

Influence of multi-decadal meteorological variability on the reference evapotranspiration in hot and humid coastal town of Annamalai nagar in Tamil Nadu state

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सार – वायुमंडलीय वाष्पीकरण की आवश्यक प्रमुख सूचक समान वाष्पोत्सर्जन (ईटीओ) है और इसका व्यापक रूप से उपयोग हाइड्रोलॉजिकल परिवर्तन का विवेचन करने के लिए किया जाता है। इस अध्ययन में भारत के तमिलनाडु राज्य में पूर्वी तट के बहुत निकट गर्म और आर्द्र शहर, अन्नामलाईनगर में समान वाष्पोत्सर्जन का आकलन एफएओ पेनमैन-मोंटेनिथ (पीएम) विधि को नियोजित करके और 1977-2016 के दौरान दैनिक मौसम डेटा का प्रेक्षण लेकर किया गया है। इस अध्ययन के दो उद्देश्य हैं : (i) मौसम संबंधी मापदंडों की बहु-दशकीय प्रवृत्ति की पहचान करने के लिए मापे गए विभिन्न प्राचलों अर्थात् अध्ययन स्थान पर हवा का औसत तापमान (टी-मीन), वाष्प दबाव की कमी (वीपीडी), वास्तविक धूप घंटे (एसएसएच), शुद्ध विकिरण (R_n) तथा पवन की गति (डब्ल्यूएस) और (ii) बहु दशकीय अवधि में वाष्पोत्सर्जन की घटती प्रवृत्ति में मुख्य योगदान देने वाले मौसम संबंधी प्राचलों की पहचान करना।

ABSTRACT. Reference evapotranspiration (ET_o) is a key pointer of atmospheric evaporation demand and has been extensively used to describe the hydrological change. In this study, the reference evapotranspiration over the hot and humid town, Annamalai nagar, very near to the east coast in Tamilnadu State, India, have been estimated employing the FAO Penman-Monteith (PM) method and the observed daily weather data during 1977-2016. The objective of the present study is two-fold: (i) To identify the multi-decadal trend of the various measured meteorological parameters namely, mean air temperature (T_{mean}), vapour pressure deficit (VPD), actual sunshine hours (SSH), net radiation (R_n) and wind speed (WS) at the study location and (ii) To identify the main contributing meteorological parameter for the detected decreasing trend in ET_o over the multi-decadal period.

Key words – Reference evapotranspiration, FAO Penman-Monteith method, Hot and humid location, Meteorological parameters, Multi-decadal trends.

1. Introduction

Evapotranspiration (ET), the sum of evaporation and plant transpiration, is one of the most dynamic and complex hydrological mechanisms that bond water balance and land surface energy balance in an ecosystem (Xu and Singh, 2005). The process of evapotranspiration governs the transfer of moisture between soil and the atmosphere in a catchment and is greatly influenced by surface land-use changes and climate variations. Reference evapotranspiration (ET_o) is often used to estimate actual ET in water balance studies (Xu and Chen, 2005).

The common belief is that global warming will direct to a rise in evaporation or evapotranspiration which is a main constituent of the hydrologic cycle. However, some

studies reported in the literature show that although with the rise in air temperature, evaporation and/or evapotranspiration decreased in some regions across the globe. This explains that apart from air temperature, there are other climatic parameters such as wind speed, relative humidity and radiation which can counteract the influence of rise in temperature on evaporation and/or evapotranspiration thereby effecting decrease in observed evaporation and/or evapotranspiration. Even though increases in temperature produced the largest increase in evaporation, each of the other climate variables acted to reduce evaporation, thereby resulting in an overall reduction in evaporation (Donohue *et al.*, 2010)

Declining trends in pan evaporation and potential evapotranspiration have been reported in India [Chattopadhyay and Hulme (1997) and

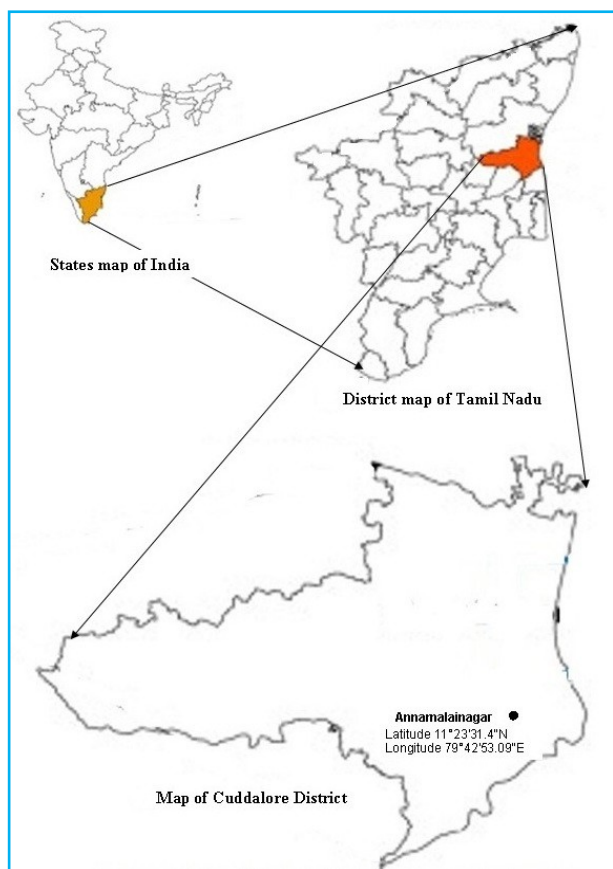


Fig. 1. Location of Study area (Annamalainagar, Cuddalore District, Tamil Nadu State)

Bandyopadhyay *et al.* (2009)], China [Xu *et al.* (2006), Zhang *et al.* (2007), Wang *et al.* (2010) and Yang *et al.* (2016)] and United States [Lawrimore and Peterson (2000)].

While Zhang *et al.* (2007) quantified the reductions as 38 percent in ET_o and 47 percent in E_{pan} , Bandyopadhyay *et al.* (2009) and Wang *et al.* (2010) attributed the decreasing trends to variability in wind speed and relative humidity. Yang *et al.* (2016) suggested annual precipitation and relative humidity as attributes.

These researches highlighted the knowledge of evapotranspiration and the significance of its trend in long-term water resources planning and proper water management. These studies also demonstrated the importance of Mann-Kendall test for trend analysis.

The objectives of the present study were two-fold: (i) To identify the multi-decadal trend of the various measured meteorological parameters namely, mean air temperature (T_{mean}), vapour pressure deficit (VPD), actual sunshine hours (SSH), net radiation (R_n) and wind

speed (WS) at the study location and (ii) To identify the main contributing meteorological parameter for the detected decreasing trend in ET_o over the multi-decadal period. In the present work, ET_o evaluation was done by Penman-Monteith method. Mann-Kendall test (parametric) and linear regression test (nonparametric) were used for trend evaluation.

2. Study area and data base

Annamalainagar is a Special Grade Panchayat town in Cuddalore District of Tamil Nadu State in India. The latitude and longitude of Annamalainagar are 11.4° N and 79.7° E respectively. Fig. 1 shows the location map of Annamalainagar. The elevation of Annamalainagar is 5.79 m above mean sea level. The Koppen-Geiger climate classification is Aw. The average annual rainfall is 1248 mm. The maximum, minimum and average temperatures in the last decade were found to vary in the ranges 39 °C to 28 °C, 29 °C to 22 °C and 35 °C to 26 °C respectively. The average wind speed was found to vary between 13.4 mph to 6.9 mph in the last decade. Daily data on weather parameters namely, maximum and minimum temperatures (°C), maximum and minimum relative humidity (%), average wind speed (km/h) at 3 m height above ground level and actual hours of bright sunshine were collected from the India Meteorological Observatory at Annamalainagar for a period of 40 years from 1977 to 2016 for the present study.

3. Methodology

3.1. Penman-Monteith method for evaluating evapotranspiration

The Penman-Monteith method has been considered as a global standard method for computation of ET_o by Food and Agriculture Organization (FAO) of the United Nations. The method is physically based and unambiguously includes both physiological and aerodynamic parameters. In this method, the computation of ET_o is given as

$$ET_o = \frac{0.409\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34) u_2} \quad (1)$$

where, ET_o is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$), T_a is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (ms^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), $(e_s - e_a)$ the saturation vapour pressure deficit (kPa), Δ is slope of

TABLE 1

Z – Values of Mann-Kendall trend test for the measured and computed meteorological parameters and estimated reference evapotranspiration

Season	Mean daily T_{mean}	Mean daily SSH	Mean daily WS @ 2 m height	Mean daily VPD	Mean daily R_n	Mean daily ET_o
Annual	2.008*	-5.105**	-7.573**	2.565**	-4.839**	-6.798**
Monsoon	1.621##	-4.016**	-7.476**	2.202*	-4.306**	-6.677**
North-east monsoon (NEM)	2.661**	-2.468**	-6.460**	2.347*	-3.242**	-3.121**
South-west monsoon (SWM)	0.339##	-3.290**	-7.693**	0.702##	-3.629**	-6.774**
Summer	0.798##	-4.065**	-6.629**	0.702##	-3.774**	-5.177**
Winter	3.218**	-2.661**	-5.903**	4.427**	-3.266**	-3.000**

** delineates significance at 0.01 level, * delineates significance at 0.05 level and ## delineates no trend

the vapour pressure ($\text{kPa } ^\circ\text{C}^{-1}$) and γ is psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$). The computation procedure given in Chapter 3 of the FAO Irrigation and Drainage Paper 56 has been used in the present study.

3.2. Trend analyses

The detection of the trends in the four decadal period (1977-2016) of the measured meteorological parameters namely, mean of daily mean temperature (T_{mean}), mean daily actual sunshine hours (SSH), mean daily wind speed (WS) at 2 m above the ground, the computed meteorological parameters namely, mean daily vapour pressure deficit (VPD) and mean daily net radiation (R_n) and mean daily reference evapotranspiration (ET_o) computed using the PM method for annual, monsoon, North-east monsoon (NEM), South-west monsoon (SWM), summer and winter seasons was identified by the Mann-Kendall test (MK test).

The MK test is a rank-based nonparametric method, comprehensively applied for trend identification in hydro-climatic time series because of its robustness against the effect of abnormal data and particularly its consistency for biased variables. The accomplishment of MK trend test involves the calculation of the statistic:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (2)$$

where,

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & (x_j > x_i) \\ 0 & (x_j = x_i) \\ -1 & (x_j < x_i) \end{cases} \quad (3)$$

where, x_i and x_j are the sequential data values and n is the length of the data set. The statistics S is

approximately normally distributed when $n \geq 8$, with the mean and the variance as follows:

$$E(S) = 0 \quad (4)$$

$$\text{Var}(S) = \frac{[n(n-1)(2n+5) - \sum_{i=1}^n t_i i(i-1)(2i+5)]}{18} \quad (5)$$

where, t is the extent of any given time.

The standardized statistics (Z) for one-tailed test is formulated as:

$$Z = \begin{cases} \frac{(S-1)}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{(S+1)}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \quad (6)$$

The null hypothesis of no trend is rejected if $|Z| > 1.96$ at the 0.05 significance level and rejected if $|Z| > 2.32$ at the 0.01 significance level. A positive value of Z represents an increasing trend and a negative value matches to a decreasing trend.

A normal linear regression model in the form of $y = \alpha t + \beta$ is used to estimate the rate of change α with t as the time in years ($t = 1, 2, 3, \dots$), y being the observed values of annual or seasonal measured or computed meteorological parameter or ET_o .

4. Results and discussion

Table 1 shows the Z -value of Mann-Kendall trend test for the different measured and computed meteorological parameters and estimated ET_o on seasonal

TABLE 2

Linear equations fitted to the time series of meteorological parameters showing very significant decreasing trends for all seasons in the four-decadal period 1977-2016

Season	Regression coefficients and R^2 values of the fitted linear equations for								
	Mean daily SSH			Mean daily WS @ 2 m height			Mean daily R_n		
	α	β	R^2	α	β	R^2	α	β	R^2
Annual	-0.041	8.286	0.564	-0.036	2.381	0.903	-0.043	13.312	0.416
Monsoon	-0.036	7.231	0.356	-0.043	2.669	0.898	-0.042	12.373	0.363
NEM	-0.032	6.675	0.172	-0.032	1.965	0.756	-0.032	10.894	0.258
SWM	-0.038	7.510	0.262	-0.051	3.199	0.914	-0.050	13.489	0.301
Summer	-0.057	10.13	0.364	-0.029	2.154	0.782	-0.052	15.816	0.316
Winter	-0.032	9.275	0.185	-0.024	1.695	0.644	-0.031	12.814	0.199

and annual basis, for the data-sets pertaining to the four-decadal period 1977-2016.

The Z values of Mann-Kendall test for daily mean wind speed (WS) are less than 2.42 for all seasons with a minimum of -7.693 in South-west monsoon and a maximum of -5.903 in winter. The decreasing trend of wind speed in four-decadal period 1977-2016 has 0.01 level of significance. Sunshine hours and net radiation also exhibited decreasing trends in all seasons with Z values less than -2.42 and level of significance 0.01.

Daily mean air temperature T_{mean} has Z values of 2.661 in NEM and 3.218 in winter revealing increasing trends with 0.01 level of significance. Z value of 2.008 for annual period signifies the similar trend but with 0.05 level. The trends for Monsoon, SWM and summer seasons are not significant.

The increasing trends in VPD for annual and winter seasons are significant with 0.01 level, while for monsoon and NEM seasons the level of significance is 0.05. The trends in VPD for SWM and summer seasons are not significant.

To summarize, sunshine hours, wind speed and net radiation depict significantly decreasing trends in all seasons of the four-decadal study period.

While significance of increasing trends in T_{mean} are confined to NEM and winter, similar trends of VPD are restricted to annual and winter seasons. Both the parameters do not reveal significant trends for SWM and summer.

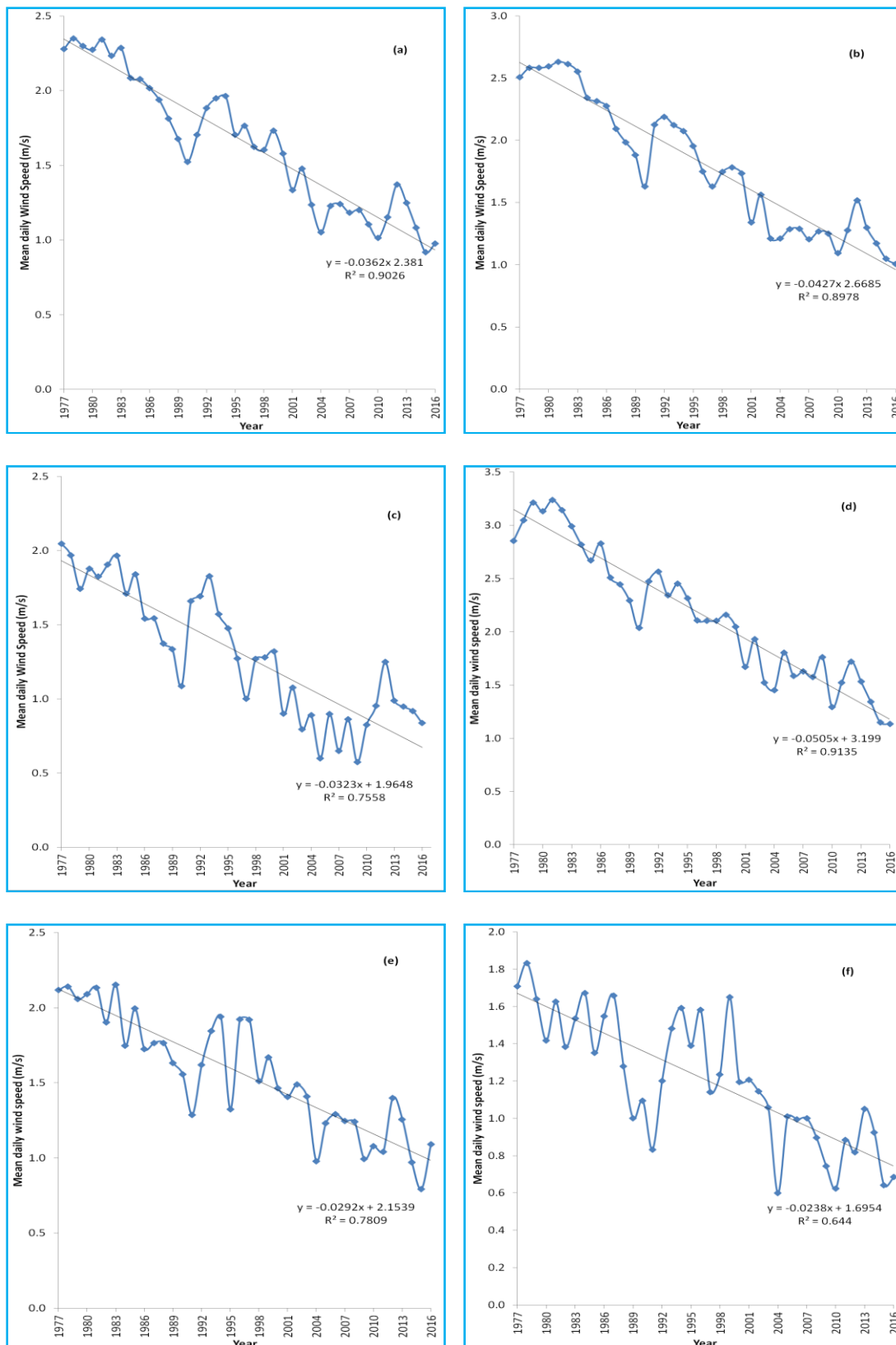
Z values for ET_o signifies a decreasing trend with 0.01 level of significance during the four-decadal study

span. Z for ET_o is minimum at -6.798 in annual season and maximum at -3.000 in winter,

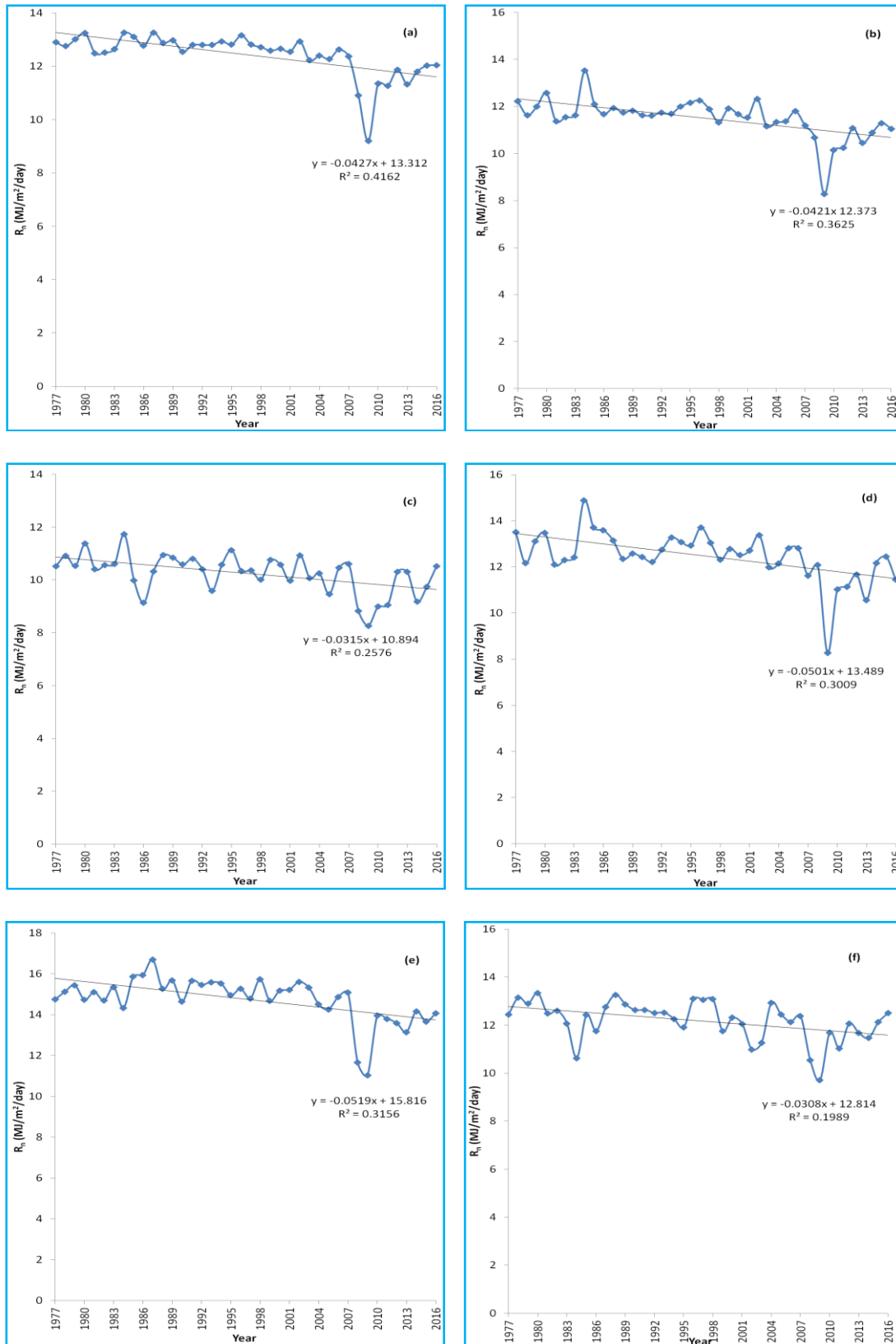
Consistently significant decreasing trends in SSH, WS and R_n in all seasons highly influence the trend of ET_o , compared to relatively less consistent and less significant increasing trends of T_{mean} and VPD.

Figs. (2-4) show the mean daily WS (in m/s), mean daily net radiation (in MJ/m²/day) and mean daily actual bright sunshine hours for the four-decadal period 1977-2016 for different seasons. Table 2 shows the linear equations fitted to the time series of meteorological parameters showing significant decreasing trends for all seasons. The rate of decrease in mean daily WS@2 m height is found to vary between 0.05 ms⁻¹ per year in SWM season to 0.023 ms⁻¹ per year in winter season. The high R^2 values obtained for the linear fits to the decreasing trends of mean daily WS for all seasons portrays the consistent and significant reduction in WS with respect to time. Wind may promote the transport of water allowing more water vapour to be taken up (Allen *et al.*, 1998). Therefore, with increase in wind speed, the reference evapotranspiration tends to increase. As the mean daily wind speed is found to show a declining trend over the years, it has resulted in a decreasing trend in ET_o due to the reduction in the transport of water vapour in the atmosphere.

The net radiation, which is the difference between the incoming net shortwave radiation and the outgoing net longwave radiation, depends upon the solar radiation. The solar radiation is directly proportional to the relative sunshine duration which is the ratio between the actual duration of sunshine (SSH) and the maximum possible duration of sunshine. Solar radiation is the largest energy source which provides the required energy to vaporize



Figs. 2(a-f). Mean daily wind speed (m/s) for the years 1977 (Year 1) to 2016 (Year 40) in (a) Annual (b) Monsoon (c) NEM (d) SWM (e) Summer and (f) Winter seasons



Figs. 3(a-f). Mean daily net radiation ($\text{MJ/m}^2/\text{day}$) for the years 1977 (Year 1) to 2016 (Year 40) in (a) Annual (b) Monsoon (c) NEM (d) SWM (e) Summer and (f) Winter seasons

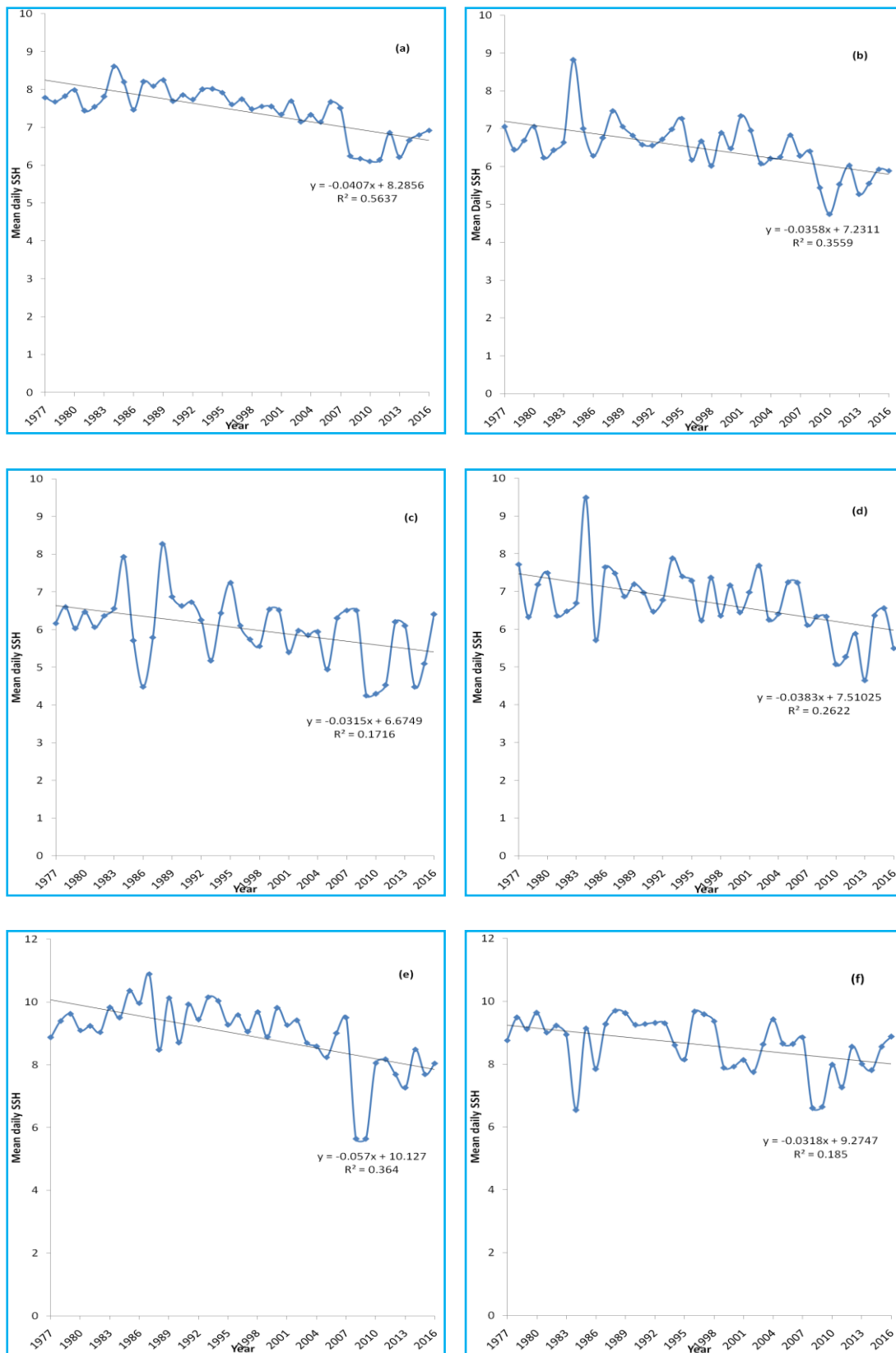


Fig. 4(a-f). Mean daily sunshine hours for the years 1977 (Year 1) to 2016 (Year 40) in (a) Annual (b) Monsoon (c) NEM (d) SWM (e) Summer and (f) Winter seasons

TABLE 3

Linear equations fitted to the time series of meteorological parameters showing significant increasing trends/no trends for a few seasons in the four-decadal period 1977-2016

Season	Regression coefficients and R^2 values of the fitted linear equations for					
	Mean daily T_{mean}			Mean daily VPD		
	α	β	R^2	α	β	R^2
Annual	0.015	27.79	0.099	0.003	1.234	0.153
Monsoon	0.013	28.13	0.068	0.003	1.252	0.113
NEM	0.021	25.73	0.155	0.004	0.686	0.149
SWM	0.007	29.94	0.016	0.002	1.679	0.018
Summer	0.010	29.28	0.030	0.0009	1.506	0.008
Winter	0.030	24.22	0.233	0.007	0.749	0.283

TABLE 4

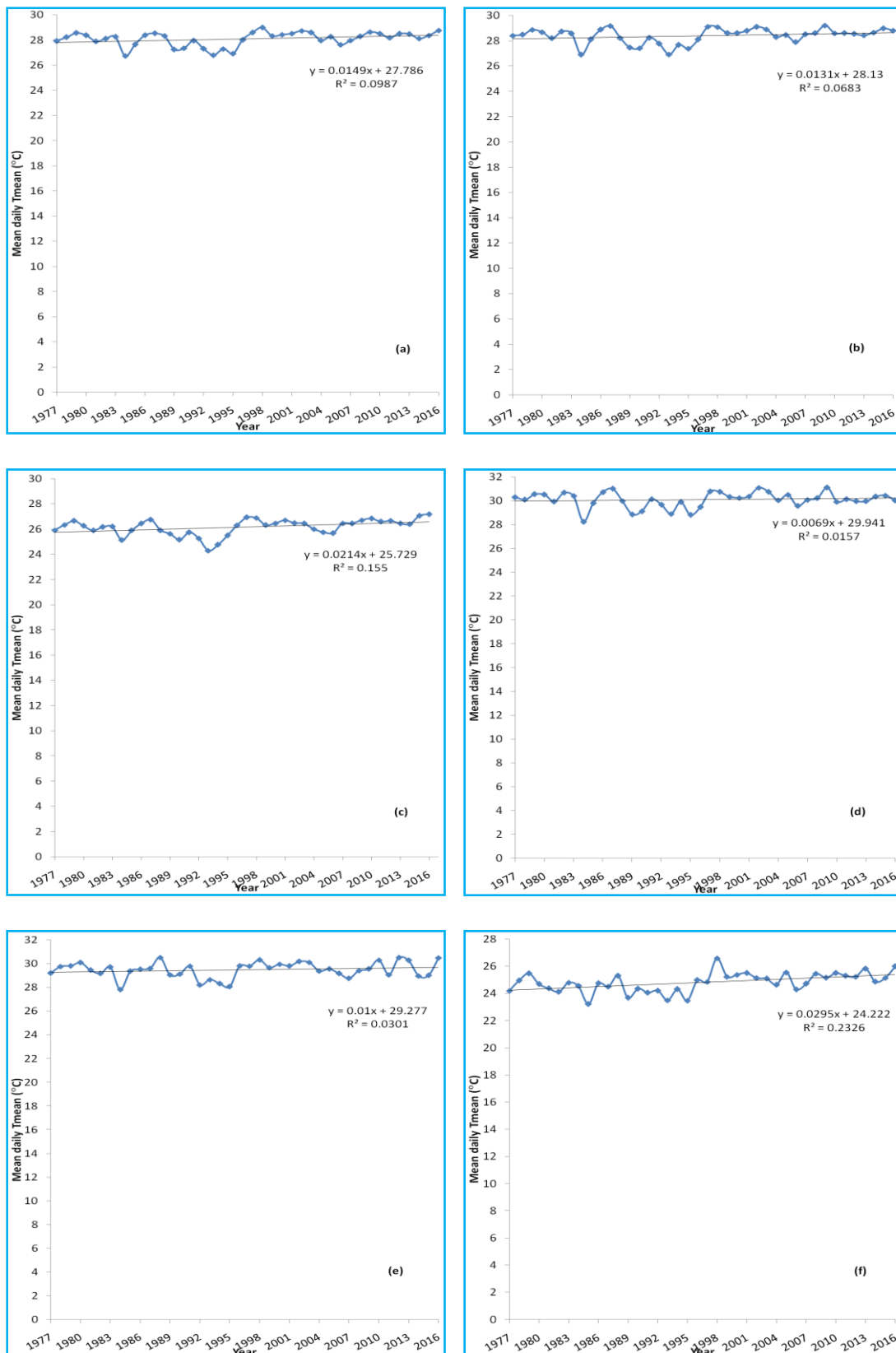
Linear equations fitted to the time series of estimated reference evapotranspiration for different seasons of a year in the four-decadal period 1977-2016

Season	Regression coefficients and R^2 values of the fitted linear equations for mean daily ET_o		
	α	β	R^2
Annual	-0.0246	5.303	0.788
Monsoon	-0.0275	5.203	0.786
NEM	-0.0091	3.681	0.148
SWM	-0.0398	6.329	0.789
Summer	-0.0284	6.238	0.557
Winter	-0.0082	4.207	0.176

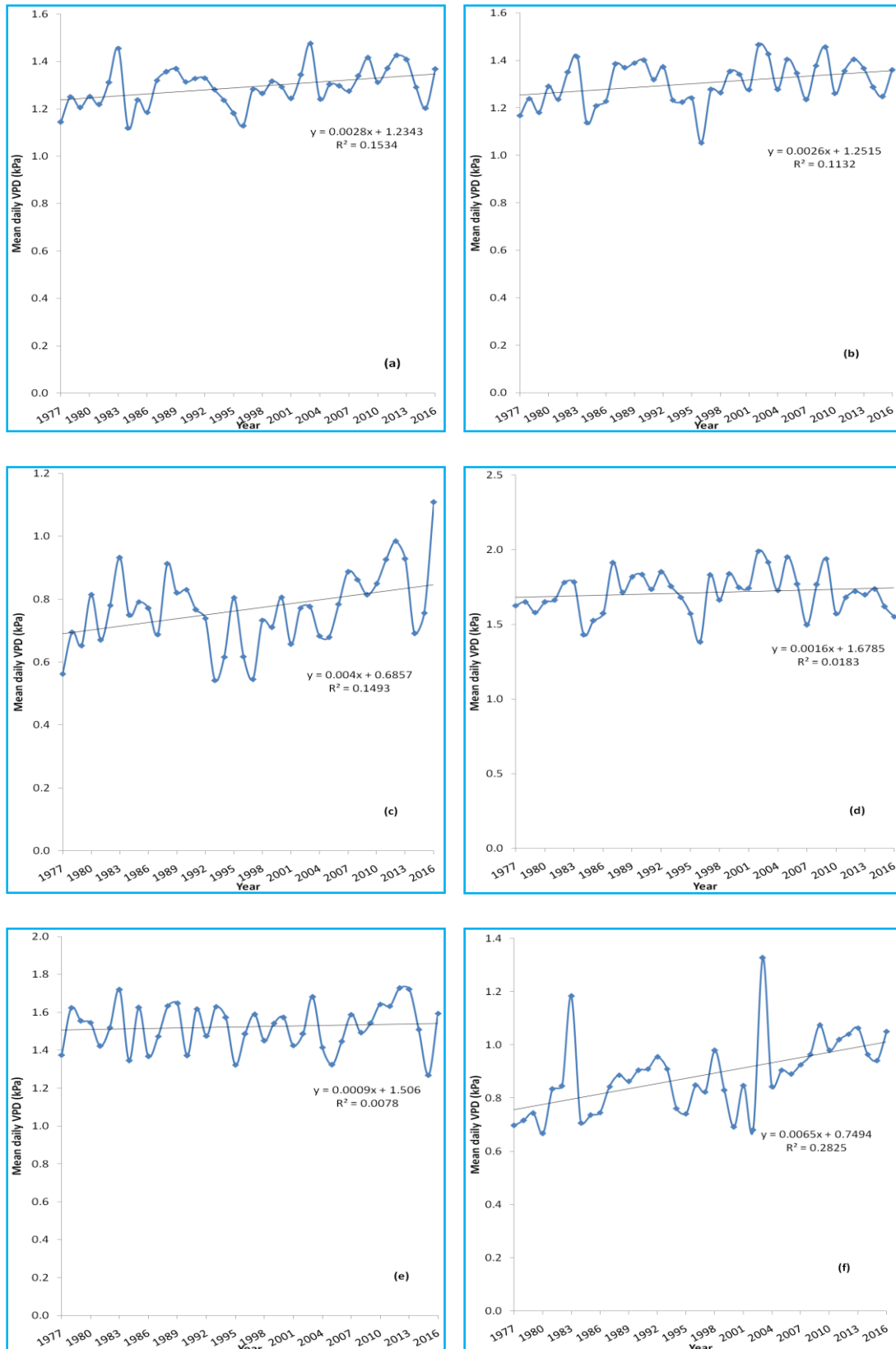
water and enhance the evapotranspiration process. As the SSH and net radiation, R_n , show declining trends for all seasons, the amount of energy available for evapotranspiration has been declining temporally in the study area. This has resulted in a decreasing rate in ET_o over the years. The rate of decrease in mean daily SSH varies from 0.057 hours per year for summer season to 0.031 hours per year for NEM and winter seasons. Mean daily net radiation decreased at the highest rate of 0.051 MJm^{-2} per year for summer season and at the lowest rate of 0.030 MJm^{-2} per year for winter season. The R^2 values of linear fits to the decreasing trends observed in SSH and R_n for different seasons varied respectively between 0.563 and 0.171 & 0.416 and 0.198. The change of R_s contributes to the long-term variation of PET (Yao *et al.*, 2014). Yao *et al.* (2014) demonstrated that the deviations of PET over the majority areas of China (excluding Inner Mongolia) are nearly consistent with deviations in R_s . From 1982 to 1993, R_s declined significantly ($p < 0.05$) by 0.3 W/m^2 and increased insignificantly ($p > 0.05$) by about 0.1 W/m^2 .

Figs. (5&6) show the mean daily T_{mean} (in $^{\circ}\text{C}$) and mean daily vapour pressure deficit (in kPa) respectively for the four-decadal period 1977-2016 for different seasons. Table 3 shows the linear equations fitted to the time series of meteorological parameters showing significant increasing trends for few seasons and no trends for few other seasons during the four-decadal period of study.

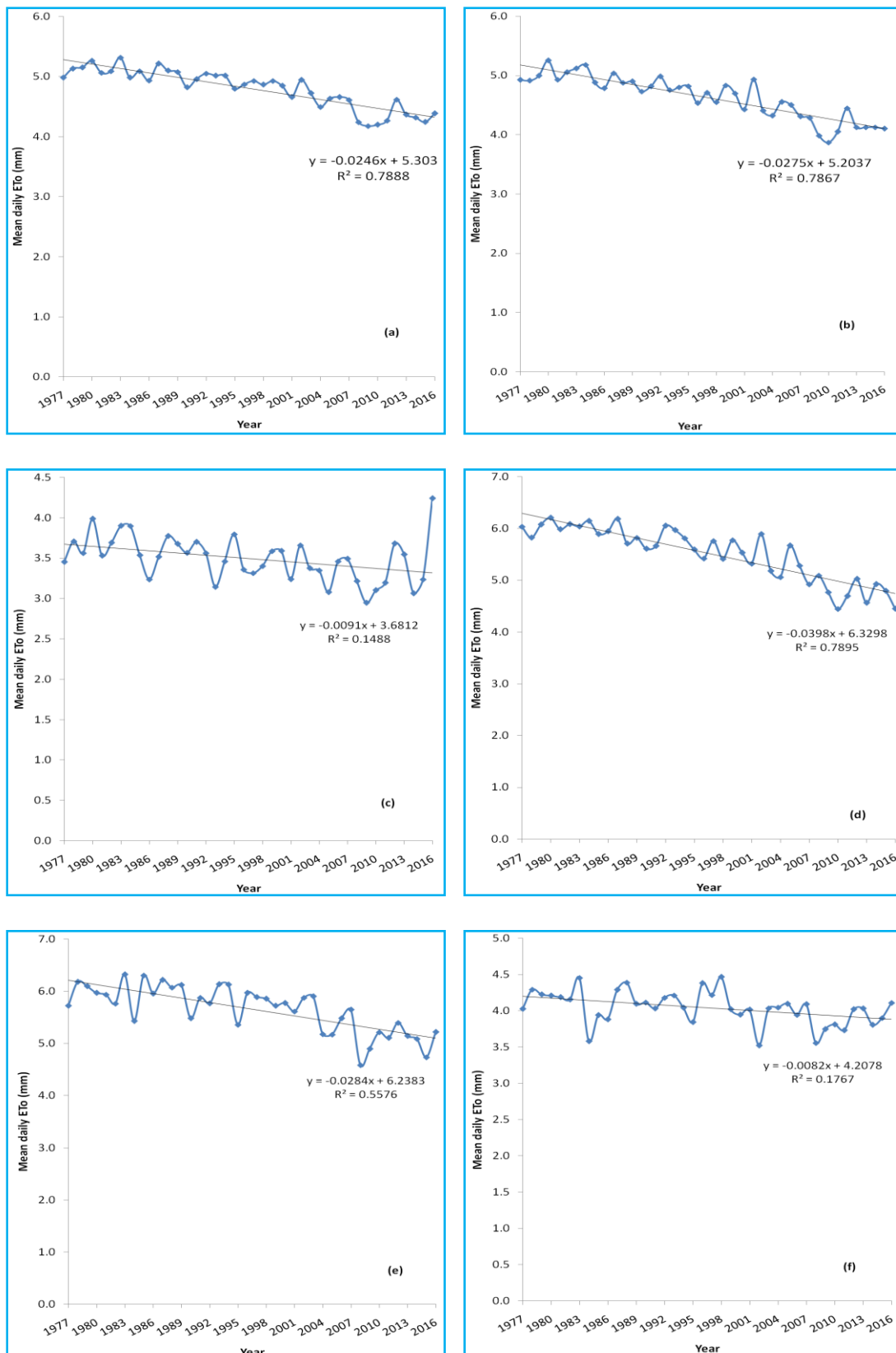
The rates of increase in mean daily T_{mean} and mean daily VPD are very less for various seasons as seen from the low values of α obtained for the respective linear fits for the trends. The rate of increase in T_{mean} was not appreciable and varied in narrow range of 0.006 $^{\circ}\text{C}/\text{year}$ (SWM season) to 0.014 $^{\circ}\text{C}/\text{year}$ (Annual period). The rate of increase in mean daily VPD for all seasons was found to be not very appreciable and varied in a narrow range of 0.0001 kPa/year (summer season) to 0.006 kPa/year (winter season). Further, the R^2 values of the liner fits obtained for both T_{mean} and VPD are very low (0.232 to 0.015 for T_{mean} and 0.282 to 0.007 for VPD) for all seasons.



Figs. 5(a-f). Mean daily T_{mean} (°C) for the years 1977 (Year 1) to 2016 (Year 40) in (a) Annual (b) Monsoon (c) NEM (d) SWM (e) Summer and (f) Winter seasons



Figs. 6(a-f). Mean daily VPD (kPa) for the years 1977 (Year 1) to 2016 (Year 40) in (a) Annual (b) Monsoon (c) NEM (d) SWM (e) Summer and (f) Winter seasons



Figs. 7(a-f). Mean daily ET_0 (millimeters) for the years 1977 (Year 1) to 2016 (Year 40) in (a) Annual (b) Monsoon (c) NEM (d) SWM (e) Summer and (f) Winter seasons

Figs. 7(a-f) show the mean daily ET_o (in millimeters) for the four-decadal period 1977-2016 for different seasons. Table 4 shows the linear equations fitted to the time series of estimated ET_o for various seasons of a year during the four-decadal period of study. The rate of decrease in mean daily ET_o is found to be higher in all seasons except in NEM and winter seasons. The mean daily ET_o decreased at the rate of 0.024 mm/year on an annual scale. The rate of decrease in mean daily ET_o is found to be high at 0.039 mm/year, 0.028 mm/year and 0.027 mm/year for SWM, summer and monsoon seasons respectively. The R^2 values obtained for the linear fits to time series of mean daily ET_o for different seasons (except for NEM and winter seasons) are found to be quite significant. Song *et al.* (2010) studied the distribution and trends in reference evapotranspiration in the North China Plain and showed a significant decrease of 11.96 mm/decade over the period of study (1961-2006).

5. Conclusions

Both the non-parametric (MK trend test) and the parametric (linear regression) tests clearly demonstrate significant decreasing trends in the three meteorological parameters namely, mean daily WS, mean daily SSH and mean daily R_n for all seasons of a year over the multi-decadal period of study (1977-2016) in the hot and humid coastal town of Annamalai Nagar. The temporal trends in mean daily T_{mean} showed increasing rates for annual, NEM and winter seasons and no trends were detected for monsoon, SWM and summer seasons. In the case of VPD, annual and winter increases are with 0.01 levels, monsoon and NEM increases are with 0.05 level. Summer and SWM figures are not significant. The decreasing trends observed for all seasons in mean daily WS, mean daily SSH and R_n are much significant and offsetting compared to the increasing trends observed for a few seasons in mean daily T_{mean} and VPD and hence, the net effect of the meteorological parameters resulted in a significant decreasing temporal trend in mean daily ET_o for all seasons except NEM and winter seasons. The findings of this study are in close agreement with those of Song *et al.* (2010) who reported that the decreasing net radiation and wind speed had a bigger impact on ET_o rates than the increases observed in maximum and minimum air temperatures in the North China Plain.

Acknowledgements/Disclaimer

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