Spatio-Temporal Variability of Evapotranspiration over the Kingdom of Saudi Arabia

M. ElNesr, A. Alazba, M. Abu-Zreig

Abstract. *Climate change and variability is receiving much attention recently. Changes in the world temperature and other natural phenomenon such as rainfall variability are being considered as indicators to climate change. These changes can have significant effect on water resources and therefore on the livelihood of society especially in water scarce countries such Saudi Arabia. The Kingdom of Saudi Arabia suffers a chronic water scarcity, despite the fact that the agricultural sector consumes around 90% of the water budget in the kingdom. The objective of this article is to study the variability in reference evapotranspiration (ET_o) demand over the kingdom during the period from 1980 to 2008 using Penman-Monteith formula and to identify possible changes in the ET_o as an indicator to climate change in the region. Studying ET_o can be an incomparable indicator for climate change because it involves various parameters including temperature, humidity, and wind speed. Identifying changes in ET_o can also help in future planning of agriculture-water projects and identify lower and higher ET_o zones for proper planning and management of agricultural projects in arid region. Results indicated that the average ET_o varied from 5 mm/d in January to more than 15 mm/d in July with extreme value ranged from as low as 1.6 to 30 mm/d. The lowest ET_o values were found in the southern region of the Kingdom during the month of November to February and starts to shift to the western region from the month of March to October. The results also indicated that the annual maximum and minimum daily averages of ET_o steadily increased over the study period. The ET_o annual daily average had increased from about 9.6 mm/d in 1980 to as high as 10.5 mm/d in 2008. Data analysis also revealed that the percentage areas of the Kingdom with high values of ET_o depth, greater than 4000 mm/year, have also steadily increased in the study period from 25% to about 40%. On the other hand, areas having lower ET_o values, less than 3600 mm/year have decreased over the studied area from about 30% in 1980 to as low as 12% of the kingdom total area. These results indicated clearly an increasing trend in the ET_o over Saudi Arabia.*

Keywords. *Evapotranspiration, Climate change, Spatial variation, Water management, Arid lands, Trends.*

Water scarcity is a chronic problem in the arid and semi-arid countries of the Middle East. The Kingdom of Saudi Arabia (KSA) suffers large water supply deficit. Agricultural water consumption in arid and semiarid countries in the Middle East comprises most of their national water budgets. In Saudi Arabia, however, agricultural water consumption is even higher and estimated at 80% to 88% (Al-Ghobari, 2000; Abderrahman, 2001) . The main solutions of the water problem are to improve management of water resources and to predict water demand precisely.

Recently, considerable interest has been shown to climate change phenomena and its effect on weather conditions and water supply (Schwartz and Randall, 2003). It seemed that the most affected sector by such changes would be the agricultural sector. This is because agricultural sector depends on local water resources as well as weather conditions including temperature, rainfall, atmospheric pressure, and solar radiation. All these factors can be gathered to a single parameter; that is evapotranspiration.

Agricultural water requirements are determined initially by determining the reference evapotranspiration (ET_0). Some researchers developed a hypothetical scenario to study the effect of possible increase on temperature over the KSA on ET_0 and subsequently on water supply. A study conducted by Abderrahman et al. (1991) concluded that a 1°C increase in temperature would increase ET_0 from 1% to 4.5%. In another study, that includes selected cities in Saudi Arabia, United Arab Emirates, and Kuwait, Abderrahman and Al-Harazin (2003) concluded that an increase in temperature by 1°C would increase ET_0 over this area by a maximum of 20%. However, no studies have been conducted to quantify time changes of temperature or ET_0 in the Arabian peninsula. Moreover, studies involving ET_0 calculation seemed to be more limited worldwide compared to other climate parameters. Consequently, the goal of this study was to quantify ET_0 and its seasonal spatial and temporal variations in Saudi Arabia during the past 30 years and to examine any changes or trends in the ET_0 over that time period.

Geography and Climate of Saudi Arabia

Saudi Arabia is the largest country of the Arabian Peninsula; it occupies about 80% of its area (Wynbrandt,

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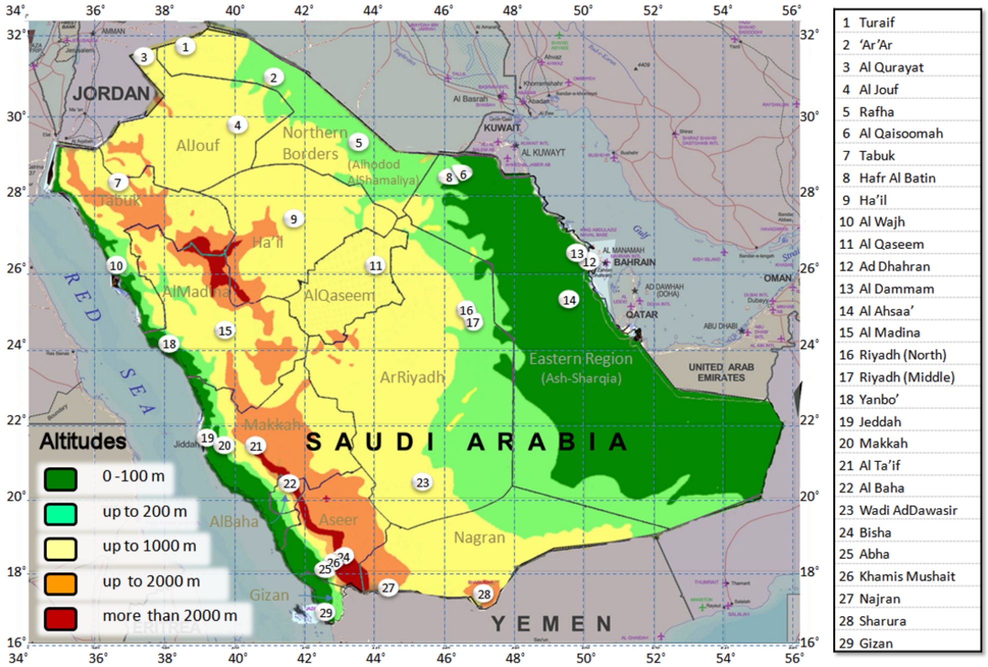


Figure 1. Three-layered map of Saudi Arabia, showing topography, districts, and meteorological stations. Base map Src: NIMA (2003). Districts Src: MOMRA (2007). Topography Src: Albakry et al. (2010).

2004). The country lies between latitudes 16°21'58''N and 32°9'57''N, and longitudes 34°33'48''E and 55°41'29''E (fig. 1). Saudi Arabia has a desert dry climate with high temperatures in most of the country. However, the country falls in the tropical and subtropical desert region. Winds reaching the country are generally dry, and almost all the area is arid. Because of the aridity and the relatively cloudless skies, there are great extremes in temperature, but there are also wide variations between the seasons and regions (AQUASTAT, 2008).

Reliable estimation of ET_o is critical because of its consequent effect on all other hydrological parameters. Any increase in ET_o results in increasing the water demands for urban, industrial, and agricultural uses. Al-Sha'lan and Salih (1987) calculated ET_o for selected sites in the KSA with 23 empirical methods and compared their results with real values obtained from published experiments using lysimeter and field-plot techniques. They concluded that the best method describing actual ET_o, at the time of the study, was the Jensen-Haise method. A similar conclusion was found by Mustafa et al. (1989) by studying 14 zones in KSA. Alazba et al. (2004) developed a computer program based on the geographical information system (GIS) to estimate ET_o in the KSA using Penman-Monteith method, as well as estimating crop water requirements for selected crops. They concluded the importance of studying ET_o variation all over the kingdom, spatially and temporally.

Calculation of Evapotranspiration

Evapotranspiration was calculated using Food and Agricultural Organization (FAO) Penman-Monteith (PM) procedure, FAO 56 method, presented by Allen et al. (1998). In this method, ET_o from standard grass reference is expressed as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \dfrac{900}{(T_a + 273)}\gamma U_2 \Omega}{\Delta + \gamma(1 + 0.34U_2)} \qquad (1)$$

where ET_o is the daily reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T_a is the mean daily air temperature at 2-m height (°C), U_2 is the wind speed at 2-m height (m s^{-1}), Ω (*omega*)is the vapor pressure deficit (kPa), Δ is the slope of vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

Calculating ET_o for longer periods like months or years can be achieved by summation of the daily ET_o for a month or a year (mm month^{-1}). Another approach can be used for calculating the average daily ET_o in a specific month by taking the average daily ET_o during that month. In this study, the average method was used when dealing with monthly data, while the summation method was used for yearly data.

Climatic data was taken from the Presidency of Meteorology and Environment in KSA, the official climate agency in the country. The data set is the most accurate one in KSA and used by all other governmental and academic agencies for climate research and prediction. Weather stations are equipped with up-to-date monitoring devices and are subjected to regular inspection and replacement for defected devices (personal communication with the Presidency of Meteorology and Environment). Data represents 29 meteorological stations, as shown in figure 1. These stations represent all the 13 districts of the KSA. The data covers 29 years of daily meteorological records for 20 stations, 24 years for 6 stations, and 3 stations with less than 20 years as shown in table 1. All of the data ends in 2008 and started at 1980 and 1985 for the 29 and 24 years logging.

All of the data are daily values, the obtained climatic data records were carefully inspected for missing and erroneous reading. Very few errors were found (median value of

Table 1. Detailed information of the meteorological stations covered by the study.

District	Station ID	Station Name	Station Coordinates: Latitude (°North)	Longitude (°East)	Altitude (m)	Logged Years	Missing or Erroneous Records (%)
Northern borders	1	Turaif	31.41	38.40	818	29	3.40
	2	Arar	31.00	41.00	600	29	2.80
	5	Rafha	29.38	43.29	447	29	1.00
AlJouf	3	Guraiat	31.50	37.50	560	4	0.70
	4	Al Jouf	29.47	40.06	671	29	0.40
Tabuk	7	Tabuk	28.22	36.38	776	29	0.10
	10	Wejh	26.12	36.28	21	29	0.40
Ha'il	9	Hail	27.26	41.41	1013	29	0.30
AlQaseem	11	Gassim	26.18	43.46	650	29	1.60
Eastern region	6	Qaisumah	28.32	46.13	358	29	0.30
	8	Hafr Al-Batin	28.20	46.07	360	19	0.80
	12	Dhahran	26.16	50.10	17	29	2.10
	13	Dammam	26.42	50.12	1	9	0.20
	14	Ahsa	25.30	49.48	179	24	0.60
Riyadh	16	Riyadh North	24.42	46.44	611	24	0.70
	17	Riyadh Middle	24.63	46.77	624	29	0.70
	23	W-Dawasir	20.50	45.16	652	24	0.10
Madina	15	Madina	24.33	39.42	636	29	0.10
	18	Yenbo	24.09	38.04	6	29	1.70
Makkah	19	Jeddah	21.30	39.12	17	29	0.40
	20	Makkah	21.40	39.85	213	24	0.00
	21	Taif	21.29	40.33	1454	29	0.40
Baha	22	Baha	20.30	41.63	1652	24	0.60
Aseer	24	Bisha	19.59	42.37	1163	29	0.10
	25	Abha	18.14	42.39	2093	29	1.50
	26	Khamis Mushait	18.18	42.48	2057	29	0.60
Nagran	27	Nejran	17.37	44.26	1210	29	0.40
	28	Sharurrah	17.47	47.11	725	24	0.50
Gizan	29	Gizan	16.54	42.35	3	29	0.00

00.45%). Errors were classified into four categories: Errors because of mistaken extreme values such as a relative humidity exceeds 100% or below 0%. Illogical errors such as the recorded maximum daily temperature (T_x) was less than the minimum daily temperature (T_n) in the same day, or if $T_x = T_n$. Missing values; i.e. T_x is present but T_n is missing. Recording an error-indication number (like 999 or 777)if the sensor is not functioning. On analyzing the data record, any value contains one or more errors was considered missing record unless the missing record could be predicted with minimal error, i.e. if the average temperature (T_a) is missing while T_x and T_n are logged with no errors; in this case $T_a = (T_x + T_n)/2$. However, the amount of missing data in the recorded period could be considered negligible in most of the stations. The last column in table 1 shows the percent of missing or erroneous records, where the average amount of perfectly recorded data is 99.22%.

Data Grouping and Contouring

After correcting the data sets, daily ET_o values were calculated for each station, then aggregated to annual and monthly values. Annual ET_o value (mm/year) for each station was calculated by summation of the daily ET_o for the entire year. On the other hand, the monthly average ET_o value was calculated by taking the average of the daily ET_o values during each month.

Evapotranspiration data were graphically represented by contour maps irrespective of the station's altitude. Analysis of ET variations with the station's altitude for each of the 30 years under study revealed no trends as shown in figure 2. Other researchers have also found no correlation between ET and station altitude in China (Thomas, 2000). Contour maps clearly present zones of common ET values as well as vividly clarify ET differences between zones and viability in long months or years. This approach has also been adopted by other researchers to study ET variability in China (Thomas, 2000; Shenbin et al., 2006).

Data was arranged in a three-column format: longitude, latitude, and ET_o. Each set of data was gridded separately using the ordinary point-Kriging method which estimates the values of the points at the grid nodes (Abramowitz and Stegun, 1972; Isaaks and Srivastava, 1989). This procedure is used by SURFER™ Software which has been used in our calculations. The resulted grid was blanked outside the political borders of the KSA. The political border's information of the KSA was grabbed from electronic map of NIMA (2003). The electronic map was digitized and converted to DMS geographic coordinate system. The

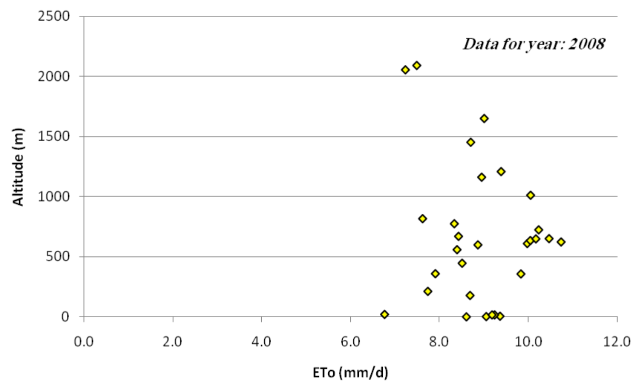


Figure 2. Illustration of ET_0 variation with altitudes of the studied sites, KSA.

blanked grid was plotted as a contour map using Surfer™ 8.0 software (Surfer, 2002). Sample plots for the average daily ET_0 during a month, June in this case, and the ET_0 in a year, 1991 in this case, is shown in figure 3a, 3b, respectively. The darker areas represent smaller magnitudes of ET_0.

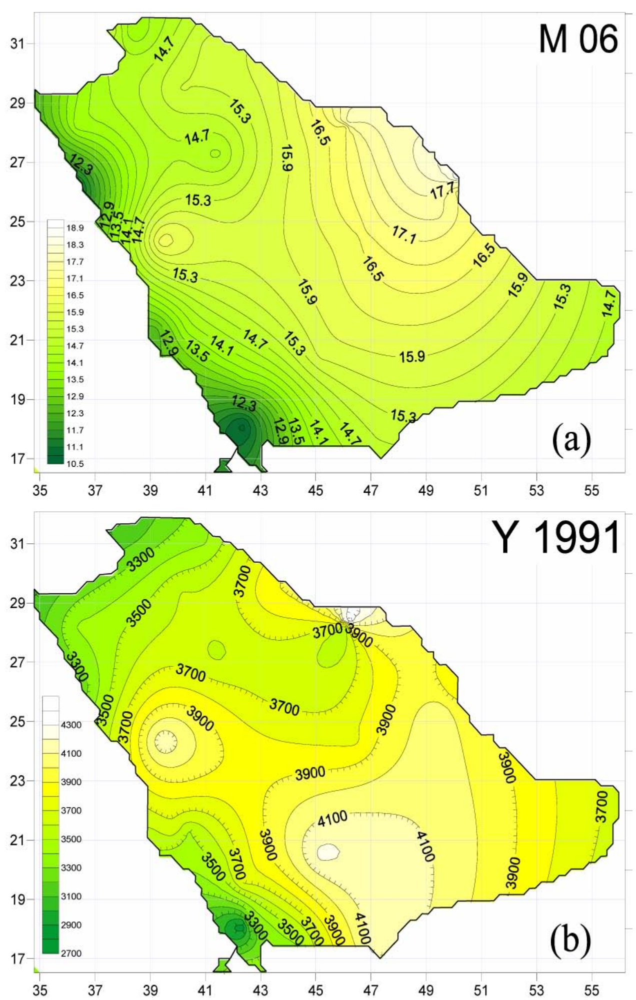


Figure 3. Sample contour map of daily and annual evapotranspiration in the KSA. (a) Average daily evapotranspiration for the month of June over a 30-year period (mm/d). (b) Annual evapotranspiration of the year 1991 (mm/y).

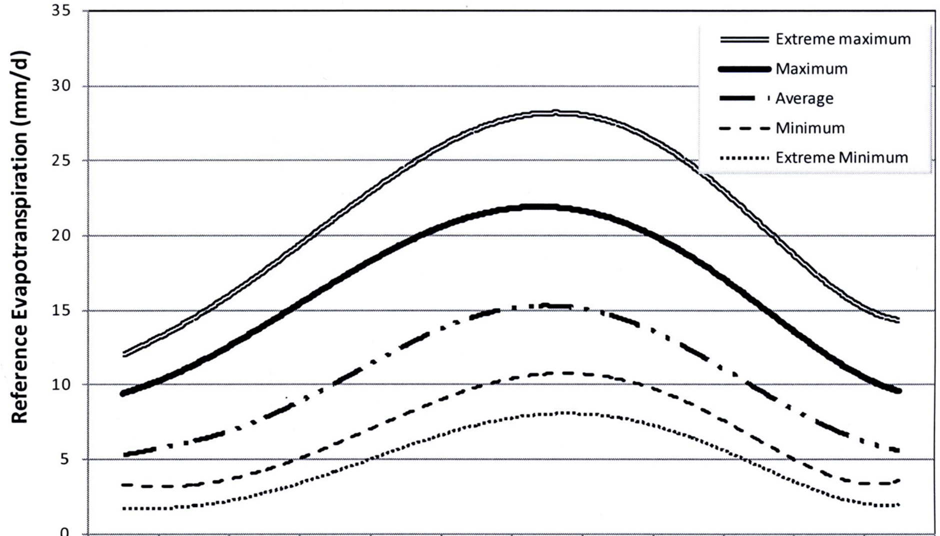
Results and Analysis

All data records were analyzed for each meteorological station, the daily, monthly, and yearly ET_0 were calculated. The monthly ET_0 is useful to determine the lowest and highest water requirement zones and its monthly variation along the year. Whereas, yearly analysis was made mainly to examine evapotranspiration trends over years of collected data and to observe any signs of climate change in the Arabian Peninsula.

The 29-year daily average ET_0 for each month was calculated along with the average maximum and minimum values, and the results are shown in figure 4. The absolute maximum and minimum ET_0 that were recorded each month during the study period is also shown figure 4. The lowest values of ET_0 occurred in the months of December and January whereas the highest values occurred during June, July, and August. The results showed high variation in ET_0 from about 5 mm/d to as much as 15 mm/d in July whereas the absolute minimum and maximum ET_0 showed even higher variation and ranged from 1.6 mm/d in June to as high as 30 mm/d in July, about 20 fold. This figure indicates the variety of climate conditions over Saudi Arabia and presents major challenges for agricultural development and water resources planning in the country.

The variation of ET_0 over the area of Saudi Arabia during an average year is shown in figure 5 where the 29-year daily average ET_0 was contoured for each month of the year. The results are shown in an analog clock shape to show how zones of lower and higher ET_0 values changed over Saudi Arabia during the year. A box diagram of 4- × 5-grids representing the area of Saudi Arabia was also plotted for each month to simplify the zones of lower ET_0 values, darker areas, over the country. As shown in figure 5, the lower ET_0 zone completely prevails in the western part of Saudi Arabia along the shore, read from the month of June and going clockwise to September. Then the lower ET_0 zone moved slowly to the northern part of the country until February from March. Low ET_0 zones start to move back again toward the western part to complete the cycle in June. In summary, this figure shows clearly those lower ET_0 zones are always in the western and northern part of the country whereas high ET_0 values prevail in the eastern and southern part of the country. This is an expected result since the western and northern part of the country is dominated with mountains and green areas, whereas the eastern and southern part of the country has a desert climate.

The average daily evapotranspiration (in mm/d) was calculated for each year for the study period, and the results are shown in figure 6. The figure clearly shows a positive trend of ET_0 with time during the study period. The ET_0 has increased from about 9.5 in 1980 to about 10.5 mm/d in 2008. Regression analysis between ET_0 and time has confirmed the positive trend and showed that the slope of the line was 0.25 with $R^2 = 0.52$. However, this relationship was not statistically significant at 95% probability level. A longer period of data analysis is needed to confirm this result. Nevertheless, the present analysis clearly indicated that the evapotranspiration demand is increasing with time at the KSA.



	Jan (1)	Feb (2)	Mar (3)	Apr (4)	May (5)	Jun (6)	Jul (7)	Aug (8)	Sep (9)	Oct (10)	Nov (11)	Dec (12)
Ex.Max.	11.89	14.73	17.82	20.21	25.61	25.71	29.35	27.97	23.48	21.05	17.21	14.13
Maximum	9.46	11.15	14.26	16.62	19.62	21.24	22.14	20.85	18.60	15.51	11.84	9.59
Average	5.25	6.18	7.82	10.02	12.62	14.66	15.31	14.42	12.45	9.72	7.10	5.57
Minimum	3.16	3.59	4.22	5.61	7.82	10.28	11.04	10.11	8.58	6.16	4.31	3.42
Ex.Min.	1.61	2.05	2.66	3.63	6.23	7.72	7.70	7.12	7.25	4.51	2.42	2.00

Figure 4. Minimum, average, and maximum daily evapotranspiration for the KSA (mm/day). Values represent about 30 years' averages of minimum, average, and maximum daily values. Extreme minimum and maximum values represent the greatest values recorded through the country over the recording period.

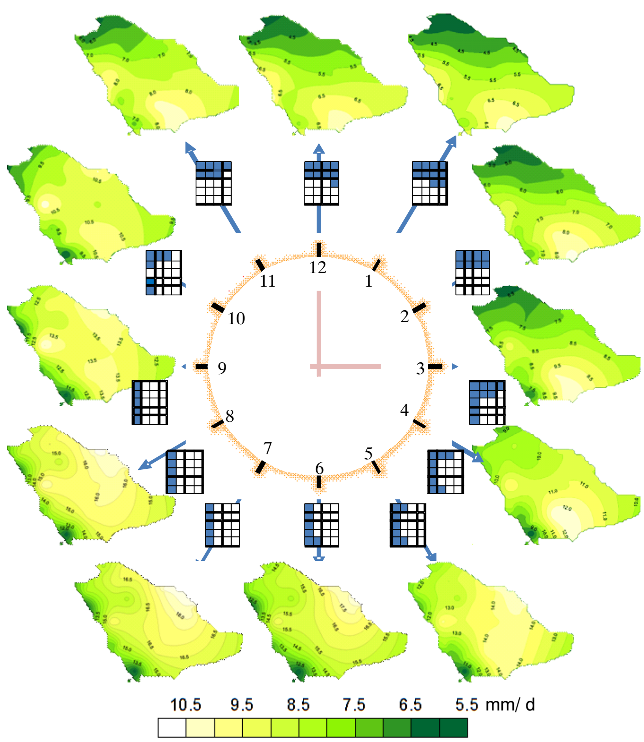


Figure 5. The cycle of lower magnitude zones of average daily evapotranspiration in the KSA (mm/d). Clock numbers indicate corresponding months. Each contour plot represents daily average of one month over the study period.

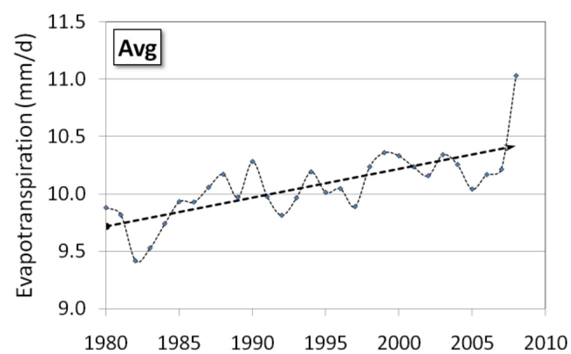


Figure 6. Annual average evapotranspiration trend in the KSA at the past 30 years. Values indicate the average daily ET_0 for each year.

To further investigate changes in ET_o with time the average maximum and minimum ET_o, values were also plotted with time during the past 29 years and the results are shown in figure 7. The results confirmed the increasing trend of ET_o with time since not only were the average ET_o values increasing with time, but the extreme ones were too (fig. 7). Regression analyses have also shown that the line slope was positive with relatively fair R^2 value of about 0.45.

The increase in ET_o over KSA is affected by many variables including temperature, solar radiation, and wind speed, which probably considered the most important ones affecting ET_o. The average temperature variations over the country were plotted with time for the 29 years under study and the results are shown in figure 8. A steady increase in the average temperature was observed during the past 29 years

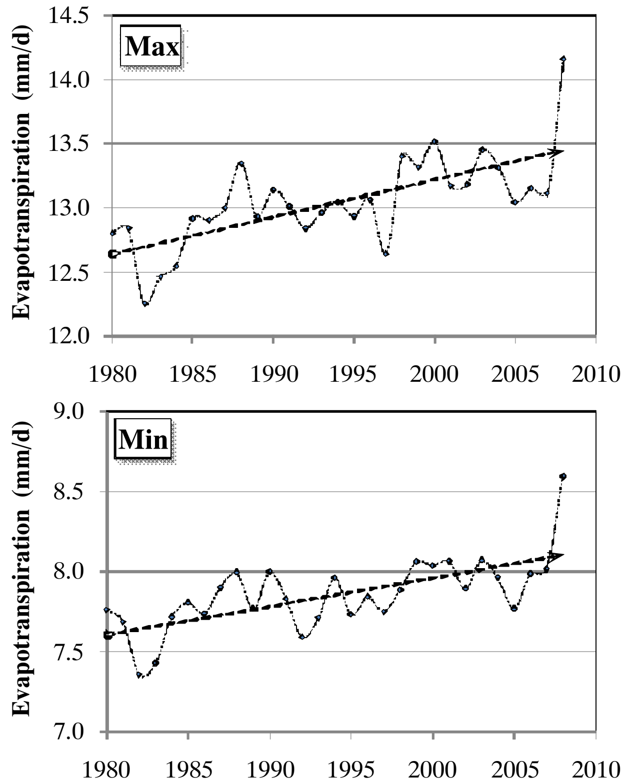


Figure 7. Annual average evapotranspiration trend in the KSA at the past 30 years. Values indicate the minimum and maximum daily ET_0 for each year.

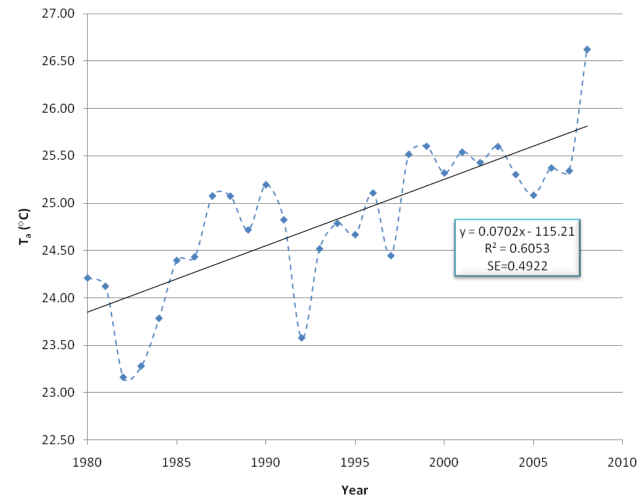


Figure 8. Average temperature development with time through the study period over the KSA, showing a noticeable increasing trend.

with R^2 value of 0.61 and standard error of 0.49. This result confirms that the observed increase in ET_0 was probably dominated by the observed increase in temperature.

Analysis of Yearly Data

Daily ET_0 was summated for each station during a year and the results were plotted in contour maps as shown in figure 3b for sample year 1991. Annual ET_0 ranged from 3000 to about 4200 mm/y. The northern and western parts of the country always have lower values of ET_0 compared to eastern and southern part of the country. However, yearly ET_0 plots were done to calculate the land area covered by a specific range of ET_0 values, i.e. land area covered by ET_0 values > 4000 mm/y. This can enable us to observe any real changes of ET_0 during the study period which could be a good indicator for climate change over the country. The procedure is clarified in figure 9 at which projection areas, shown in dark colors, having yearly ET_0 values greater than 4000 mm/y, between 3600 and 4000 mm/y, or less than 3600 mm/y were calculated for the sample year of 1991 in this case. The projected area of each slice was calculated by Simpson's method using Surfer™ software (fig. 9). The resulted area was expressed as a ratio to the total projected area of the country.

The procedure was done for the study period and the results are shown in figure 10 for the three ET_0 periods. The areal coverage was expressed as a percentage of the total area of Saudi Arabia. The results shown in figure 10 are very exciting. The area having ET_0 greater than 4000 mm/y increased steadily with time for the study period from about 23% to as high as 40%. On the other hand, moderate ET_0 values ranging from 3600 to 4000 seemed to dominate constant area with time and no changes in areal coverage was observed. However, the area covered with relatively low ET_0 values seemed to decrease gradually with time from about 30% in 1980 to about 13% in 2008. These results indicated clearly a changing trend in ET_0 and the associated climate parameters over KSA. The changes in the extreme values of ET_0 and other climate parameters are one of best indicators for climate changes (Mirza, 2003).

The results of the previous analysis are shown graphically in figure 11 and indicate the fluctuation of the projection area, maximum and minimum years, covered with ET_0 values greater than 4000 mm/y. The percentage area coverage for the years 1980, 1988, 1999, and 2003 were the highest the study period and ranges from 40% to as high as 60%. However, the years of 1983, 1996, and 2006 were the coolest since the percentage area coverage were much lower than those shown in the aforementioned 4 years and ranged from about 8% to only 20%. This high fluctuation in the real coverage of extreme ET_0 values is a compelling indicator for climate change over Saudi Arabia.

Calculating the projection area covered by a specific range of ET_0 as shown in figure 9 and 10 may overlook the ET_0 fluctuation within these ranges. Therefore, similar procedures were carried out to calculate the ET_0 volume within a specific ET_0 range rather than the projection area. The ET_0 contour maps were sliced at a specific ET_0 range, as shown in figure 9, and the ET_0 volume (ha-mm) was calculated by Simpson's method using Surfer™ software. The resulted ET_0 volume was expressed as a percentage ratio to the total ET_0 volume over Saudi Arabia and the results are shown in figure 12.

Figure 12 showed the percentage ET_0 volume covered by five ET_0 periods, namely: >4000; 3600-4000, 3200-3600, 3000-3200, and <3000 mm/y. The figure indicated that ET_0 volume increased steadily for the ET_0 period of >4000, 3600-4000, and 3200-3600 in the study period. Trend line regression showed a week but positive slope value ranged from 0.07 and R^2 = 0.07 for the greater than 4000-mm/y period to 0.39 and 0.27 for the period ranged from 3600-4000 and 3200-3600 mm/y with strong R^2 of 0.5 and 0.3, respectively. Again, and similar to the projection area

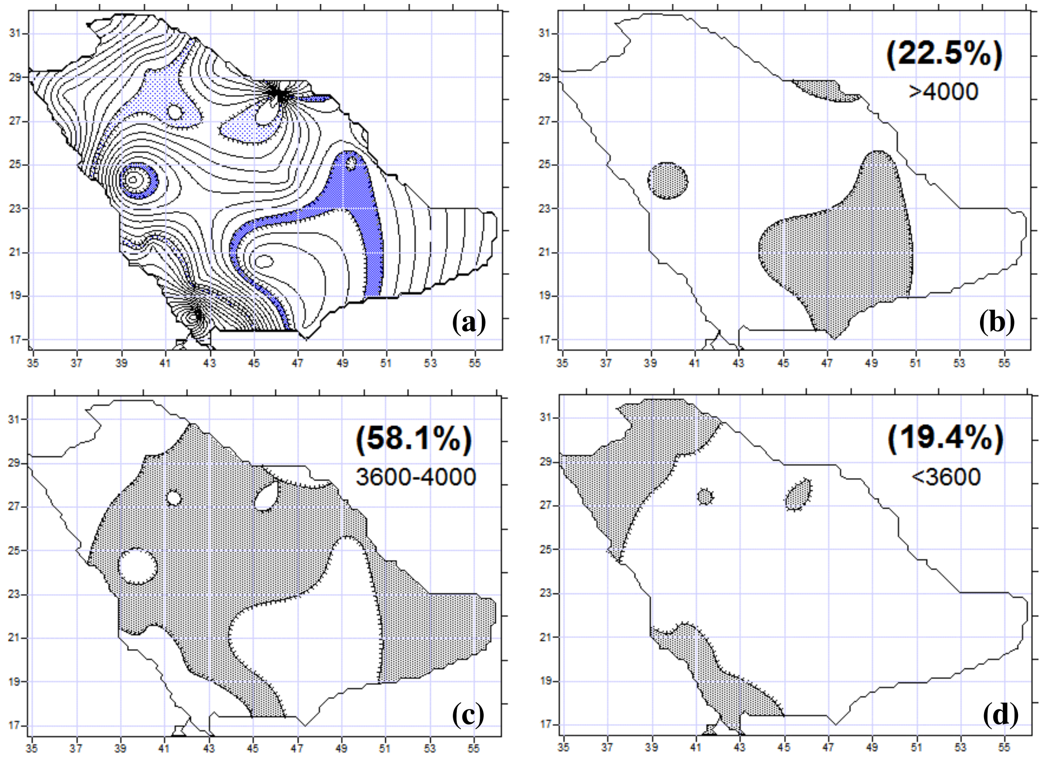


Figure 9. Plot (a) shows the contour map of evapotranspiration distribution for the sample year of 1991. This map has been sliced into three maps of projected areas. Plot (b) for areas having yearly ET more than 4000 mm/y, plot (c) between 3600 mm/y and 4000 mm/y, plot (d) less than 3600 mm/y.

percentage, moderate ET_o volume remained unchanged during the years but lower ET_o values less than 3000 showed a progressive decrease during the study period with a negative slope value of -0.8 and R^2 of 0.41. These results indicated that extreme values are changing over the years indicating a climate change over the country.

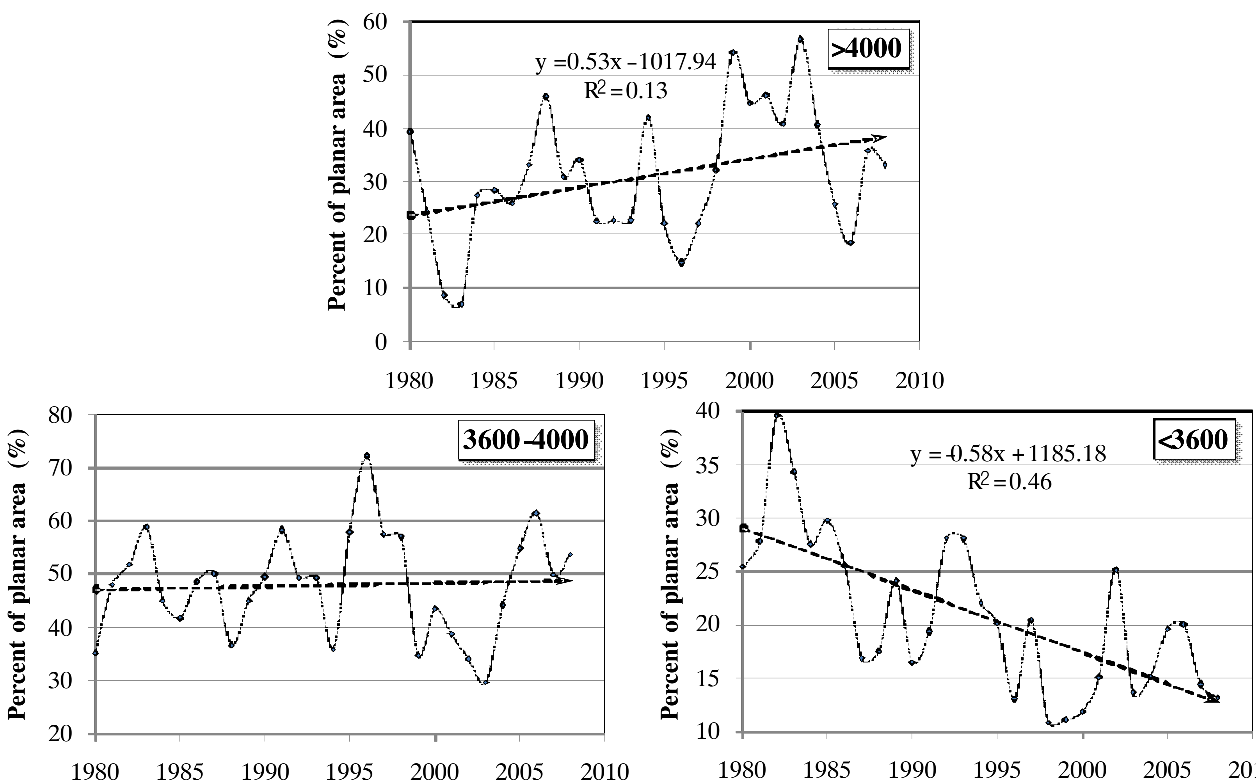


Figure 10. Percent of projected (planar) area of the sliced contour maps of yearly evapotranspiration. Horizontal axis represents years. Each plot represents a slice range denoted on the legend box upright.

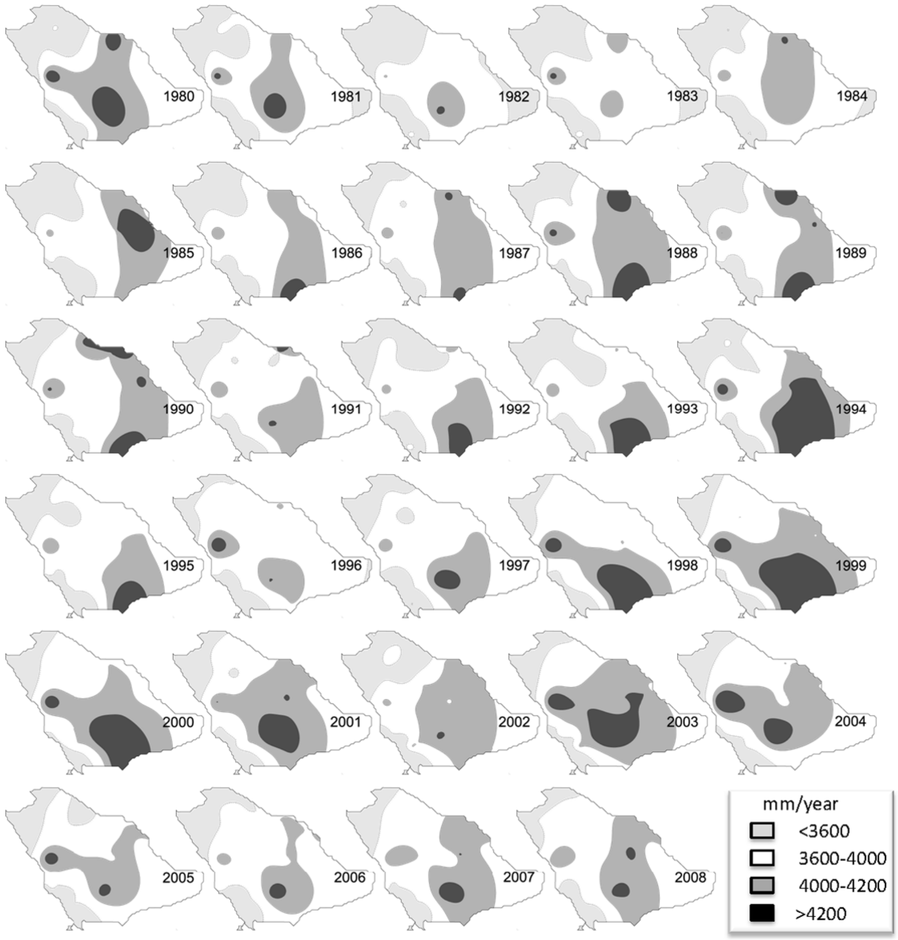


Figure 11. Contour maps representing yearly evapotranspiration for years from 1980 to 2008.

Conclusion

The water scarcity problem can be solved by proper management of water usage. Most of the depleted water in KSA is consumed through agriculture. Identifying the ET_o trend and knowing the zones having the least ET_o values can help in determining the future plans of agricultural and water expansions. Historical analysis of daily, monthly, and annual ET_o in Saudi Arabia was carried out using FAO Penman Monteith equation for 29 meteorological stations distributed on the 13 districts of the country for the study period. The average daily ET_o in monthly bases varied from about 5 mm/d in January to 15 mm/day in July which is hottest month. The corresponding annual ET_o varied from about 3000 mm/y to more than 4200 mm/y. The western and southern areas of the country had the lowest ET_o values compared to that in the eastern and southern part of the country. Chronological analyses revealed that ET_o has been increasing steadily during the study period. The average daily ET_o increased from about 9.5 to about 10.5 mm/d in 2008. Similar results were observed for minimum and extreme ET_o values. Furthermore, the projected land areas and evapotranspiration volume has been shown to cover larger area with time. The percentage of land area with annual ET_o > 4000 mm increased from about 20% to as high as 40% in the study period. However, the lower ET_o values, less than 3600 mm, seemed to cover smaller areas over the kingdom with time decreasing from about 30% to 12%. This demonstrates that ET_o fluctuation is increasing with time that can be considered a significant sign for climate change. An analysis of longer historic data is needed to confirm these findings. Nevertheless, the findings of this research stress the importance of taking climate change in planning for future agricultural and water resources projects.

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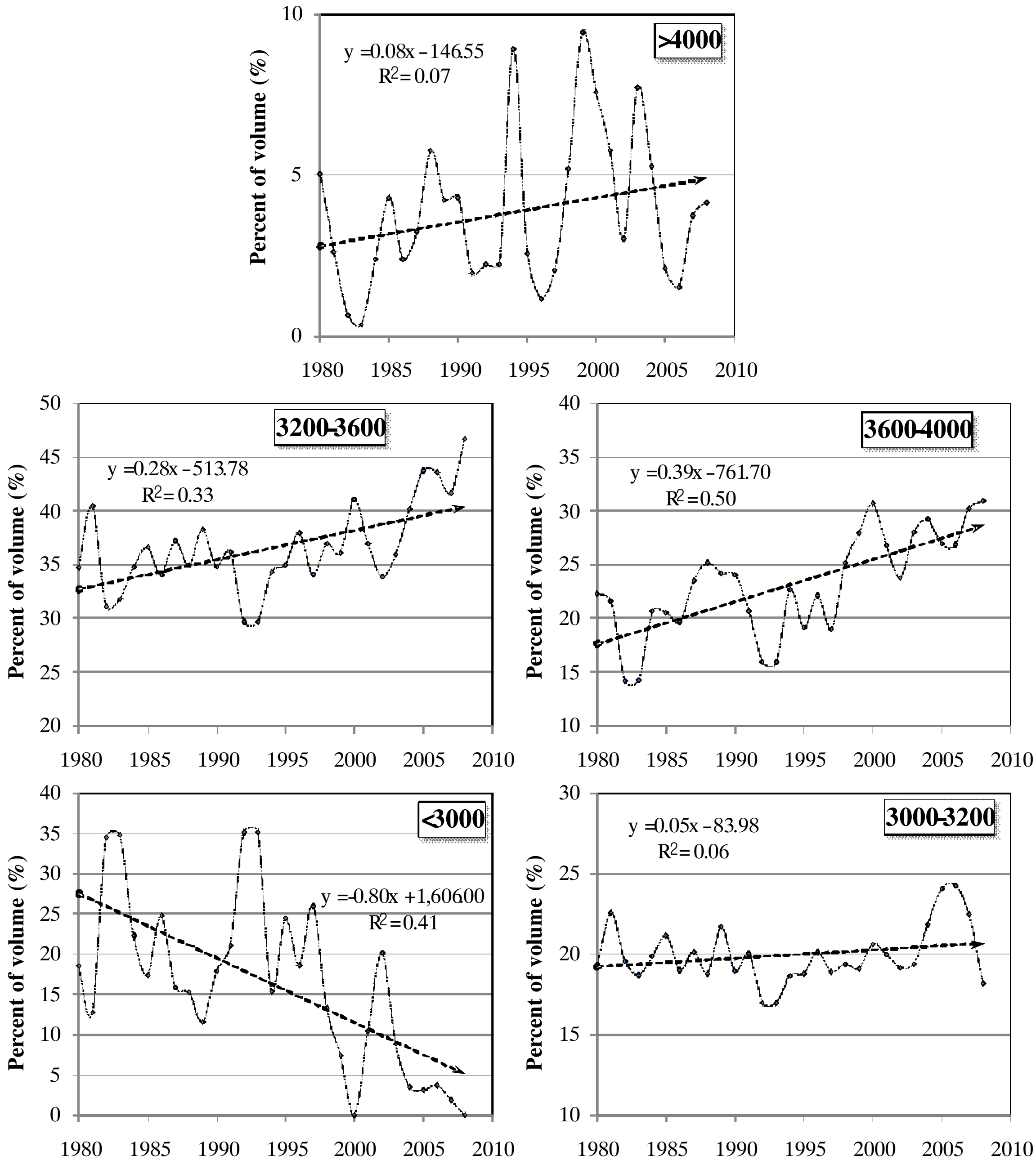

Figure 12. Percent of virtual volume (ha-mm/d) of the sliced contour maps of yearly evapotranspiration. Horizontal axis represents years. Each plot represents a slice range denoted on the legend box upright.

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