Received: 3 May 2018 | Revised: 28 October 2019 | Accepted: 7 November 2019 | Published on: 9 December 2019

DOI: 10.1002/met.1859

RESEARCH ARTICLE

Meteorological Applications RMetS

Variability in meteorological parameters and their impact on evapotranspiration in a humid zone of Pakistan

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Funding information
Higher Education Commission of Pakistan, Grant/Award Number: 8035/Balochistan/NRPU/R&D/HEC/2017; Pakistan Science Foundation, Grant/Award Number: PSF/NSFC-Earth/C-COMSATS-lsb (07)

Abstract

Pakistan lies in the region over the globe where effects of climate change due to global warming are more likely to occur. These climatic changes are reflected in significant gradual fluctuations in measurements of meteorological parameters. Agricultural activity in any region depends upon the role of components of hydrological cycle over the region. An important component of hydrological cycle is evapotranspiration (ET), which is closely linked with changes in meteorological parameters. This study investigates impact of probable variation in four important meteorological parameters i.e. temperature (T), net solar radiation (R_n), vapour pressure (e_a) and wind speed (U) on ET to estimate possible changes in reference ET in a humid zone of Pakistan by employing observed climatological records for 30 years (1981–2010). Analyses are done on the basis of possible ±20% changes in climatological mean values of the observed meteorological parameters. The analyses indicate that 20% rise in observed values of T, R_n and U increases value of total (annual) ET demand in the zone up to 11.93%, 16.37% and 2.83% respectively, and 20% rise in the observed values of vapour pressure decreases value of total (annual) ET till −2.5%. Moreover, the analyses also showed that ET is more sensitive to T and R_n in monsoon, vapour pressure in winter, and to wind speed in summer. Hence, this study might be useful in planning and formulating future strategies to meet expected future water requirements due to global warming in humid zone of Pakistan and its surrounding region.

KEYWORDS

climate change, evapotranspiration, humid zone, hydrological cycle

1 | INTRODUCTION

There are considerable evidences regarding rising of global mean temperatures as both the intensity and spatial extent of significant warming events are increasing (Hansen *et al.*, 2012). The substantial impacts on hydrological parameters i.e. evapotranspiration (ET), runoff, ground water and soil moisture are likely to be caused by abnormally warmer climatic conditions (Bultot *et al.*, 1988). To monitor spatiotemporal changes in hydrological cycle and water resources, several studies have been conducted in relevance to regional variability in climatic conditions induced by global warming (e.g. Feddema, 1999; Yue and Wang, 2002; Xu *et al.*, 2006; Han *et al.*, 2012; Ullah and Gao, 2013; IPCC, 2014). The hydrological cycle mainly depends upon precipitation and ET that are closely associated with crop water requirements. Soil moisture is prime variable not only from its evident agricultural importance but also as a variable that links near-surface climate by exerting a strong control over temperature. Furthermore, it restrains photosynthesis and transpiration process of plants in different regions of world with significant impact on water, energy and biogeochemical cycles (Seneviratne *et al.*, 2010). ET along with soil moisture is also a key component of water budget and ascertains the crop water demands. The main components that affect ET are further dependent upon several meteorological parameters including air temperature, sunshine hours, rainfall, humidity, wind speed along with plant characteristics and stomata behaviour in different agro-climatic regions (Mamassis *et al.*, 2014). Increase in temperature enhances the saturation pressure exponentially and also affects water vapour holding capacity of air. If all other meteorological factors are kept constant, then warming causes dryness and hence results in more ET. ET is enhanced due to decrease in cloud cover, vapour pressure and increase in solar radiation intensity (R_n) (Gong *et al.*, 2006). Moreover, ET rises due to dry and warm wind and drops due to moist and cold wind. It is less sensitive to winter because of coldness as compared to summer. Importantly, ET rises significantly due to extreme temperature and low vapour pressure (humidity), also enhances high irrigation demands and ultimately lead to aggravate the drought situation in all agro-climatic regions (Le Houerou, 1993; Smakhtin and Schipper, 2008).

Pakistan has agro-based economy which contributes to 21% of its annual gross domestic production (GoP, 2017). Rainfall is the main source of livelihood for agriculture, livestock and people living in humid region. The high annual variability of rainfall (112.9 mm to 1,333.7 mm with maximum of 1,713.2 mm), keeps the region always at risk. Furthermore, rainfall deficiency has caused intense drought (mild to severe) in the past, and seasonal droughts are more common in this region (Adnan *et al.*, 2017a). The gravity of the problem is even more severe in Pakistan. Mostly humid regions are rainfed and agriculture activity directly depends upon seasonal rainfall (Adnan and Khan, 2009; Adnan *et al.*, 2009). Keeping in view of future climatic change, comprehensive study is required over humid region. Studies on impacts of global warming are being conducted around the world as a major future challenge. Atmospheric temperature is perhaps the most extensively used sign of climatic change. The above-mentioned evidence provides the motivation to assess sensitivity of ET in terms of percentages due to possible ±20%

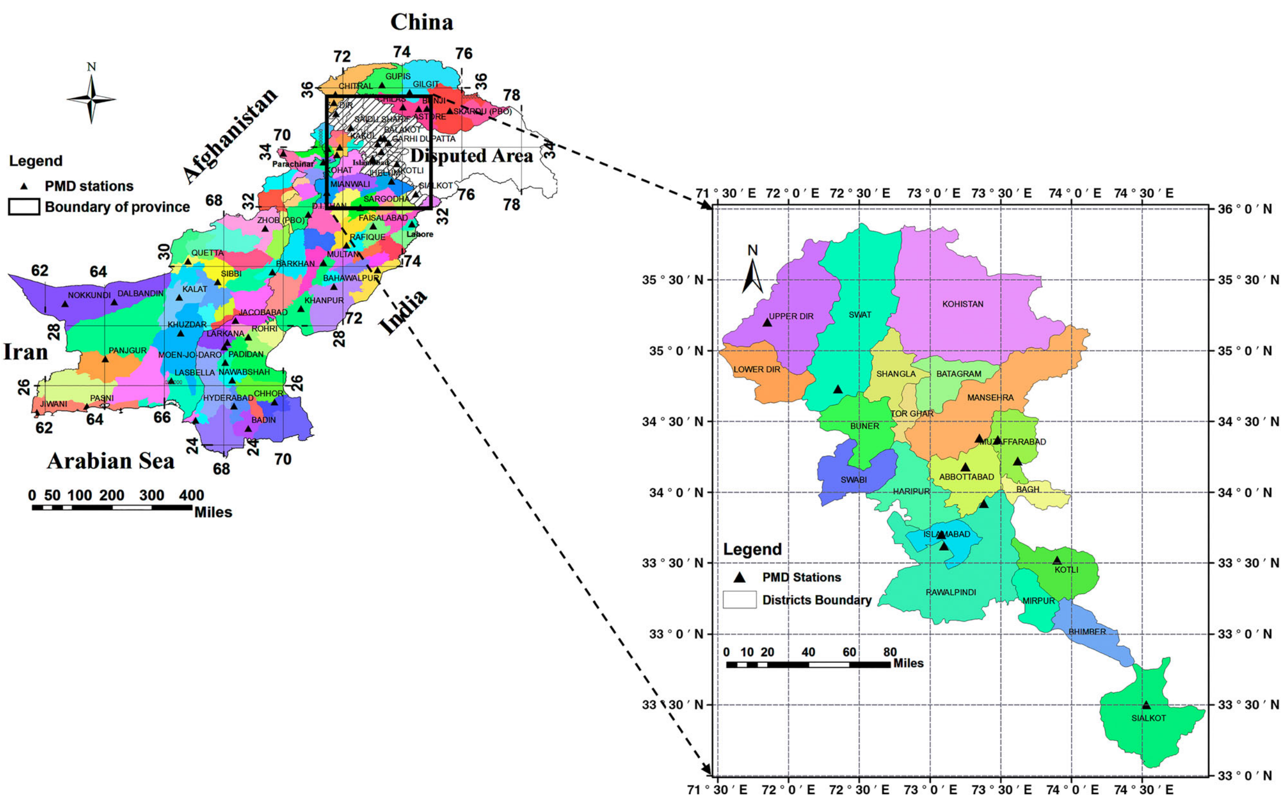

FIGURE 1 Location of the humid zone of Pakistan and 11 meteorological stations

variations in the meteorological parameters: temperature (T), solar radiation (R_n), vapour pressure (e_a) and wind speed (U).

There are three sections in this paper. First section comprises three subsections. First subsection describes important characteristics of study area that are linked with ET, directly or indirectly. Details of data and formulae applied are included in second subsection. It contains information about sources and period of data, involved meteorological parameters, and associated formulae applied to the data. Methodology and future scenarios are explained in third subsection. Second section contains results. It describes effects of possible ±20% changes in ET with respect to changes in meteorological variables. Third section encompasses concluding remarks. It elaborates results and conclusions that can be drawn from the results.

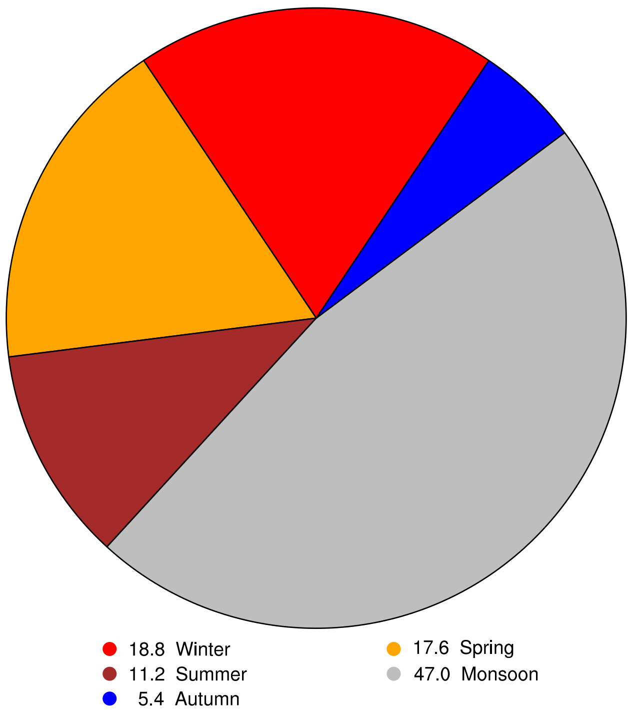

FIGURE 2 Season-wise percentage of annual rainfall in humid zone

2 | DATA AND METHODOLOGY

2.1 | Relevant features of the study area

The study area is a humid zone of Pakistan. The country's 51% of the area is marked between extremely arid to arid, 31% is semi-arid, while 18% lies in the humid zone (Sajjad and Adnan, 2014; Adnan *et al.*, 2017a). The maximum change in ET is caused by temperature and solar radiation in monsoon, vapour pressure in winter and wind speed in summer in extremely arid, arid and semi-arid regions of Pakistan (Adnan *et al.*, 2017b). Rainfall, percentage distribution of seasonal rainfall and temperature climatology of study area are shown in Figures 2 and 3. Pakistan receives most of the rainfall during the monsoon as *per* rainfall climatology (Adnan *et al.*, 2015). The humid zone of Pakistan extends from 32.56° N to 35.12° N and from 71.51° E to 73.43° E (Sajjad and Adnan, 2014). Elevation of humid zone from mean sea level ranges from 251 m to 2,169 m. According to the census of Pakistan held in 1998, this zone comprises approximately 57,110 km^2 with population density of 498.12·people per km^2. This zone includes 17% of cultivable land of the country as reported by the GoP (2014). The humid zone is also called the rain-fed region as agricultural activity in that area mainly depends upon rainfall. Due to shallow water table and complex topography, rainfall is the only source of irrigation. Humid regions

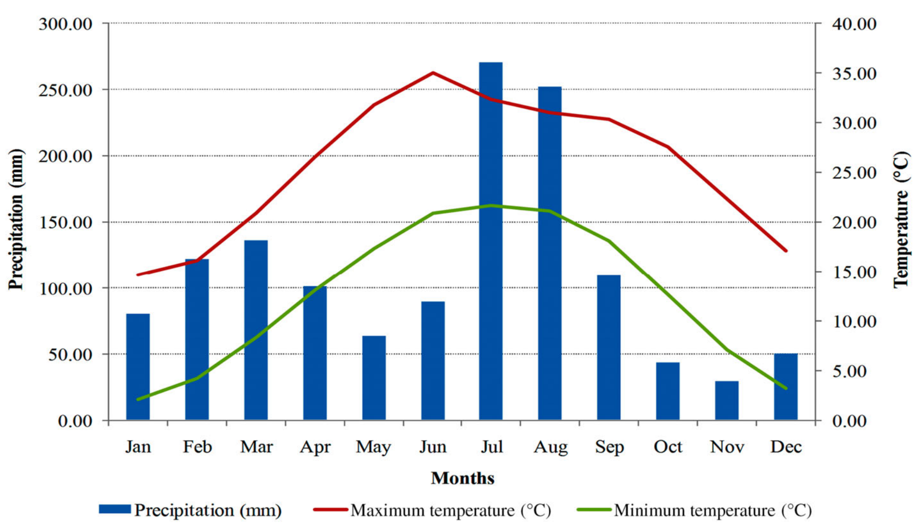

FIGURE 3 Rainfall and temperature climatology of the study area

TABLE 1A Location of meteorological stations and length of precipitation series

Station	District	Latitude	Longitude	Elevation (masl)	Period of record
Balakot	Mansehra	34.38	73.35	980	1961–2014
Dir	Upper Dir	35.20	71.85	1,369	1967–2014
Ghari Duptta	Muzaffarabad	34.22	73.62	812	1961–2014
Islamabad	Islamabad	33.70	73.08	543	1967–2014
Kakul	Abbottabad	34.18	73.25	1,308	1961–2014
Kotli	Kotli	33.52	73.90	613	1961–2014
Murree	Rawalpindi	33.92	73.38	2,167	1961–2014
Muzaffarabad	Muzaffarabad	34.37	73.48	701	1961–2014
Rawalpindi	Rawalpindi	33.62	73.10	507	1961–2014
Saidu Sharif	Swat	34.73	72.35	961	1974–2014
Sialkot	Sialkot	32.50	74.53	251	1961–2014

are highly vulnerable to drought and flash floods. Major crops of the region are wheat, maize, pulses, apple, peach, peanut, apricot, groundnuts etc. Rice is also cultivated in some areas of the zone because of high percentage of rainfall received. The humid zone receives considerable amounts of rainfall in both cultivation seasons, that is, Rabi (October–April) and Kharif (May–September) as investigated by Adnan and Khan (2009). This region receives its maximum amount of rainfall in summer (monsoon) as well as in winter (western disturbance system), whereas the rest of country receive rainfall either in summer or winter (Adnan *et al.*, 2009). Four seasons, that is, winter (December–February), spring (March–April), summer (May–June) and autumn (October–November) along with a wet summer monsoon (July–September) are normally observed in humid region. Both geographical location of the study area and 11 meteorological stations whose data are used in the present study are shown in Figure 1.

2.2 | Data and formulation

As demonstrated by Martin *et al.* (1989), four meteorological parameters (discussed above) are used to determine the sensitivity on ET in humid zone of Pakistan. In addition, ET has been calculated due to different combination of meteorological variables as indicated by Liu *et al.* (2010). Thirty years (1981–2010) monthly observational meteorological data of the four parameters of 11 *in-situ* observatories are gathered. This data is obtained from Pakistan Meteorological Department (PMD), which is of relatively long record. Names, locations and districts of the stations along with meteorological parameters and ET seasonal climatology are listed in Tables 1a and 1b.

Many scientists used several models for calculation of reference evapotranspiration (ET_0) (e.g. Wilson, 1974; Doorenbos and Pruitt, 1977; Viessman *et al.*, 1977; Eagleson, 1978; Subramanya, 1984; Mavi, 1986; Michael, 1986). Food and Agriculture Organization (FAO)-Penman–Monteith (PM) equation (Monteith, 1965) was used in different agro-zones of Bangladesh to identify the influence on ET due to meteorological variables (Ali *et al.*, 2009). Quantity and accuracy of available data, and possible computations with data lead to the most suitable method to calculate ET for a selected region. ET estimation is carried out using FAO-PM technique, considered as best method to calculate ET in all agro-zones (Allen *et al.*, 1998). Similar study was conducted to evaluate the performance of ET by identified FAO-PM equation which provides more appropriate results over the different climate zones of Pakistan and it may be adopted to determine more accurate and realistic estimates of crop water demands (Rasul and Mahmood, 2009). A recent study investigated that PM method provides best estimates of ET when the data of all variables is available (Vicente-Serrano *et al.*, 2014)

The modified PM equation is explained by Allen *et al.* (1998) as:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\left[\frac{900}{T+273}\right]u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \quad (1)$$

where ET_0 = reference evapotranspiration (mm/day); Δ = slope of the saturation vapour pressure (kPa/°C); G = soil heat flux density (MJ/m^2/day); R_n = net radiation (MJ/m^2/day); T = mean temperature (°C); u_2 = average daily wind speed (m/s); $e_s - e_a$ = vapour pressure deficit; e_a = atmospheric water vapour pressure and γ = psychrometric constant (kPa/°C).

TABLE 1B Seasonal climatology of meteorological parameters and evapotranspiration of humid region

Meteorological parameters	Winter	Spring	Summer	Monsoon	Autumn
Maximum temperature (°C)	16.3	24.1	33.8	31.6	25.3
Minimum temperature (°C)	3.1	10.6	18.9	20.4	9.6
Rainfall (mm)	240.6	220.0	140.2	631.6	72.2
Net radiation ($MJm^{-2}\cdot day^{-1}$)	4.34	9.71	13.42	11.67	6.08
Relative humidity (%)	69.5	61.4	51.5	75.1	66.1
Wind ($km\cdot hr^{-1}$)	2.0	3.3	3.5	2.2	1.5
Sun-hours	5.4	6.8	8.8	6.8	7.6
ET ($mm\cdot day^{-1}$)	1.32	3.32	5.28	3.98	2.04

The water vapours exert a partial air pressure which measure water content and directly linked to the amount of water in air as:

$$e_s = \left[\frac{e^0(\mathrm{T_{max}}) + e^0(\mathrm{T_{min}})}{2}\right], \tag{2}$$

where e_s = mean saturation vapour pressure; $T_{\max}$ = maximum temperature; and $T_{\min}$ = minimum temperature.

$$e^0(\mathrm{T}) = 0.6108\exp\left[\frac{17.27\mathrm{T}}{\mathrm{T}+237.3}\right] \tag{3}$$

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27\mathrm{T}}{\mathrm{T}+237.3}\right)\right]}{(\mathrm{T}+237.3)^2}. \tag{4}$$

The actual vapour pressure is represented as e_a:

$$e_a = \left[\frac{e^0(\mathrm{T}_{min})\left(\frac{\mathrm{RH}_{max}}{100}\right) + e^0(\mathrm{T_{max}})\left(\frac{\mathrm{RH}_{min}}{100}\right)}{2}\right]. \tag{5}$$

The difference $R_{ns} - R_{nl}$ between incoming solar radiations R_{ns} and outgoing solar radiations R_{nl} is known as net solar radiations R_n. In terms of equation, it is written as:

$$R_n = R_{ns} - R_{nl} \tag{6}$$

$$R_{ns} = (1-\alpha)\,.\,R_s \tag{7}$$

where α represents surface albedo and R_s is the insulation, as calculated and discussed by Doorenbos and Pruitt (1977).

$$R_s = \left(0.25 + 0.50\frac{n}{N}\right).\,R_a \tag{8}$$

where $\frac{n}{N}$ shows relative sunshine hours, and R_a is the extraterrestrial radiation (Allen *et al.*, 1998).

The net longwave radiation is expressed as:

$$R_{nl} = \sigma\left[\frac{\mathrm{T}^4_{max,k} + \mathrm{T}^4_{min,k}}{2}\right].(0.34 - 0.14\sqrt{e_a}).\left[1.35\frac{R_s}{R_{so}} - 0.35\right] \tag{9}$$

where R_{nl} is the net longwave radiation ($MJm^{-2}\cdot day^{-1}$); $T_{\max}$ and $T_{\min}$ are the maximum and minimum temperatures, respectively; σ is the Stefan Boltzmann constant; and R_{so} is shortwave radiation (for clear sky).

2.3 | Methodology

FAO-PM method calculates ET on seasonal as well as annual basis. Moreover, sensitivity of ET is determined by possible change of ±20% in various meteorological variables. This technique previously has been used in arid land of India and extremely arid to semi-arid land of Pakistan (Goyal, 2004; Adnan *et al.*, 2017b). Global average temperature would rise by 2.0–4.5°C in different regions around the world due to double emissions of CO_2 in 21st century (IPCC, 2007). Therefore, a future scenario is developed by changing (±20%) of aforementioned meteorological variables to identify impacts of these changes on ET in a humid zone of Pakistan.

ET is calculated by varying one parameter and keeping the rest three constant at a time within the range. The authors increased/decreased single parameter by 5%, 10%, 15% or 20% and kept the rest parameters constant. For example, for 5% increase in temperature, net radiation, vapour pressure and wind speed were kept constant to its means value. Similarly, total ET demands are hypothetically determined to anticipate changes in each climatic parameter due to climate change. This gives an idea about the impacts on ET, which corresponds to the meteorological parameters during each season in the humid zone. This is achieved by a temperature increase of 10% along with all probable changes of ±10% in the meteorological parameters with percentage change in their normal values. Lastly, percentage possible changes of ET correspond to probable change of ±20% for T, e_a, R_n and U are also calculated.

3 | RESULTS AND DISCUSSIONS

The impact of meteorological variables on ET is difficult to identify both spatially and temporally in the changing climate scenario. ET sensitivity with respect to the different possible change in the meteorological variables for each season is shown in Table 2. The scenario is developed by a 10% increase in temperature with the possibility of ±10% change in the meteorological parameters (Table 3). This approach was conducted to identify the annual change in ET by keeping the temperature increase (10%) constant and vary the rest of the meteorological parameters with a possible change of ±10%. Temperature plays a key role to influence ET regardless of any season. The scenarios (cases 1–14) determined the combination of meteorological parameters that would influence ET if temperature increase is ceased. The ET determines the crop water requirement of a region. Therefore, variability in ET may directly impact the crop water demand, that is, a ±20% change in ET would definitely change the crop water requirement (±20%), as determined by Chowdhury *et al.* (2016). Additionally, ET ranges from −4.44% (−10% R_n, 10% e_a, −10% U) to a maximum 21.76% (10% R_n, −10% e_a, 10% U) and it is shown in bold letters in Table 3. Increasing normal vapour pressure by 10% along with a 10% decrease in net radiations results in reduction of the total ET by −2.99%. An increase in temperature by 10% and a decrease in the other meteorological variables

TABLE 2 Impact of seasonal change in meteorological parameters (%) on total evapotranspiration (mm)

		Change in the total ET (mm) due to the percentage change in meteorological parameters								
Meteorological parameters	**Season**	**−20%**	**−15%**	**−10%**	**−5%**	**0%**	**5%**	**10%**	**15%**	**20%**
Temperature (T_{max}, T_{min})	W	110.50	113.29	116.14	119.05	122.02	125.03	128.09	131.20	134.35
	S	172.48	177.20	181.96	186.76	191.58	196.43	201.31	206.20	211.12
	Su	276.15	285.08	294.03	303.00	312.00	321.04	330.11	339.23	348.42
	M	324.36	335.63	347.06	358.65	370.43	382.40	394.59	407.00	419.68
	At	119.73	123.78	127.89	132.07	136.30	140.60	144.95	149.36	153.83
	An	1003.21	1034.98	1067.09	1099.53	1132.33	1165.50	1199.05	1233.01	1267.40
Net radiation (R_n)	W	103.13	107.92	112.71	117.49	122.02	127.06	131.85	136.64	141.42
	S	162.48	169.75	177.03	184.30	191.58	198.85	206.12	213.39	220.67
	Su	264.72	276.49	288.26	300.02	312.00	323.56	335.33	347.10	358.87
	M	303.65	320.34	337.02	353.71	370.43	387.08	403.76	420.45	437.14
	At	112.99	118.81	124.63	130.46	136.30	142.11	147.93	153.75	159.58
	An	946.97	993.31	1039.65	1085.98	1132.33	1178.66	1224.99	1271.33	1317.67
Vapour pressure (e_a)	W	129.41	127.68	125.91	124.11	122.02	120.42	118.53	116.62	114.68
	S	198.88	197.13	195.33	193.47	191.58	189.63	187.65	185.63	183.58
	Su	314.16	313.72	313.18	312.53	312.00	310.98	310.08	309.12	308.09
	M	376.49	375.14	373.66	372.08	370.43	368.61	366.75	364.80	362.77
	At	137.38	137.17	136.92	136.62	136.30	135.90	135.49	135.04	134.56
	An	1156.31	1150.83	1144.99	1138.81	1132.33	1125.54	1118.50	1111.20	1103.68
Wind speed (u_2)	W	117.10	118.34	119.57	120.80	122.02	123.22	124.42	125.61	126.79
	S	184.46	186.26	188.05	189.83	191.58	193.32	195.05	196.76	198.46
	Su	300.16	303.15	306.12	309.07	312.00	314.91	317.80	320.67	323.52
	M	365.17	366.49	367.81	369.12	370.43	371.73	373.02	374.31	375.59
	At	132.51	133.46	134.41	135.36	136.30	137.24	138.18	139.11	140.04
	An	1099.39	1107.71	1115.97	1124.18	1132.33	1140.43	1148.47	1156.47	1164.40

An: annual; At: autumn; M: monsoon; S: spring; Su: summer; W: winter.

TABLE 3 Annual changes in total estimated evapotranspiration with respect to change in meteorological parameters by keeping the temperature constant at 10% increase and vary the other parameters (±10)

Case number	Percentage change in: Net solar radiation (R_n)	Actual vapour pressure (e_a)	Wind speed (u_2)	Estimated annual reference ET	% change over the control (normal parameters)
1	+	0	0	1,324.1	16.94%
2	–	0	0	1,131.9	–0.04%
3	+	+	0	1,290.7	13.98%
4	+	–	0	1,357.5	19.89%
5	–	–	0	1,165.3	2.91%
6	–	+	0	1,098.5	–2.99%
7	+	+	+	1,305.6	15.30%
8	+	+	–	1,275.5	12.64%
9	+	–	+	**1,378.7**	**21.76%**
10	+	–	–	1,336.1	18.00%
11	–	+	+	1,114.6	–1.56%
12	–	+	–	**1,082.1**	**–4.44%**
13	–	–	+	1,187.7	4.89%
14	–	–	–	1,142.7	0.91%

by 10%, results a meagre increase in total ET (0.91%). Based on both seasonal and annual analysis, the percentage change in ET due to a probable change in the meteorological variables (T, e_a, R_n, U) is shown in Figure 4a–d. ET varies annually from −11.40% to 11.93% due to change in temperature (±20%). ET is less sensitive to a decrease in temperature than increase; establish temperature is a prime parameter that influences ET more than the rest of the parameters, irrespective of the seasons as mentioned by Xu *et al.* (2006). However, temperature has less effect during winter (−9.44 to 10.11)% as compared to rest of the seasons because winter is mostly cold with moisture content not being much high. The maximum change (−12.44 to 13.29)% in ET is observed during the monsoon season because of the highest concentration of moisture in the soil. Monsoon season might make volumetric soil moisture transition from wilting to critical values and therefore, transition from a regime where the evaporative fraction (i.e. ET normalized by R_n = ET/R_n) is controlled by the soil moisture content to one where this dependence is lost, and ET can no longer change except from net available radiation (Seneviratne *et al.*, 2010).

Despite of the increase in surface temperature, a decrease in pan evaporation observation across the United States and all over the world is known as the pan evaporation paradox (PEP). The detrending approach in sensitivity analysis over China identified that changes in solar radiation, wind speed and relative humidity overcompensate the positive contribution of increasing air temperature in pan evaporation (E_{pan}) and lead to PEP (Wang *et al.*, 2017).

As pan evapotranspiration (ET_p) is a function of net available energy (temperature). As the average global temperature increases, it is generally expected that the air will become dry and evaporation will increase. Actual evapotranspiration (ET_a) is a function of ET_p, which is decreasing globally, while global temperature is increasing. Therefore, ET_a should be decreasing. Pan evaporation has deceased as the evaporation from the surrounding environment of the pan has increased. Secondly, solar irradiance reduction resulting from clouds/aerosols increased the pollution that weakens the hydrological cycle (Szilagyi, 2001).

The annual change (0 to ±20%) in net solar radiations has more effect (±16.37%) on ET except in case of monsoon season (±18.02%). The actual vapour pressure has an inverse effect on ET, which shows that increasing trends in vapour pressure decreases ET and vice versa. By changing the vapour pressure from 0 to ±20%, ET varies from 2.1% to −2.5% annually, except for winter (5.8% to −6.2%) due to the high elevation. Wind speed has a minimum effect (−2.91 to 2.83)% on ET annually and a maximum effect (about −4.03 to 3.92)% during winter due to cool and dry characteristics of wind, which causes more ET from the surface as compared to rest of the seasons, as mentioned by Subramanya (2008).

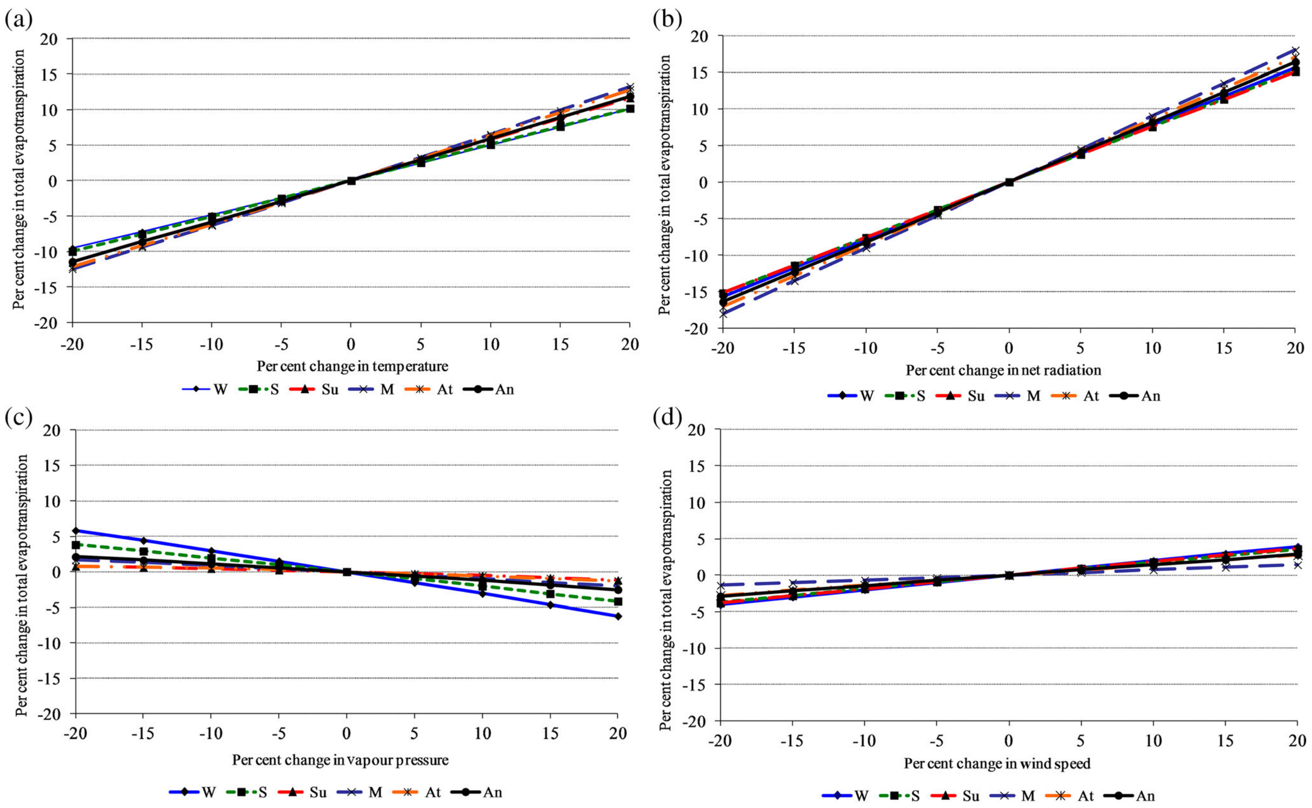

FIGURE 4 % changes in evapotranspiration *versus* percentage change in meteorological parameters: (a) temperature (b) net radiation (c) vapour pressure (d) wind speed

4 | CONCLUSIONS

The results of this study describe and quantify impacts of varying meteorological parameters on ET both season-wise and annually in humid zone of Pakistan. Temperature, wind speed and solar radiations are directly proportional to ET, but the vapour pressure is inversely proportional to ET. The maximum change observed in ET for temperature and net radiations is −12.44% to 13.29% and ±18.02%. Both vapour pressure and wind speed change from 5.8% to −6.2% during the monsoon, and from −4.03% to 3.92% during winter season. The increase (10%) in both temperature and vapour pressure and the decrease (−10%) in both net solar radiations and wind speed cause minimum decrease (−4.44%) in ET. Furthermore, when temperature, net solar radiation and wind speed increases (10%) and vapour pressure decreases (−10%), a maximum increase in ET is observed as 21.76%. A significant increase in temperature enhances ET that impacts on agricultural water requirements and water resources in humid zone. Although these results are estimated but provide a helpful insight for sustainable agriculture and water resource management. It also provides a way towards climate smart agriculture to plan irrigation schedule in humid regions. Hence, the present study provides a look in to future behaviour of ET with respect to meteorological parameters and enable us to determine the crop water demands of humid zone.

ACKNOWLEDGEMENTS

The study was supported by grants from the Pakistan Science Foundation (Grant No. PSF/NSFC-Earth/C-COMSATS-lsb (07)) and the Higher Education Commission of Pakistan (Grant No. 8035/Balochistan/NRPU/R&D/HEC/2017). The authors are thankul to Global Precipitation Climatological Centre (GPCC), University of Delaware (UDEL), USA, Climate Research Unit (CRU, University of East Anglia (UEA), UK), and Pakistan Meteorological Department. The authors would also like to thank the anonymous reviewers and the editor for their valuable comments.

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How to cite this article: Adnan S, Ullah K, Ahmed R. Variability in meteorological parameters and their impact on evapotranspiration in a humid zone of Pakistan. *Meteorol Appl*. 2020;e1859. https://doi.org/10.1002/met.1859