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Earlier winter wheat heading dates and warmer spring in the U.S. Great Plains[☆]

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Abstract

Phenological change of plants is an indication of local and regional climate change, independent of the instrumentation records and associated bias/error. Although some phenological changes have been identified for native and perennial species and used to infer climate change in various regions of the world, little has been known for changes in agricultural plants/crops. In this study, heading or flowering dates of winter wheat cultivar Kharkof are examined from 70 years of data at six locations in the U.S. Great Plains. Results indicate a consistent trend of earlier heading or flowering dates across all sites, but rates of the trend differ (from 0.8 to 1.8 days per 10-year). Because the heading or flowering date is governed primarily by temperatures, the earlier heading or flowering dates indicate warming temperatures in the spring. Further examinations reveal increase in spring daily minimum temperatures. Findings of this study add a diverse species to the plant community for detecting the ''fingerprint'' of regional and global climate change.

Keywords: Plant phenology; Winter wheat heading date; Temperature; Climate change; U.S. Great Plains

1. Introduction

There is a general consensus among scientists that increased atmospheric greenhouse gases have caused increased surface temperatures (Houghton et al., 2001). While greenhouse gases can be accurately measured following established protocols, it is much more difficult to discern the temperature change signal. Direct measurement of the temperature change can be corrupted by changes in sensors, sensor calibration, station location, environment around station, observer, variable observing times, and problems associated with quality control and archiving the data (e.g., Lin and Hubbard, 2004; Weiss and Hays, 2005). Physical (e.g., melting glaciers, rising in sea level, decreased periods of permafrost) and/or biological surrogates can be used to determine the temperature change, as these natural phenomena integrate the environment (Spano et al., 1999; Post et al., 2001; Peñuelas and Filella, 2001; Walther et al., 2002; Jump and Peñuelas, 2005). However, the surrogate responses must be understood to ensure that the response is related to temperature and not confounded by another factors/causes.

A biological surrogate is the plant phenology—the timing of important developmental stages in the life cycle of a plant. Plant phenology is governed mainly by temperature and may be modified by photoperiod and

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vernalization. If warmer than normal temperatures occurs up to an optimal temperature for plant development, the plant would develop at a grater rate and would reach a new developmental stage on an earlier date. (If there is a temperature change that is greater than this optimal temperature, then this change is probably no longer a subtle change and surrogates are not needed.) Thus, a persistent earlier occurrence of a development stage of a plant would indicate a rise of temperature from its previous value.

Phenological changes in native and perennial plant species have been used to quantify changes in temperature at various locations across the continents (Walther et al., 2002; Fitter and Fitter, 2002; Root et al., 2003; Parmesan and Yohe, 2003; Chuine et al., 2004). Walther et al. (2002) listed numerous plant species that have shown flowering and leaf unfolding 1–2 days per decade earlier in Europe and in North America. Fitter and Fitter (2002) identified 15 genera of British annuals and perennials showing earlier flowering date in the recent decades. Few research efforts have evaluated changes in phenology of agricultural crops, however. One reason for not using agricultural crops in this type of evaluations is that the planted cultivars are constantly changing to meet yield demands. Thus, changes in phenology might be due to changes in the genetics of the new cultivars, as well as to temperature. However, if the same cultivar was planted over many years at several locations, analysis of phenological data of the cultivar could provide a measure of temperature change. In this effort, the heading or flowering date of winter wheat (*Triticum aestivum* L.) at six locations along a north–south transect of the U.S. Great Plains hard red winter wheat region (Fig. 1) will be evaluated as a surrogate for temperature change. The techniques used in this study can be employed with other long-term records of phenology of agricultural crops to detect the ‘‘fingerprint’’ of regional climate change.

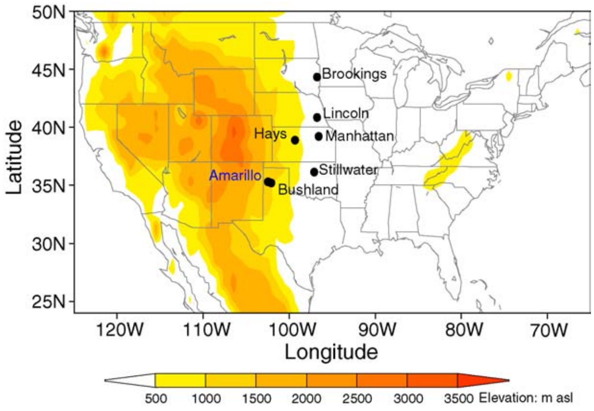

Fig. 1. Geographical distribution of the study locations. Location of Amarillo weather station also is marked. The shading shows the terrain elevation with the scale shown below the figure.

2. Materials and methods

The heading or flowering dates of the winter wheat cultivar Kharkof grown under rainfed conditions in several long-term experiments were used in this study. Heading date was recorded when the head (spike) on 50% of the wheat plants had completely emerged from the flag leaf. Flowering date was recorded when 50% of the heads (spikes) had extruded anthers, i.e., the beginning of the reproductive phase. The protocol for these long-term experiments required that plants were sown at the optimal sowing dates and plant population densities for each location. Data of the heading dates were collected from five locations in the U.S. Great Plains: Brookings, SD; Hays and Manhattan, KS; Stillwater, OK; Bushland, TX, and flowering dates were collected at Lincoln, NE (Fig. 1 and Table 1). The period of record for these locations ranged from 1935 to 2004, although for each location, there are varying amounts of missing data; eight missing observations at Hays, KS; 10 at Stillwater, OK; 14 at Bushland, TX; 18 at Manhattan, KS; 24 at Lincoln, NE; and 21 at Brookings, SD.

If the temperature pattern during the winter wheat growing season is similar over many growing seasons, the same cultivar should show the similar phenology and similar heading dates in each growing season. Changes in the heading or flowering date would indicate changes in the spring temperatures. When evaluating changes of the heading or flowering date and its relationship with temperatures there are several potential uncertainties in the heading or flowering date data that must be addressed; genetic modifications of a cultivar, sowing date differences, seeding rate, fertilizer, and short-term weather and climate fluctuations. These concerns are addressed in the following paragraphs in

Table 1
Name, elevation, latitude, and longitude of study locations and data range at each location

Location name	Elevation (m)	Latitude (°N)	Longitude (°W)	Data range
Brookings	500	44.32	96.77	1957–2004
Manhattan	325	39.20	96.58	1935–2001
Hays	613	38.87	99.33	1936–2004
Stillwater	273	36.12	97.10	1935–2004
Bushland	1164	35.18	102.08	1940–2004
Lincoln	357	40.83	96.77	1935–2004

order to establish the use of these heading or flowering date data to evaluate changes in air temperatures.

Like all wheat, Kharkof is a self-pollinated, inbred line. This reproductive process helps the cultivar maintain stable genetics and reduce the variability in characteristic, including phenology from generation to generation. Of course there is the possibility that Kharkof may have been subjected to some genetic changes over time or among locations (through distribution). For example, Kharkof was introduced from Russia to the United States more than once in the last century (http://www.ku.edu/carrie/texts/carrie_books/malin/16.html) and a Canadian cultivar also was released as a selection of Kharkof (Klinck and Grant, 1964). Such changes are unlikely to cause persistent trends of changes in the heading date, however. With stable populations of the cultivar in a region, gradual and persistent heading date change should largely result from changes in the growing environment.

The sowing date of winter wheat will have little influence on the heading or flowering date, assuming that the sowing date falls within the range of acceptable sowing dates for a region. The reason that sowing date does not influence heading or flowering date is that the wheat plant will have been exposed to sufficiently low temperatures to be completely vernalized by the time the plant breaks dormancy in the spring. Development after vernalization (to heading or flowering and subsequent phenological stages) will be a function of temperature modified by photoperiod sensitivity of the winter wheat cultivar up to the reproductive phase and temperature thereafter. A detailed example of the influence of different sowing dates on plant development has been given in Streck et al. (2003).

Besides the sowing date, it also is reasonable to question if the seeding rates and other management factors, such as fertilizer application, may have influenced the winter wheat heading or flowering date. As elaborated by Geleta et al. (2002), the reasonable seeding rates have a steady effect on the heading date in the range of +1 and −1 days. Thus, over time the seeding rates have no noticeable net influence on the heading date. With respect to the possible effects of fertilizer application, higher soil fertility tends to increase tillering with the additional tillers being later, thus causing later heading or flowering date. Hence, the heading or flowering date is unlikely to occur earlier from improved soil fertility in recent decades.

Finally, the short-term fluctuations of local climate could cause fluctuations in the heading date. Such fluctuations are, however, unlikely to present a permanent trend in the heading or flowering date because over time heading or flowering date variations resulting from short-term climate fluctuations, e.g., droughts and wet periods, will cancel out and leave no net changes (no trend). Thus, the long-term data records of heading or flowering date used in this study will prevent short-term climate fluctuations from influencing the trend of the heading date.

The climatic data used in this study were from the National Weather Service Cooperative stations at each location, except for Bushland, TX, as it has no weather station. The data were obtained from the National Climatic Data Center and subjected to quality controls. The data for each location were maximum and minimum daily temperatures and daily total precipitation from 1935 to 2004. For Bushland, TX, observations from the nearest Coop station at Amarillo, TX, were used (Amarillo station is 35 km west of Bushland, see Fig. 1). The temperature data were analyzed for their variations and compared to winter wheat heading or flowering date at each location.

Kendall's tau slope estimator (Sen, 1968; Gilbert, 1987) was used to evaluate the trend in heading or flowering date changes of the winter wheat. This is a nonparametric method assuming no a priori distribution of variations in the given data series, and has been used frequently for trend analysis in environmental and climatic change studies (e.g., Libiseller and Grimvall, 2002; Zhai et al., 2005). The procedure is applied as follows. Suppose the time series of heading or flowering date for one site are: $x_1, x_2, \ldots, x_n$, where x_j is the heading or flowering date in jth year (converted to day of the year starting at 1 on 1 January in each year), and n is the total number years with heading or flowering date observation. Because of missing data, n is less than 70 for the study period 1935–2004. The slope or the trend of the time series is estimated by using the following procedure developed by Sen (1968):

$$Q_{j,k} = \frac{x_j - x_k}{j - k}, \quad k = 1, 2, \ldots, n-1, \text{ and } j = k+1, k+2, \ldots, n. \tag{1}$$

In Eq. (1), x_j and x_k are the heading or flowering date for year j and k, respectively.

There is a total of $n(n-1)/2$ elements of $Q_{j,k}$ and their median is the slope, or trend, of the heading or flowering date series.

The significance of the slope is tested using the Mann–Kendall statistic (Gilbert, 1987), in which we first calculate the parameter S as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sign}(x_j - x_k), \qquad (2)$$

where $\mathrm{sign}(x_j - x_k)$ is −1, 0, or +1 if $x_j - x_k$ is <0, $=0$, or >0, respectively. Then the parameter V is calculated as

$$V = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_\mathrm{p}(t_\mathrm{p}-1)(2t_\mathrm{p}+5)\right]. \qquad (3)$$

In Eq. (3), g is the number of tied groups (each tied group has the same heading date, for example, the years with the same heading date on 15 April are considered as one tied group) and t_p is the number of years in the pth tied group. From (2) and (3), the test statistic Z is calculated as

$$Z = \begin{cases} \dfrac{S-1}{[V]^{0.5}}, & \mathrm{if}\, S > 0, \\ 0, & \mathrm{if}\, S = 0, \\ \dfrac{S+1}{[V]^{0.5}}, & \mathrm{if}\, S < 0. \end{cases} \qquad (4)$$

If $|Z| > Z_{0.95} = 1.645$, the slope estimated by (1) is significant at 95% confidence level (further details of this method are given in Gilbert, 1987).

In addition to examining the individual location's heading or flowering date trend, the average trend of heading date over the five locations with heading date data was evaluated with a composite method. One advantage of this composite method is that it minimizes the missing data effects on the trend at individual locations. In this method, the years when all five locations had heading date observations were identified. Those years were: 1958, 1960, 1963, 1970, 1986, 1988, 1990, 1991, 1993 and 2001. These years were then used as reference years and their heading dates were used to calculate the mean heading date for each location. This mean heading date was different at each location, and served as a "local reference" of the heading date variation. By removing this mean heading date, a time series of heading date anomalies was obtained for each location. Because the local average heading dates were removed, the variations of heading date anomalies at different locations can now be compared. The five anomaly time series derived from this procedure were then averaged for each year to form the composite heading date anomaly series for the 70-year period. This composite series has heading date data from at least two locations for each year, free from the problem of missing data. This continuous composite heading date anomaly series was then evaluated for its trend using the same method previously described.

3. Results and discussions

Fig. 2 shows the variations and trends of the winter wheat heading or flowering dates at the six locations. At each location, the trend indicates that heading or flowering has been occurring at earlier dates, particularly after 1948. (There was apparently a tendency of delayed heading date for the data before 1948. However, it cannot be confirmed because of the short record from 1935 to 1948. Thus this analysis will focus on the period from 1948 to 2004.) In the 1948–2004 data, the heading dates were significantly earlier (Eq. (4)) at the 95% confidence level except for

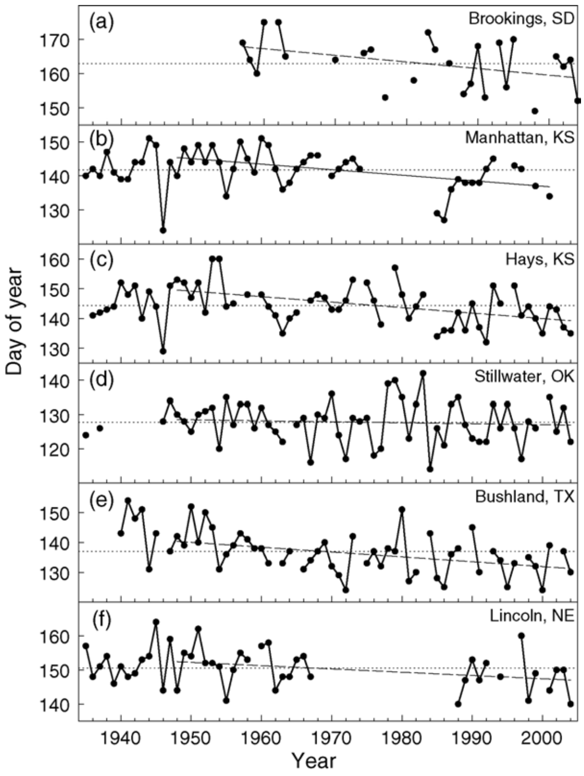

Fig. 2. (a)–(e) are time series of winter wheat heading dates (as day of year) at the five locations, and (f) shows the flowering date (as day of year) at Lincoln, NE. Dotted line in each panel shows the long-term averaged heading or flowering date, and dashed line shows the trend of the heading or flowering date change in 1948–2004.

Table 2
Mean heading date, trend of heading date change, and correlations of heading date change vs. spring season (March–May) daily minimum temperature, r (heading date, $T_{\min}$), accumulated thermal time in March–May, r (heading date, thermal time), and winter and spring (December–May) precipitation, r (heading date, Pr), for 1948–2004

Location name	Mean heading date (day of year)	Trend (days per 10-year)	r (heading date, $T_{\min}$)	r (heading date, thermal time)	r (heading date, Pr)
Brookings	162	-1.9^{*}	-0.588^{*}	-0.654^{*}	−0.03
Manhattan	142	-1.6^{*}	-0.631^{*}	-0.722^{*}	0.009
Hays	144	-1.8^{*}	-0.573^{*}	-0.636^{*}	0.242
Stillwater	128	−0.3	-0.340^{*}	-0.361^{*}	0.246
Bushland	137	-1.6^{*}	-0.487^{*}	-0.510^{*}	0.095
Lincoln	151	-1.0^{*}	-0.532^{*}	-0.785^{*}	0.192

Mean flowering date, its trend, and correlations were for Lincoln, NE.
[*] The correlation is statistically significant at 95% confidence level.

Stillwater, OK. The flowering dates in Lincoln's 1948–2004 data also were significantly earlier at the 95% confidence level (Fig. 2f). The slopes of the trend at the individual locations were summarized in Table 2. The largest heading date trend of 1.8 days per 10-year occurred at Hays, KS (which has fewer missing records than Brookings, SD, and is more reliable). At this rate, the heading date was earlier by nearly 10 days in 2004 than in 1948. The composite result for all five heading date locations depicts a significant shift to an earlier heading date in the region at an average rate of 1.5 days per 10-year since 1948 (Fig. 3).

The earlier heading or flowering dates at these locations were probably an indication of physiological responses of the winter wheat cultivar to local and regional climate change. Because temperature is the main driving force in winter wheat development (e.g., Xue et al., 2004), and because "…plant (winter wheat) growth and flowering depend on accumulated temperature …" (Peñuelas and Filella, 2001), the earlier heading or flowering date would indicate warmer temperatures in the spring.

Increases of average daily minimum temperatures have been found at all six locations for the spring season (March–May), Fig. 4. At these locations, the daily minimum temperature has been increasing at various rates since 1948. These results are consistent with findings from recent climate studies on frost and

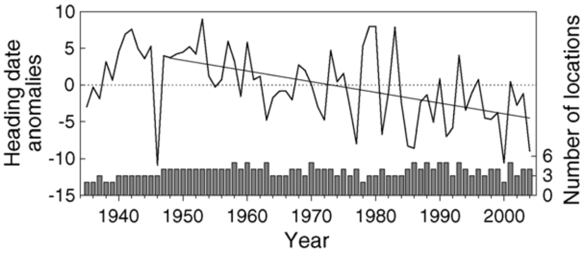

Fig. 3. Composite time series of winter wheat heading date anomaly for five locations (Fig. 2(a)–(e)). The solid line shows the trend of the change for 1948–2004. The histogram at the lower section of the figure shows number of locations whose data were used in the composite (see text for details of the composite procedure).

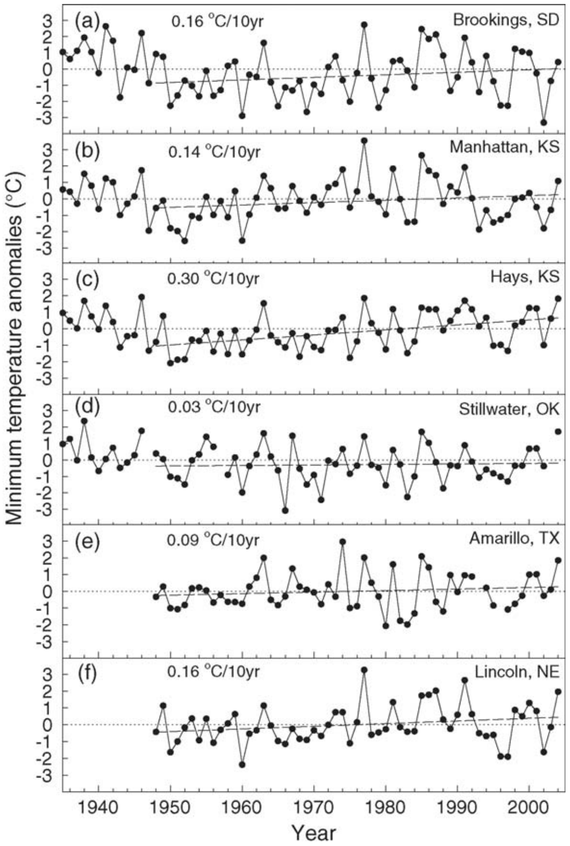

Fig. 4. Anomaly time series of spring season average daily minimum temperatures at the study locations (after the long-term mean of the entire data series at each location was removed). Temperature data from Amarillo, TX (e) were used to approximate that in Bushland, TX. The trend of the minimum temperatures change from 1948 to 2004 is shown by the dashed line and the rate of change is marked in each panel.

frost-free days in agricultural environments (e.g., Easterling, 2002; Feng and Hu, 2004). Statistically significant (at confidence level of 95%) negative correlations are shown between daily minimum temperatures and heading dates at all the locations (Table 2). Although the heading date change at Stillwater, OK, is small and insignificant, the heading date itself is significantly associated with the spring season minimum temperatures, a result suggesting weak warming in temperatures at that location compared to the others (Fig. 4). At Bushland, TX, there was a rather large and significant change of heading date since 1948, which was associated with a weak increase of minimum temperature similar to that at Stillwater, OK. This result may be partially attributed to the source of the weather data used for Bushland, TX, which was Amarillo, TX, about 35 km west of Bushland.

Daily maximum temperatures for the same period showed different trends and a less consistent relationship with the heading or flowering date changes. Specifically, daily maximum temperature increased at Bushland (0.11 °C per 10-year), Hays (0.25 °C per 10-year), Lincoln (0.30 °C per 10-year), and Manhattan (0.28 °C per 10-year), but decreased slightly at Brookings (−0.14 °C per 10-year) and Stillwater (−0.19 °C per 10-year). Different trends in daily maximum and minimum temperatures in the last century have been identified in regions across the United States and in other parts of the world (e.g., Easterling et al., 1997). Given the consistent pattern of changes in the daily minimum air temperature as contrasted with the daily maximum air temperature in relation to the winter wheat heading or flowering dates at the study locations, it is concluded that the earlier winter wheat heading or flowering date in recent decades has been associated with the increase in spring season daily minimum temperatures. Reasons for this conclusion are that increased daily minimum temperature would have reduced the number of frost days in spring and led to earlier start of growing season (see Fig. 1 in Feng and Hu, 2004). Additionally, significant increases in the daily minimum temperature and the either unchanged or slightly decreased daily maximum temperatures in the region (see Fig. 2 in Easterling et al., 1997) have resulted in increased spring season accumulations of thermal time (°C day). Accumulated thermal time is calculated as $\sum_{P_\mathrm{b}}^{P_\mathrm{e}}[0.5(T_\mathrm{max}+T_\mathrm{min})-T_\mathrm{b}]$, where P_b and P_e are the beginning and ending day of the period of interest, T_max and T_min are the daily maximum and minimum temperatures, and $T_\mathrm{b} = 0$ °C is the base temperature below which winter wheat stops growing (McMaster and Wilhelm, 1997). The significant negative correlation between heading or flowering date and accumulated thermal time strongly indicates an earlier heading or flowering date for winter wheat in this region (Table 2).

Madden and Williams (1981) and Hu and Willson (2000) detected a relationship between simultaneous changes in temperature and precipitation in our study region. This relationship raises a question about the role of precipitation and the relationship between temperature and the earlier heading or flowering date. To address this concern, the winter and spring precipitation variations and their relationship with winter wheat heading or flowering date change at each location were examined. The results were summarized in the last column of Table 2, which indicates that precipitation was not correlated with the heading or flowering date. This result and observations showing nearly unchanged precipitation in the central United States, including Nebraska and Kansas, in the last century (e.g., Hu et al., 1998) support the conclusion that the earlier wheat heading or flowering dates at our study locations were an indication of increased spring season daily minimum temperatures in recent decades.

4. Conclusions

This study examined change in the heading or flowering date of a winter wheat cultivar, Kharkof, over 70 years at six locations in the U.S. Great Plains. Results showed that the heading or flowering date of the Kharkof at six locations in the Great Plains occurred 6–10 days earlier in 2004 than in 1948. Because the heading or flowering date of winter wheat is primarily a function of spring temperatures (Xue et al., 2004), the earlier heading or flowering dates indicate warmer spring season temperatures in the region. Further analysis of temperatures showed that this heading or flowering date shift to earlier time is significantly correlated with the increase in spring season (March–May) daily minimum temperatures. Although this signal of warmer spring daily minimum temperatures is obtained from the instrumental records, the confirmation of this signal by changes in the heading or flowering date offers independent evidence for the temperature change, free of possible instrumentation biases or errors. This warming temperature signal is further supported by the result showing a trivial relationship between the heading or flowering dates and winter and spring precipitation at all the study locations. This trivial correlation with precipitation points to rising minimum daily temperatures as the sole explanation of the earlier winter wheat heading dates.

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References

Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., Ladurie, E.L.R., 2004. Historical phenology: grape ripening as a past climate indicator. Nature 432, 289–290.

Easterling, D.R., 2002. Recent changes in frost days and the frost-free season in the United States. Bull. Am. Meteor. Soc. 83, 1327–1332.

Easterling, D.R., Horton, B., Jones, P.D., Peterson, T.C., Karl, T.R., Parker, D.E., Salinger, M.J., Razuvayev, V., Plummer, N., Jamason, P., Folland, C.K., 1997. Maximum and minimum temperature trends for the globe. Science 277, 264–367.

Feng, S., Hu, Q., 2004. Changes in agro-meteorological indicators in the contiguous United States: 1951–2000. Theor. Appl. Climatol. 78, 247–264.

Fitter, A.H., Fitter, R.S.R., 2002. Rapid changes in flowering time in British Plants. Science 296, 1689–1691.

Geleta, B., Atak, M., Baenziger, P.S., Nelson, L.A., Baltenesperger, D.D., Eskridge, K.M., Shipman, M.J., Shelton, D.R., 2002. Seeding rate and genotype effect on agronomic performance and end-use quality of winter wheat. Crop Sci. 42, 827–832.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring. Van Nostrand Reinhold, New York, 320 pp.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., 2001. Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 882 pp.

Hu, Q., Willson, G.D., 2000. Effects of temperature anomalies on the Palmer Drought Severity Index in the central United States. Int. J. Climatol. 20, 1899–1911.

Hu, Q., Woodruff, C.M., Mudrak, S.E., 1998. Interdecadal variations of the annual precipitation in the central United States. Bull. Am. Meteor. Soc. 79, 221–229.

Jump, A.S., Peñuelas, J., 2005. Running to stand still: adaptation and the response of plants to rapid climate change. Ecol. Lett. 8, 1010–1020.

Klinck, H.R., Grant, M.N., 1964. Registration of Kharkov MC22 wheat. Crop Sci. 4, 235–236.

Libiseller, C., Grimvall, A., 2002. Performance of partial Mann–Kendall test for trend detection in the presence of covariates. Environmetrics 13, 71–84.

Lin, X.M., Hubbard, K.G., 2004. Sensor and electronic biases/errors in air temperature measurement in common weather station networks. J. Atmos. Oceanic Tech. 21, 1025–1032.

Madden, R.A., Williams, J., 1981. The correlation between temperature and precipitation in the United States and Europe. Mon. Wea. Rev. 106, 142–147.

McMaster, G.S., Wilhelm, W.W., 1997. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. 87, 291–300.

Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421, 37–42.

Peñuelas, J., Filella, I., 2001. Responses to a warming world. Science 294, 793–794.

Post, E., Forchhammer, M.C., Stenseth, N.C., Callaghan, T.V., 2001. The timing of life-history events in a changing climate. Proc. R. Soc. London 268, 15–23.

Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rsoenzweig, C., Alanpounds, J., 2003. Fingerprints of global warming on wild animals and plants. Nature 421, 57–60.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389.

Spano, D., Cesaraccio, C., Duce, P., Snyder, R.L., 1999. Phenological stages of natural species and their use as climate indicators. Int. J. Biometeorol. 42, 124–133.

Streck, N.A., Weiss, A., Xue, Q., Baenziger, P.S., 2003. Improving predictions of developmental stages in winter wheat: a modified Wang and Engel model. Agric. For. Meteorol. 115, 139–150.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesank, C., Beebee, T.J.C., Fromentin, J.-M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416, 389–395.

Weiss, A., Hays, C.J., 2005. Calculating daily mean air temperatures by different methods: implication from a nonlinear algorithm. Agric. For. Meteorol. 128, 57–65.

Xue, Q.W., Weiss, A., Baenziger, P.S., 2004. Predicting phenological development in winter wheat. Climate Res. 25, 243–252.

Zhai, P., Zhang, X., Wan, H., Pan, X., 2005. Trends in total precipitation and frequency of daily precipitation extremes over China. J. Climate 18, 1096–1108.