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Historical changes of temperature and vapor pressure deficit during the crop growing season in Iran

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Abstract

Climate change variables have rarely been analyzed specifically for the growing season of crops. In this study, changes in minimum (T_{min}) and maximum temperature (T_{max}), daily maximum saturated vapor pressure (VP_{sat}) and estimated daily VPD weighted for transpiration (VPD_{tran}) were examined at five locations in Iran over 40 years during the growing seasons of chickpea and maize. The results of this analysis showed a general trend of increasing T_{max}. The increase in T_{max} was especially pronounced during the period when maize is grown. Increasing T_{max} resulted in the calculation of increasing VP_{sat} at all locations. Minimum temperature also showed a clear increase at four of the five locations. The one exception in increasing T_{min} was a location (Isfahan) leeward of the Zagros mountains where the air may be dried as it traverses the mountain, likely resulting in the observed stability of the dew point at this location. City growth encroached in the vicinity of the weather stations so some of the warming might be attributed to the expansion of city boundaries. At the four locations where both T_{max} and T_{min} increased, no increase in VPD_{tran} was identified. Therefore, no increasing trend for increasing water requirement by the crops was identified. On the other hand, the lack of an increase in T_{min} at Isfahan resulted in an increase in atmospheric VPD_{tran}. The increased VPD_{tran} results in higher water requirement in growing crops. Using the genotypes with breakpoint in their transpiration rate at high VPD might alleviate the deleterious effect of high VPD_{tran} on growth of rainfed crops at Isfahan.

Keywords: Chickpea; Climate change; Maize; Maximum temperature; Minimum temperature; Vapor pressure deficit.

Introduction

Temperature and vapor pressure deficit are critical in evaluating the growth potential of crops in any environment. Temperature has a large influence on plant development rate; higher temperatures increase rate of development shortening the growing season of the crop. Vapor pressure deficit (VPD) describes the gradient driving crop transpiration rate, and increased VPD results in an increased water requirement in growing crops. Changes in both of these weather variables are of concern as a result of anthropogenic climate change. Key questions exist about past changes in each of the variables as an approach to gain insight about the future. A number of analyses have examined historical changes in temperature, but these have generally been examined on monthly and annual basis (Karl et al., 2006; IPCC, 2007; Zhang et al., 2000; Gaffen and Ross, 1999; Shabbar et al., 1997; Chmielewski et al., 2004). Virtually no studies have focused on changes in average temperature at shorter intervals during the growing periods of some crops.

A critical aspect of a temperature increase is that the saturation vapor pressure of the atmosphere increases exponentially with temperature. Therefore, temperature increases during daylight hours result in proportionally greater increases in saturated atmospheric vapor pressure, and possibly VPD. The consequences of high VPD have been documented in a number of studies. For example, Saitoh and Ishihara (1987) conducted an experiment on rice and found that transpiration rate increased rapidly, and photosynthetic rate, diffusive conductance and leaf intercellular CO_2 concentration decreased gradually with increasing VPD; radiation use efficiency also decreased. In castor bean (*Ricinus communis* L.), CO_2 assimilation rate also decreased as VPD increased (Dai et al., 1992). In examining midday stomatal conductance in *Prosopis juliflora*, Pathre et al. (1998) found VPD was a more significant factor than temperature in causing midday depression. Iio et al. (2004) reported photosynthesis rate, stomatal conductance and transpiration of *Fagus crenata* Blume decreased more than 50% under VPD of about 2.5 kPa as compared to VPD of about 1.0 kPa even under well-watered conditions.

Recent studies have documented transpiration responses to increasing VPD that indicate the importance of water hydraulics in the plant. For example, Fletcher et al. (2007) and Sadok and Sinclair (2009) found that transpiration rate of some soybean (*Glycine max* (L.) Merr.) cultivars increased linearly with VPD up to a threshold value, and then at greater VPD transpiration rate was essentially constant. The threshold apparently reflected the maximum rate of water transfer in the plant, and at VPD above the threshold stomata closure prevents plant desiccation. This response has been observed in japanese brome (*Bromus japonicas* Thunb. ex Murr), king ranch bluestem (*Bothriochloa ischaemum* L.) (Maherali et al., 2003), broad bean (*Vicia faba* L.), common bean (*Phaseolus vulgaris* L.) (Mott and Parkhurst, 1991), maize (Zea mays L.) (Ray et al., 2002) and peanut (*Arachis hypogea* L.) (Devi et al., 2010). If the VPD to which crops will be subjected increases to deleterious levels, then genotypes can be selected with lower threshold VPD that allows crops to conserve water. Of course, the negative aspect of a low threshold VPD is that stomata closure results in decreased photosynthetic rate.

Given the importance of VPD on the use of water by crops, it is surprising that little climate change analysis has included studies on possible changes in atmosphere vapor pressure and VPD. Gaffen and Ross (1999) and Robinson (2000) found that dew point temperature, which reflects the actual vapor pressure of the atmosphere, has increased by several tenths of a degree per decade for most regions in the U.S. In spite of this, Szilagyi et al. (2001) found for the period of 1948 to 1996 across the U.S. there had been no statistically significant change in VPD. These latter results indicate that the increase in saturation vapor pressure based on daytime temperatures was offset by the increase in dew point. Again, these few studies have focused on changes on an annual basis rather than specifically during the growing season.

The objective of this study was to examine possible past changes in minimum and maximum temperature as well as maximum daily saturated vapor pressure and daily VPD weighted for transpiration during the growing season of arid and semi-arid environments of Iran. Five environments were studied. Changes in temperature and vapor pressure VPD were examined during the growing season of chickpea (*Cicer arietinum* L.) and maize (*Zea mays* L.) using approximately 40 years of weather data. The changes in these variables were calculated at 13-day intervals during the growing seasons for these two crop species.

Materials and Methods

Historical weather data for five locations in Iran were studied: Isfahan (32.67 °N, 51.87 °E and 1600 m asl), Shiraz (29.55 °N, 52.60 °E and 1488 m asl), Kermanshah (34.32 °N, 47.12 °E and 1322 m asl), Tabriz (38.13 °N, 46.28 °E and 1364 m asl) and Mashhad (36.27 °N, 59.63 °E and 999.2 m asl). These locations represent different geographical characteristics (Figure 1) and are of major agricultural importance in Iran. Daily weather was obtained from Islamic Republic of Iran Meteorological Organization (IRIMO) for 39 years for Tabriz (1966 to 2004) and 44 years for the other four locations (1961-2004). The data used in this analysis was daily minimum and maximum temperature.

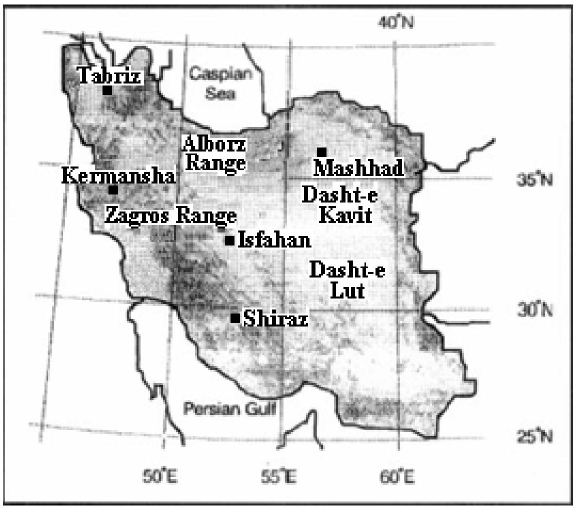

Figure 1. Map of Iran showing main mountain ranges (more highlighted areas) and selected stations (filled squares) for this study.

The analysis of climate changes was initiated at different times of the year for each location to reflect differing growing seasons. The average value for each of the variables was calculated for fifteen 13-day periods in each year and location. The 13-d interval was selected because it conveniently divided the 165 d growing season into equal duration period of about 2 wks. To match the approximate sowing date of chickpea at each location, the first 13-day period began on day of the year 64 for Shiraz, 68 for Isfahan, 81 for Mashhad, 93 for Kermanshah, and 105 for Tabriz. The first eight 13-day periods corresponded approximately to the growing season (104 days) for chickpea in each location. Maize sowing in each location is approximately 65 days after chickpea so 13-day periods #6 through #15 reflected a 130-day growing period for maize.

Unfortunately, the weather data did not include values of atmospheric humidity so neither daily maximum saturated vapor pressure (VP_{sat}) nor daily VPD weighted for transpiration (VPD_{tran}) could be obtained from direct measurements. Instead, these variables were estimated based on daily temperature data. The daily maximum value of VP_{sat} was calculated from maximum temperature (T_{max}) using the following equation.

$$VP_{sat} = 0.6108 \times \exp(17.27 \times T_{max}) / (T_{max} + 237.3) \quad (1)$$

The actual vapor pressure of the atmosphere (VP_{act}) was approximated from the minimum temperature (T_{min}) by assuming that each night temperature decreased to near the atmospheric dew point, i.e. minimum temperature. Therefore, VP_{act} was estimated from the daily T_{min} data by using Equation (1). The daily value of VPD_{tran} was estimated using the values of VP_{sat} and VP_{act}. The value of VPD_{tran} has been shown to be approximately 75% of the daily maximum VPD (Tanner, 1981; Abbate et al., 2004). Therefore, VPD_{tran} was estimated using the following equation.

$$VPD_{tran} = 0.75\,(VP_{sat} - VP_{act}) \quad (2)$$

Changes in T_{max}, T_{min}, VP_{sat}, and VPD_{tran} were calculated across years for individual 13-day periods during the growing seasons of chickpea and maize. The average value of each variable across years was calculated for each of the fifteen 13-day periods. In several cases, there appeared to be a break in the trend for a variable roughly at about 1980. To account for the possibility that a trend in each variable might have developed only in the later time frame, all data were subjected to a two-segment linear regression using Prism 2.01 (GraphPad, Software Inc., San Diego, CA). Prism identified the year of a breakpoint between two segments and generated the regressions for the two segments if the segments had slopes that were significantly different ($P<0.05$). If two segments were not identified as being significantly different, all data for that variable and time period were subjected to a single linear regression across all years.

As discussed above, VPD (i.e., $VP_{sat} - VP_{act}$) may be important in assessing the possibility of midday decreases in transpiration and photosynthetic rates if a threshold VPD for the crop is exceeded. That is, on days of high VPD water loss by the crop might be constrained by the limitation of maximum crop water loss rate. Of course, midday stomata closure will result in a loss of photosynthetic activity and crop growth. For this analysis, a threshold value of 3.5 kPa for ($VP_{sat} - VP_{act}$) was used based on the observations of Ray et al. (2002) regarding maize transpiration response to drying soil. The fraction of days during the growing season of each crop on which ($VP_{sat} - VP_{act}$) exceeded this maximum was calculated for each location.

Results

The two-segment linear regression over years identified several situations where the two-segment linear regression was appropriate for characterizing the change in the various climate variables. In the cases best described by the two-segment linear regression, there was a wide range in the years for the breakpoint. The breakpoint was identified to occur as early as 1971 and as late as 1990, with most values in the range or 1978 to 1989. Prior to the breakpoint year there tended to be no change or even a negative change in a variable across years. In those cases where a two-segment regression was found significant, the results for the regression of the later years are presented. In the figures, those values obtained using only data obtained after a breakpoint year are indicated with a different symbol.

Maximum temperature tended to increase over years at all locations and periods. Only in periods #1, #2, and #4 at Shiraz and period #3 and #4 at Mashhad was the regression slope for T_{max} across years negative (Figure 2). Only two of these five negative slopes were significant. For the growing season of chickpea (periods #1 to #8), there were only a few cases where T_{max} was found to exhibit a significant increase. The periods representing the growing season of maize (periods #6 to #15) had no periods at any location where there was a decrease in T_{max} over the years of this study (Figure 2). In fact, most of periods exhibited significant increases in T_{max} during periods of maize growth. The largest increases of T_{max} were recorded at Isfahan, Kermanshah, and Mashhad with the rate of temperature increase in some periods was approximately 0.1 °C per year.

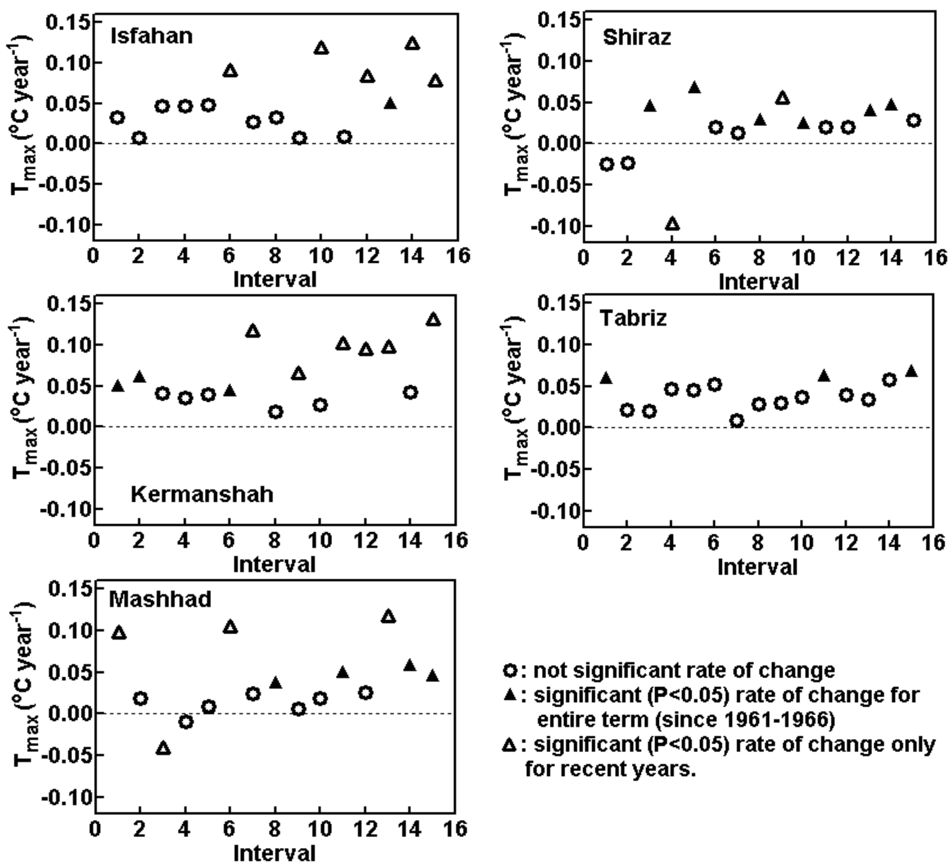

Figure 2. The rate of change in averaged maximum temperature (T_{max}) over 13-days intervals in growing period of chickpea and maize for five locations of Iran. The growing period of two crops overlap over intervals #6 to #8.

The change in T_{min} was even more pronounced than was the change in T_{max} (Figure 3). Except for Isfahan, the regressions at the other four locations resulted in positive slopes for all periods. In most cases, the slopes were significant. Significant T_{min} increases were found across all years at Shiraz, Kermanshah, and Tabriz, and the increase in T_{min} was significant in the later years at Mashhad. The greatest T_{min} increases were at Shiraz and Mashhad where the increase was commonly near or greater than 0.1 ^{o}C per year. In contrast to the other four locations, the results at Isfahan showed no significant trend in T_{min} across years.

Since VP_{sat} is a direct function of T_{max} (Equation (1)), the changes in VP_{sat} over years (Figure 4) paralleled to some extent the results for T_{max}. That is, a positive regression for VP_{sat} over years was found in most cases; with most significant increases obtained during the maize growing season. The greatest increases in VP_{sat} were identified at Isfahan and Kermanshah where the increase was greater than 0.03 kPa per year. Significant increases in VP_{sat} of about 0.01 kPa per year were identified at Shiraz and Tabriz.

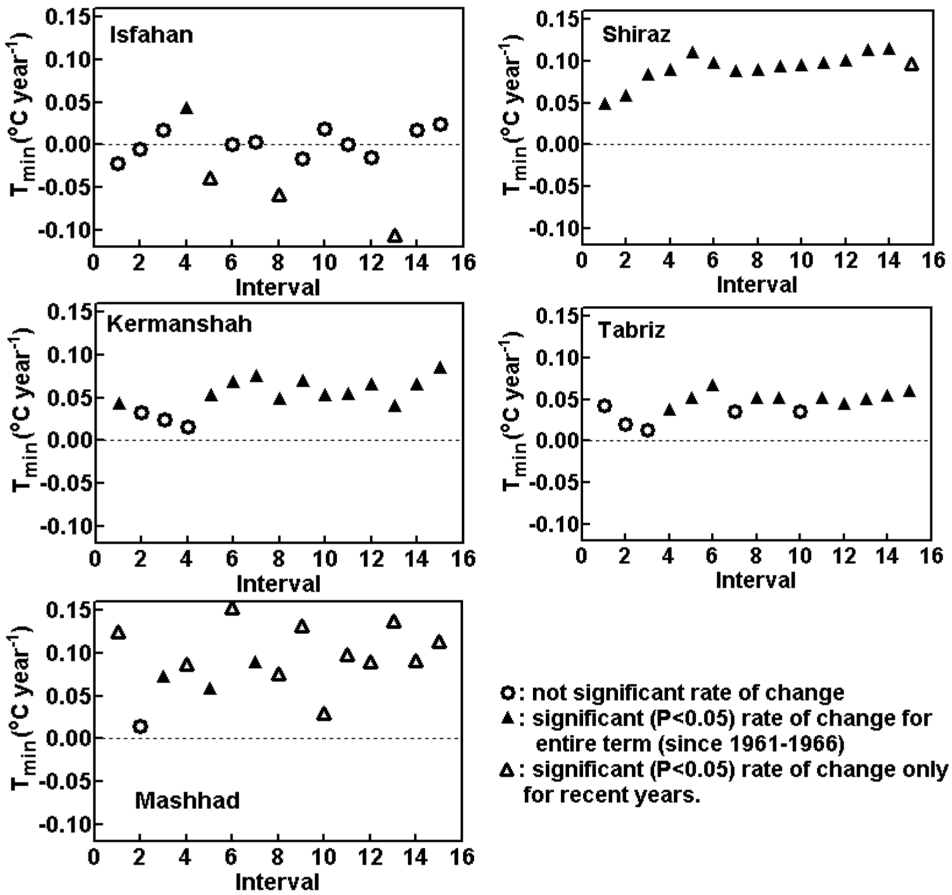

Figure 3. The rate of change in averaged minimum temperature (T_{min}) over 13-days intervals in growing period of chickpea and maize for five locations of Iran. The growing period of two crops overlap over intervals #6 to #8.

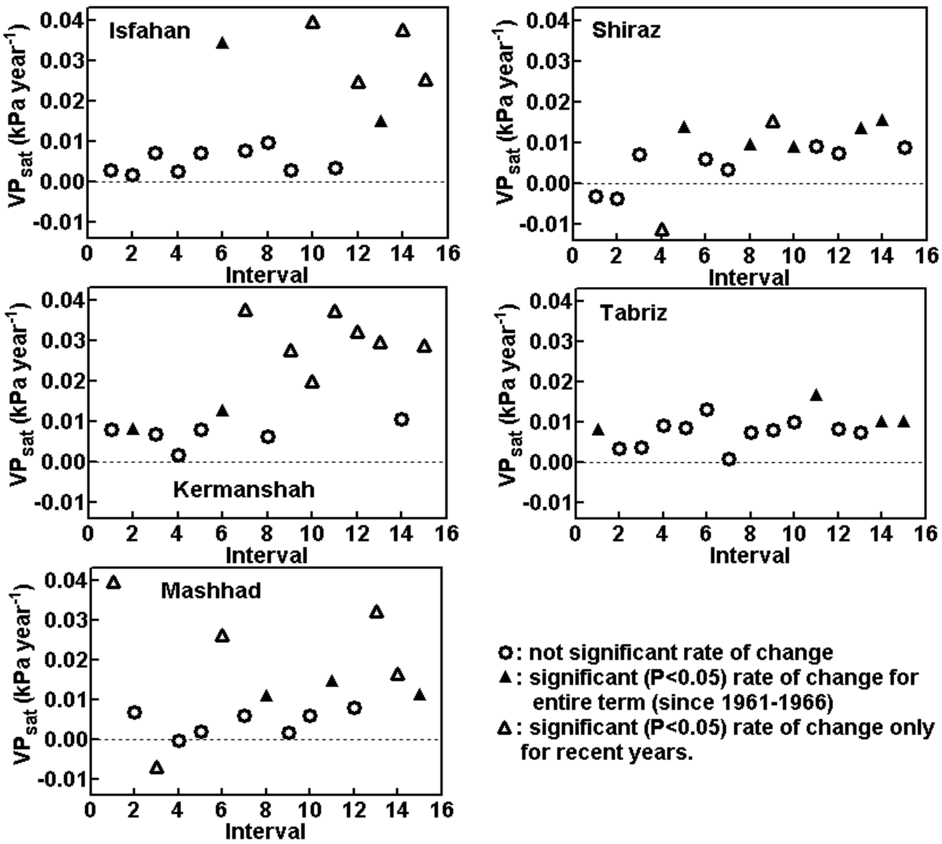

Figure 4. The rate of change in averaged daily maximum saturated vapor pressure (VP_{sat}) over 13-days intervals in growing period of chickpea and maize for five locations of Iran. The growing period of two crops overlap over intervals #6 to #8.

The estimate for the daily value of VPD_{tran} depends both on VP_{sat} and VP_{act} (Equation (2)) so the relative change in VPD_{tran} is influenced by changes in both variables. There is no consistent trend in the change in VPD_{tran} across locations (Figure 5). Tabriz and Mashhad, along with many periods at Kermanshah showed no trend in VPD_{tran} across years. The results from Isfahan showed a significant increase in VPD_{tran} in recent years for nearly all periods. The increase at this location was about 0.02 kPa per year for most periods. Shiraz had the interesting trend of decreased VPD_{tran} during the chickpea growing season and a lessening of the decrease through the maize growing season until no change was found in periods #11 to #15.

During the growing period for chickpea (#1 to #8), the fraction of days when (VP_{sat} - VP_{act}) exceeded the 3.5 kPa threshold for plant response was 2%, 4%, 8%, 8%, and 26% for Tabriz, Isfahan, Mashhad, Shiraz, and Kermanshah, respectively. The fraction of days that (VP_{sat} - VP_{act}) exceeded the 3.5 kPa threshold during the periods #6 to #15 of maize growth was 5%, 12%, 27%, 65%, and 76% for Tabriz, Isfahan, Mashhad, Shiraz, and Kermanshah, respectively. These results clearly indicate more severe aridity of the atmosphere during the maize growth period than for the chickpea growth period.

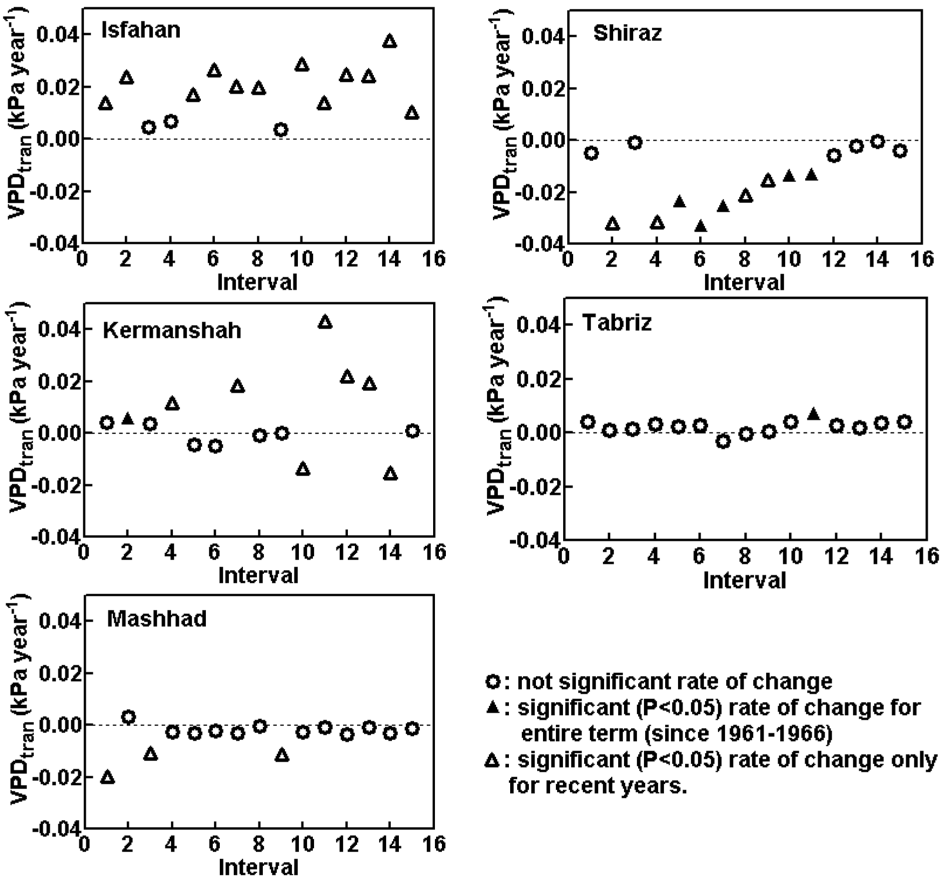

Figure 5. The rate of change in averaged daily vapor pressure deficit weighted for transpiration (VPD_{tran}) over 13-days intervals in growing period of chickpea and maize for five locations of Iran. The growing period of two crops overlap over intervals #6 to #8.

Discussion

Changes in T_{max}, T_{min}, VP_{sat}, and VPD_{tran} were examined for 13-day periods for the growing seasons of chickpea and maize in the arid climate of Iran. Segmenting the growing season into fifteen periods allowed a close examination of these variables at different times in the season. The higher time resolution in examining historical weather data contrasts with previous studies that used seasonal time scales (Gaffen and Ross, 1999; Shabbar et al., 1997; Chmielewski et al., 2004), entire crop-growing seasons (Gholipoor, 2008), or annual time scales (Zhang et al., 2000). The 13-day periods showed that considerable variability in the change in the weather variables across years. The analysis of T_{max} for periods of chickpea growth did not indicate a consistent trend across periods in significant change. However, during the maize growing periods all regressions were positive for an increase in

T_{max}. Three locations-Isfahan, Kermanshah, and Mashhad-exhibited periods of increases in T_{max} as great as 0.1 ^{o}C per year. Such a rapid increase in T_{max} if sustained for several decades will result in temperature increases that would likely have marked influences on crop development.

The change in T_{min} over years also differed among locations. At Isfahan, there was no clear trend in a change of T_{min} across the fifteen periods. At the other four locations, the regressions of T_{min} over years for all periods were always positive and most of the results were significant. An increase in T_{min} is consistent with an increase in the vapor pressure of the atmosphere as reflected in an increased dew point. These results for these locations in Iran are consistent with increases found in dew point temperatures in the U.S. of a few tenths of a degree per decade (Gaffen and Ross, 1999; Robinson, 2000). The failure to observe an increase in T_{min} over years at Isfahan may be a result of its geographical location. Isfahan is centrally located in Iran (Figure 1) at a high elevation on the east side of the Zagros Mountains. Consequently, the atmosphere at Isfahan had been dried as the air rose crossing the mountains. The elevation of these mountains was a high as 4040 m for Shahankooh Mountain in the eastern fringes of the Zagros range. This would have a major influence on the VP_{act} experienced at Isfahan.

Overall these results of increased T_{max} and T_{min} are consistent with past studies in which these two variables were examined separately. These results are similar to those found by Soltani and Soltani (2008) for change in T_{max} and T_{min} by month at three locations in Khorasan province of Iran, the province where Mashhad is located. The breakpoints found in this study appear to be due to rapid expansion of mentioned cities around 1980. Actually because of the expansion, weather stations that were previously outside or near the city were surrounded by the city. They found for the months March to September (almost the growing season of the crops used in this study) that T_{max} increased in five of the seven months at one location, but the other two locations showed no consistent change. A similar result was obtained for T_{min}.

Skinner and Gullett (1993) reported significant increases in both T_{max} and T_{min} during spring for the prairie region of Canada from 1950 to 1989. Kukla and Karl (1993) analyzed data from several countries, including the USA, Canada, China, Russia, Australia, Sudan, Japan, Denmark, Finland, Pakistan, South Africa and some European countries and reported an increase in T_{min} with exception of the Eastern coast of North America, where it decreased. Franke et al. (2004) reported increase in temperature in all seasons and especially in winter in Saxony, Eastern Germany.

Lobel et al. (2005) reported a cooling trend in nighttime temperature in Mexico. However, Molua (2006) reported strong positive temperature trends for the months of July, August, and September in Cameroon during 1960-2000 periods. Pathak et al. (2003), studying in the Indo-Gangetic Plains, found a negative trend of T_{min} at three sites, whereas six sites showed a positive trend. Qian and Lin (2004) observed trends of increasing warm days in the upper-middle Yellow River Valley and other regions such as along the Coast of South China, while there are decreasing trends scattered in the central part of East China.

Due to the dependence of VP_{sat} on T_{max} (Equation (1)), the changes in VP_{sat} over years were very similar to the changes in T_{max} (Figure 3). In most periods at all locations there was a positive regression for the change in VP_{sat} over years. There tended to be greater increases in VP_{sat} during the later part of the crop growing season when maize is grown. While individual periods at Isfahan, Kermanshah, and Mashhad exhibited increases of 0.03

kPa per year or greater, most values were in the range of 0.01 kPa per year. Hence the increases in VP_{sat} at these five locations have thus far been very modest.

In contrast to the increase in VP_{sat}, no consistent trend in the estimate of VPD_{tran} was observed except for the significant increases at Isfahan. At Isfahan, there was an increase in VP_{sat} while VP_{act} remained nearly constant. The results from the locations other than Isfahan indicate that the rates of increase in VP_{act} were about the same as the rates of VP_{sat} increase resulting in a fairly stable VPD. These results are consistent with the results of Szilagyi et al. (2001) in the U.S. showing no long-term trend in VPD.

The results for the fraction of days (VP_{sat} - VP_{act}) exceeding 3.5 kPa was quite different for the growing seasons of chickpea and maize. In the case of chickpea, the threshold of 3.5 kPa was exceeded on only a small fraction of days except at Kermanshah. Hence, if the 3.5 kPa accurately represent the sensitivity of chickpea to VPD, then there would be little inhibition of leaf gas exchange, and hence crop growth. However, there is no data available for chickpea to document the threshold for the response of leaf gas exchange to (VP_{sat} - VP_{act}). For the maize growing season, the fraction of days on which (VP_{sat} - VP_{act}) exceeded 3.5 kPa was substantial except at Tabriz and Isfahan. These results indicate a midday inhibition of maize gas exchange would be common at Shiraz and Kermanshah.

Overall, these results indicated that there has been an increasing trend in temperature in recent years across the five locations studied in Iran. The one exception to the temperature increase was the stable T_{min} at Isfahan. This exception may be a consequence of its geographical location and elevation. The temperature increases if continued for several decades in the future have important ramifications on the possibility of increasing the rate of crop development. To maintain the current length of growing season, genetic modifications may be needed in these crops to decrease sensitivity to temperature in order to increase the length of their development periods. This is especially true for maize since the larger temperature increases tended to be during periods of maize growth. Vapor pressure changes may not be an immediate concern in crop production. While there were consistent increases in VP_{sat}, VPD_{tran} remained fairly constant over years at all locations except Isfahan. Therefore, these results at the four locations of stable VPD_{tran} indicate that crop water requirements have not changed to any great extent. Using the genotypes with breakpoint in their transpiration rate at high VPD might alleviate the deleterious effect of high VPD_{tran} on growth of rainfed crops at Isfahan. Fortunately, genetic variation has been found among genotypes of soybean (Fletcher et al., 2007; Sadok and Sinclair, 2009), sorghum (Gholipoor et al., 2010) and chickpea (data not published) for transpiration rate at higher levels of VPD. In a simulation study in Australia Sinclair et al. (2005) limited the transpiration rate of sorghum to 4 mm h^{-1} during high VPD conditions and this resulted in average yield gains of about 5-7%.

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