by standard pans and employ totally empirical methods for estimating pan-coefficients as a function of local wind speed, humidity, and surrounding land surface characteristics. Numerous forms of ET_p equations have been developed and tested in different parts of the world, however, their performance is widely variable with the physically based Penman-Monteith (PM) equation, which uses a more theoretical momentum/vapor diffusivity wind function, suggested to provide the best estimates (Shuttleworth 1993 and Chin et al 1995). Unfortunately, the PM method requires measurements of the resistance factors which are not available for the region under investigation. The semi-empirical Penman, which combines the two factors influencing the rate of evapotranspiration: the energy input, and the rate of aerodynamic exchange of vapor

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from the surface, gives good estimates of ET_p and its variables can be obtained directly or derived from standard meteorological data. Totally empirical methods for estimating ET_p are less accurate and their accuracy decreases substantially outside the location of calibration.

Most previous attempts to estimate ET_p in Saudi Arabia (e.g. Saleh and Sendil 1984; Saeed 1986; Mustafa et al 1989; Alomran and Shalaby 1992; and Al-taher 1992 and 1996) relied on totally empirical methods. The aim of this paper is to provide better estimates of ET_p using the semi-empirical Penman's equation for several stations representing the main agricultural regions of Saudi Arabia and to analyze the temporal and spatial variability of it.

Methods:

The general form of Penman equation for estimating ET_p is:

$$ET_p = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} E_a$$

where ET_p is potential evapotranspiration in mm/day, Δ is the slope of saturation vapor pressure-temperature curve at mean temperature in mb/°K, γ is the psychrometric constant in mb/°K, R_n is net long-wave and short-wave radiation in mm/day water equivalent, and E_a is an aerodynamic vapor transport term in mm/day. Net radiation is not measured at any of the stations but it can be estimated as (Doorenbos and Pruitt 1977):

$$R_n = (1.0 - \alpha) R_s - \sigma T_a^4 (0.34 - 0.044 e_d^{0.5}) (0.10 + 0.90 \frac{n}{N})$$

where α is surface albedo, R_s is incident short wave solar radiation in mm/day water equivalent, σ is the Stefan-Boltzman constant mm/day °K⁴, T_a is mean air temperature in °K, n/N is the ratio of actual to possible hours of sunshine, and e_d is saturation vapor pressure (mb) evaluated at dew point temperature (T_d) at 2-m height. The most used form for the E_a term is:

$$E_a = f(u) (e_s - e_d)$$

with $f(u)$ denoted as

$$f(u) = 0.263 (a + bu)$$

where u is wind speed (km/day), e_s is saturation vapor pressure (mb) evaluated at mean air temperature at 2-m height, and a and b are empirically derived parameters with their values depend on the units for u , e_s , e_d , R_n , and ET_p . For the units used in this work, Doorenbos and Pruitt (1977) Suggested values of 1.0 and 0.01 for a and b , respectively. Saturation vapor pressure is not given at any of the stations but it can be given by (Stull 1988 p. 276):

$$e_s = 6.112 \exp \left[\frac{17.67 (T - 273.16)}{T - 29.66} \right]$$

where T is the relevant temperature (T_a or T_d) in $^{\circ}\text{K}$. Since daily possible sunshine hours measurements are not available, they have to be calculated as:

$$N = 24 \frac{H}{\pi}$$

where H is the length of half day expressed in radians which can be computed as (Sellers 1975,p.15):

$$\cos H = - \tan \varphi \tan \delta$$

where φ is latitude and δ is solar declination which is given by (Rosenberg et al 1983, p. 15):

$$\delta = 23.5 \cos \left[\frac{2 \pi (D - 172)}{365} \right]$$

where D is the day of the year.

Data

The data that were used in this study are monthly data for incoming solar radiation, temperature, relative humidity, wind speed, and sunshine duration from six weather stations in the main agricultural regions of Saudi Arabia (Fig.1) obtained by the Ministry of Agriculture and Water in Saudi Arabia for the period 1981-1990.

Results and Discussions

Monthly ET_p was estimated using Eq. 1 for each month of the ten-year period

then average monthly and yearly ET_p were calculated. Estimated monthly and yearly averages of ET_p for the six stations are given in Table 1 and depicted in Figs. 2 and 3. Average annual ET_p ranged from 2284 mm in Abha, located in the mountainous 'Asir region in southwestern Saudi Arabia (2200 m a.s.l), to 3126 mm in 'Unayzah in the central region of the country. During the winter months, there is no big difference in monthly ET_p among the stations with the exception of Sakaka which has lower values of ET_p . This is attributed to lower solar radiation due to increased cloudiness (Figs. 4 and 5) during the winter months. However, during the summer months, the difference in monthly ET_p among the stations is considerable

Table (1)
Calculated average monthly and yearly ET_p (1981-1990)

Month	Abha	Hufuf	Kharj	Hail	Unayzah	Sakakah
Jan.	147	145	135	138	142	100
Feb.	138	164	151	154	171	120
Mar.	191	206	206	223	238	169
Apr.	181	233	219	263	271	208
May.	207	292	272	327	351	253
Jun.	238	320	306	371	379	281
Jul.	229	303	311	374	370	288
Aug.	200	274	279	344	337	255
Sep.	232	255	256	306	304	236
Oct.	208	199	199	240	243	176
Nov.	174	177	168	176	186	127
Dec.	139	134	124	135	134	95
Annual	2284	2702	2629	3051	3126	2308

Figure (1)
Map of Saudi Arabia Showing the Spatial Distribution of the Stations

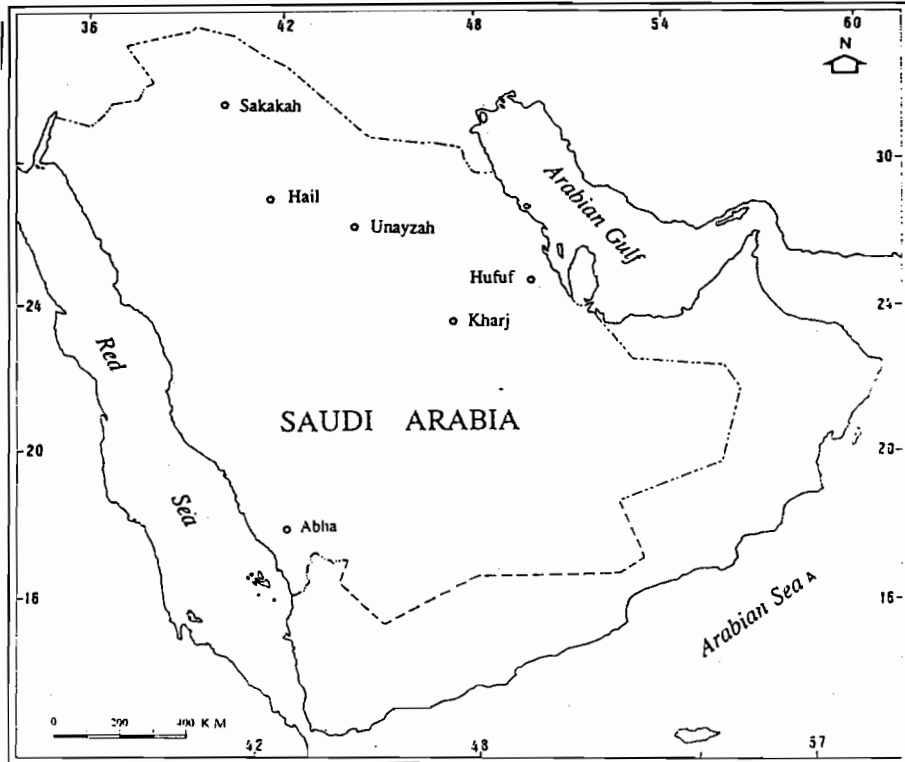


Figure (2)
Average Monthly Potential Evapotranspiration (1981-1990)

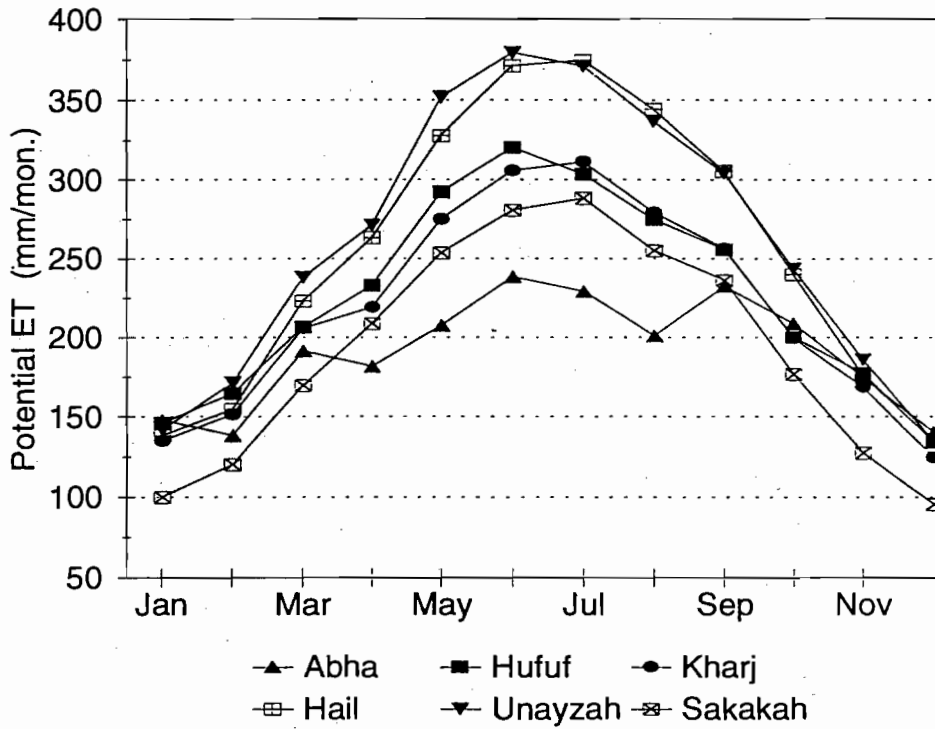


Figure (3)
Temporal and Spatial Variation of Potential Evapotranspiration (mm/mon)

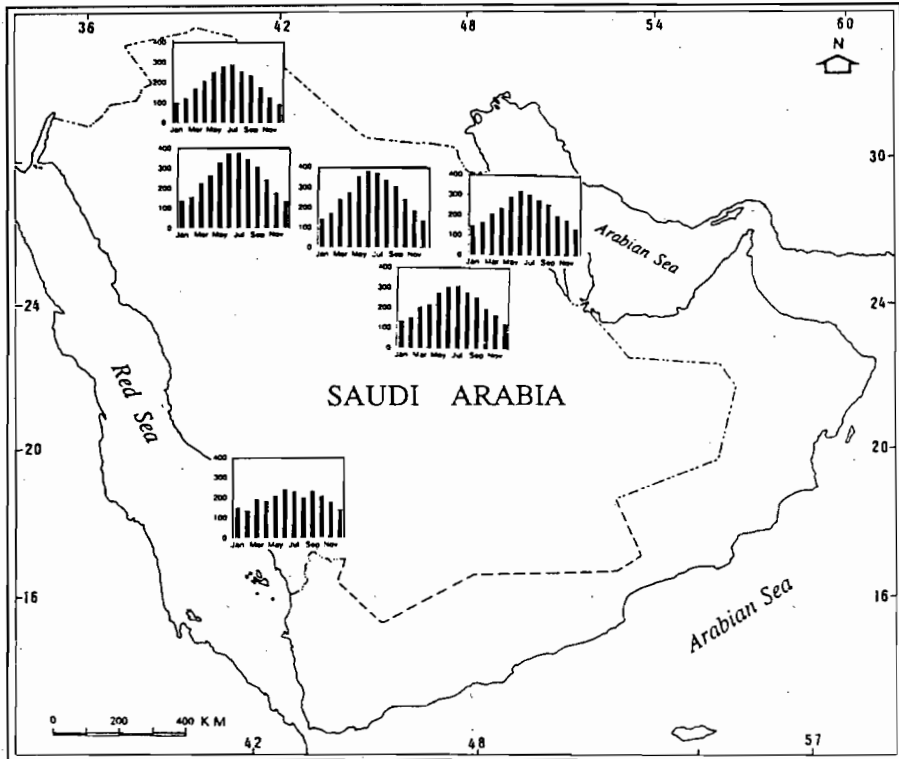


Figure (4)
Average Monthly Solar Radiation (1981-1990)

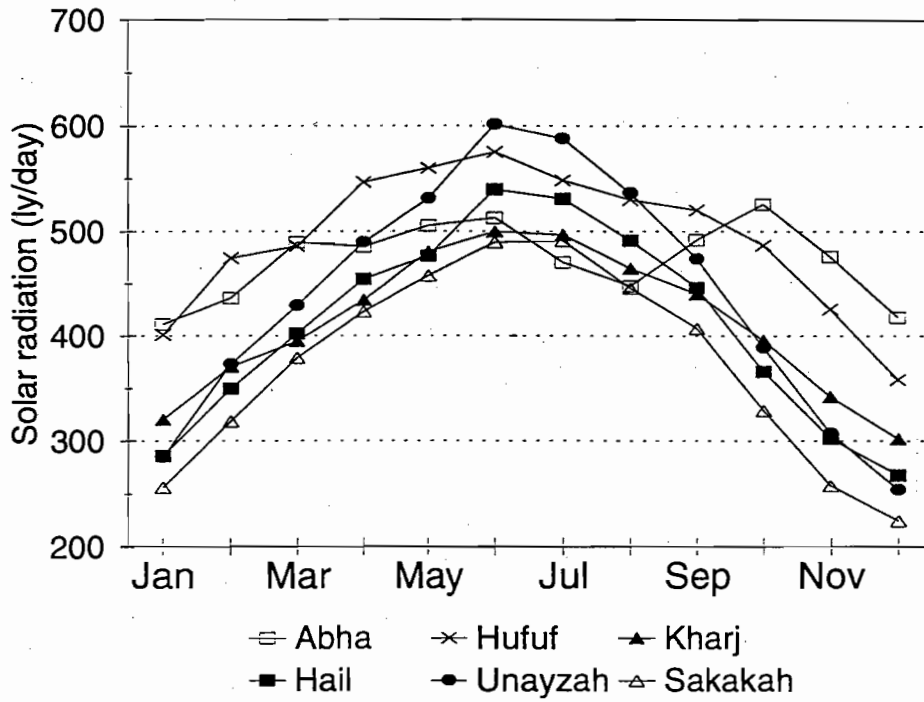
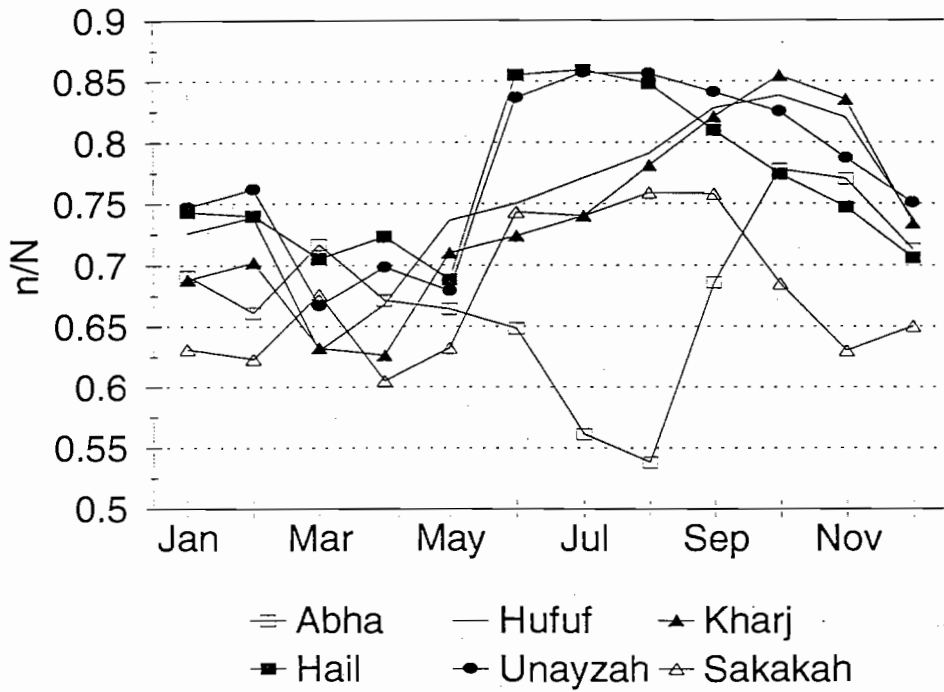


Figure (5)
Average monthly n/N (1981-1990)



with 'Unayzah having the highest ET_p rate (379 mm) and Abha the lowest (200 mm). The big differences in ET_p rates during the summer months among the stations despite the fact that there are no big changes in the differences among the stations in temperature, cloudiness, wind speed, and solar radiation from winter to summer (Figs. 6,5,7, and 4, respectively) are due to considerable differences in relative humidity (Fig.8) The amplitude of ET_p curves is lowest (100 mm) for the station having the lowest mean annual ET_p (Abha) and highest (245 mm) for the station having the highest mean annual ET_p ('Unayzah) Which is in accordance with the amplitudes of solar radiation, temperature, and relative humidity curves.

The temporal trend of monthly ET_p for Abha station is different from the trends shown by the rest of the stations in the sense that there are fluctuations superimposed on the general trend. The low ET_p rates in the months of August and April compared to the surrounding months are explained by the corresponding significant decrease in R_s (Fig. 9) In the case of August, the local minima in the R_s curve is caused by significant increase in cloud cover during that month (Fig. 10). Although n/N value is slightly lower for May than its value for April, its value for April, the effect of this difference on R_s is small compared to the effect of the difference in solar radiation received at the top of the atmosphere on R_s . This makes the resultant R_s higher for May than April despite the slight increase in cloudiness during May. The fact that R_s value is lower for April than its value for March in spite of increased solar radiation received at the top of the atmosphere during April is due to the significant increase in cloud cover which blocks incoming solar radiation. The above two facts explain the local minima in the R_s curve in April. The low ET_p rate in February compared to the surrounding months is due to increasing relative humidity.

Figure (6)
Average Monthly Temperature (1981-1990)

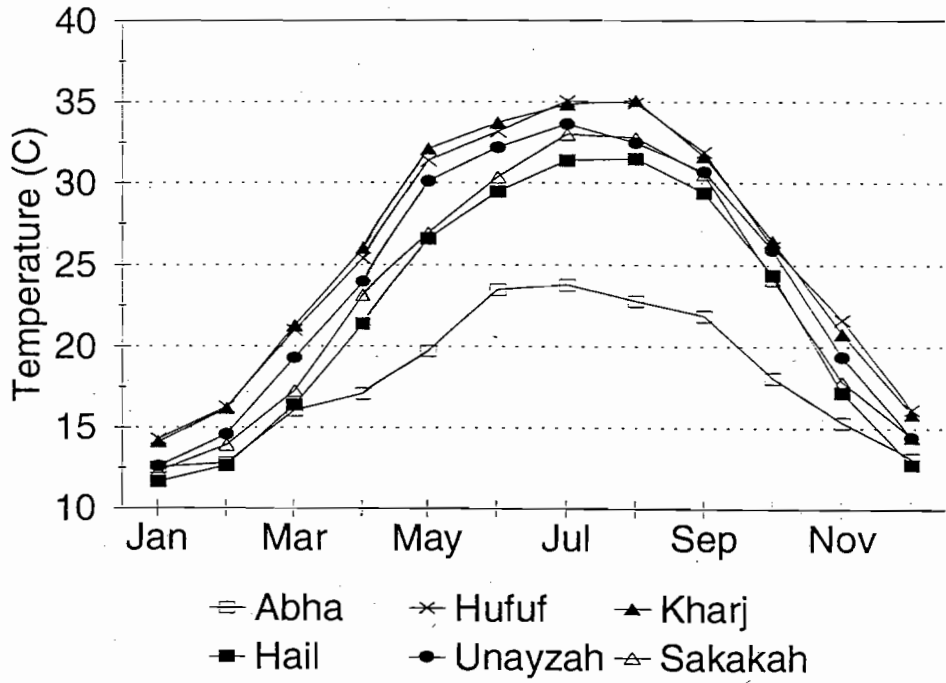


Figure (7)
Average Monthly Wind Speed (1981-1990)

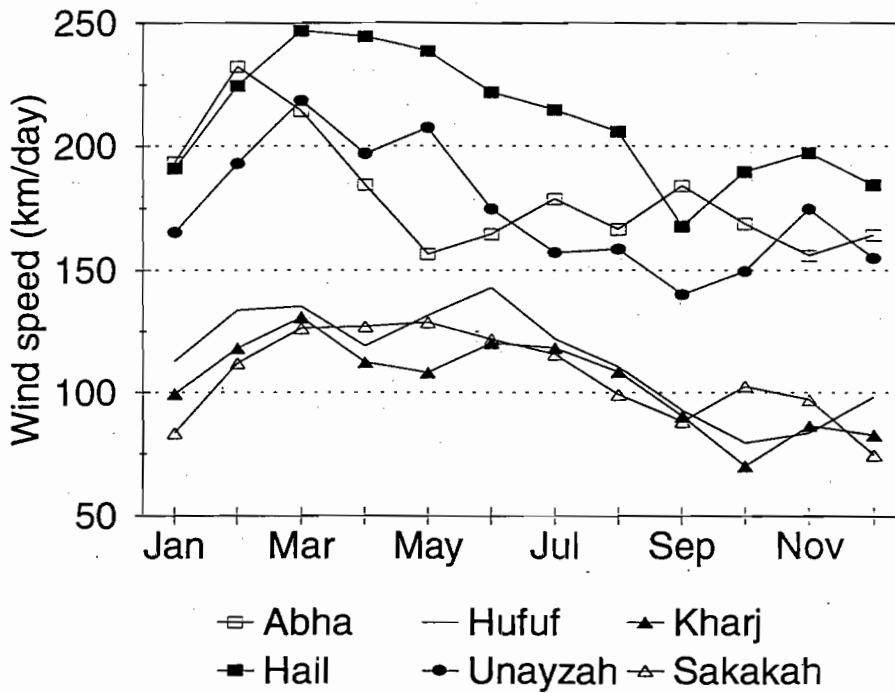


Figure (8)
Average Monthly Relative Humidity (1981-1990)

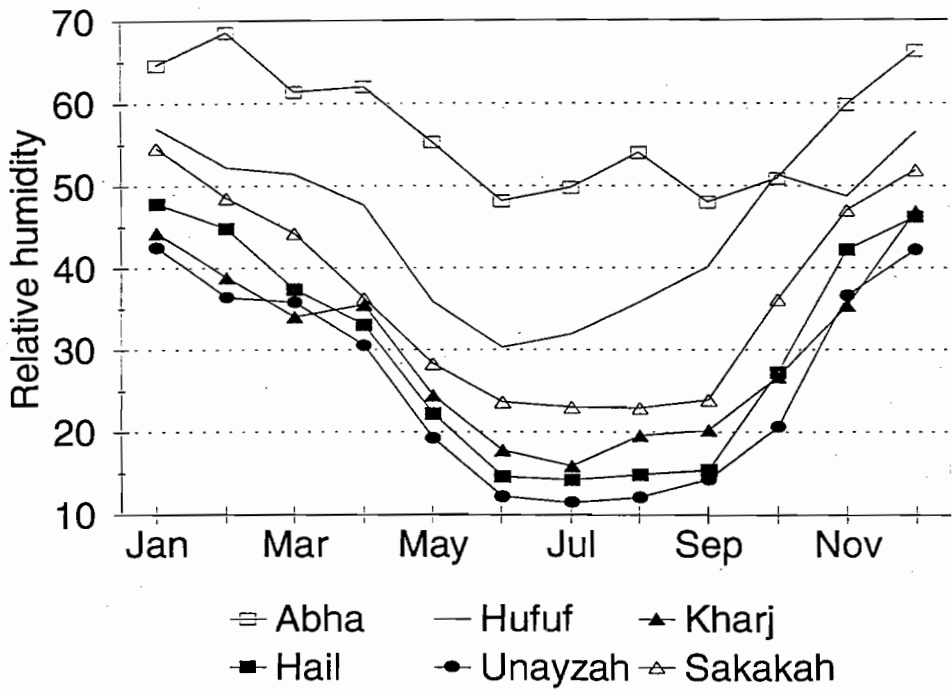


Figure (9)
Average Monthly Potential Evapotranspiration, Wind Speed,
and Solar Radiation for Abha (1981-1990)

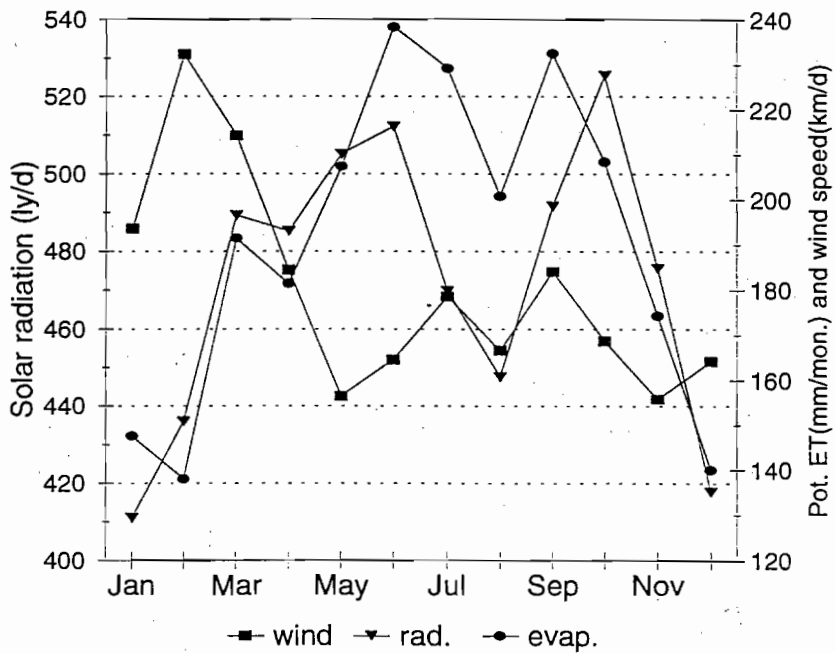
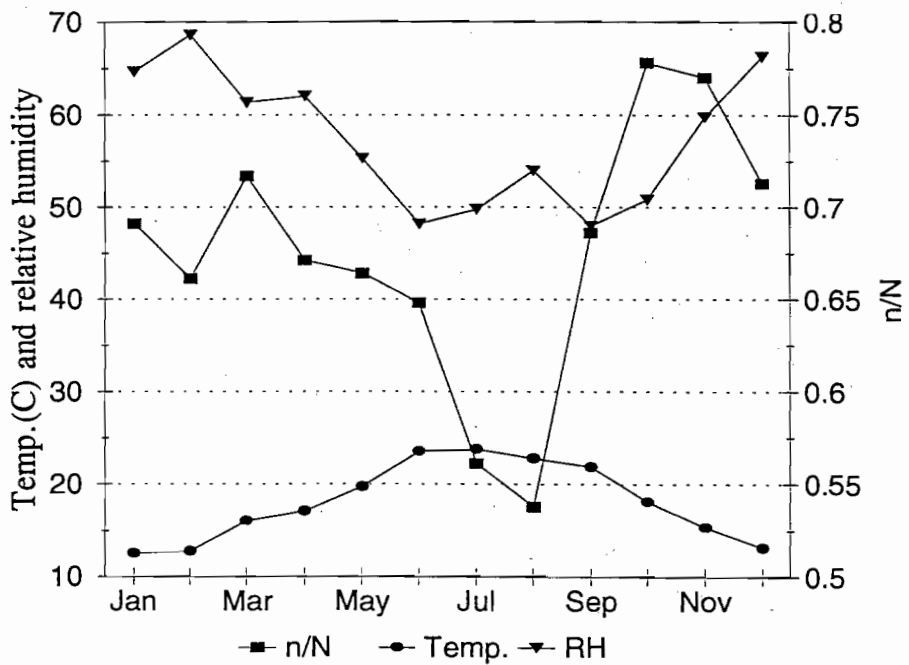


Figure (10)
Average Monthly Temperature, Relative Humidity and n/N
for Abha (1981-1990)





Summary

Average monthly and annual potential evapotranspiration was estimated using the semi-empirical Penman's method for Abha, Hufuf, Kharj, Hail, 'Unayzah and Sakakah stations in Saudi Arabia. The data used to carry out the calculations were standard meteorological data covering ten-year period extending from 1981 to 1990. Since some of the variables needed to use the Penman equation are not measured at the stations, estimates by well-tested equations were provided in this work. Estimated monthly and yearly averages of ET_p for the six stations were provided in both tabular and graphical forms and their temporal and spatial variations were discussed. Average annual ET_p ranges from 2284 mm/yr in Abha to 3126 mm/yr in 'Unayzah. Differences in monthly ET_p among the stations during the winter months were minimal with the exception of Sakaka station which experiences lower solar radiation due to increased cloudiness during the winter months. During the summer months, however, the differences in monthly ET_p among the stations are considerable and can be attributed to big differences in relative humidity during this period of the year. The oscillations that were superimposed on the general trend of Abha's ET_p curve were explained by local minima in R_s in two cases and by local maxima in relative humidity in another case.

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