Assessing satellite-based start-of-season trends in the US High Plains

X Lin¹, K G Hubbard², R Mahmood³ and G F Sassenrath¹,⁴

¹ Kansas State University, Department of Agronomy, Manhattan, Kansas, USA
² University of Nebraska-Lincoln, School of Natural Resources, Lincoln, Nebraska, USA
³ Western Kentucky University, Department of Geography and Geology, Bowling Green, Kentucky, USA
⁴ Southeast Agricultural Research Center, Parsons, Kansas, USA

E-mail: xlin@ksu.edu

Received 20 May 2014, revised 19 August 2014
Accepted for publication 26 September 2014
Published 20 October 2014

Abstract
To adequately assess the effects of global warming it is necessary to address trends and impacts at the local level. This study examines phenological changes in the start-of-season (SOS) derived from satellite observations from 1982–2008 in the US High Plains region. The surface climate-based SOS was also evaluated. The averaged profiles of SOS from 37° to 49°N latitude by satellite- and climate-based methods were in reasonable agreement, especially for areas where croplands were masked out and an additional frost date threshold was adopted. The statistically significant trends of satellite-based SOS show a later spring arrival ranging from 0.1 to 4.9 days decade⁻¹ over nine Level III ecoregions. We found the croplands generally exhibited larger trends (later arrival) than the non-croplands. The area-averaged satellite-based SOS for non-croplands (i.e. mostly grasslands) showed no significant trends. We examined the trends of temperatures, precipitation, and standardized precipitation index (SPI), as well as the strength of correlation between the satellite-based SOS and these climatic drivers. Our results indicate that satellite-based SOS trends are spatially and primarily related to annual maximum normalized difference vegetation index (NDVI, mostly in summertime) and/or annual minimum NDVI (mostly in wintertime) and these trends showed the best correlation with six-month SPI over the period 1982–2008 in the US High Plains region.

Keywords: spring phenology, satellite, start-of-season, surface climate, trends, land use

1. Introduction
Numerous studies have documented the effects of recent climate change on the plant phenological indicator by using surface-based phenological data (Linderholm 2006, Schwartz and Hanes 2009, Schwartz et al 2013), satellite data (Zhang et al 2007, White et al 2009, de Jong et al 2011), and surface climate data (Frich et al 2002, de Beurs and Henebry 2008, Ault et al 2011). For North America, studies have reported trends toward earlier spring blooming (e.g. Schwartz et al 2006) and an increase in thermal growing season length (e.g. Frich et al 2002 ) based on daily climate observations from the 1950s to the 2000s. White et al (2009) reported ten satellite-based ‘start of season’ (SOS) measures for inter-comparison, interpretation, and assessment of spring phenology in North America from 1982 to 2006. Thus, understanding whether or not vegetation phenology trends have changed in response to climatic drivers can help us to better understand the future dynamics of vegetation phenology in a changing climate.

Vegetation phenology can be highly sensitive to climate variability and change (Schwartz et al 2006, Richardson et al 2013), and hence, may be a good indicator of changes in climatic drivers. For example, long-term data indicate increased normalized difference vegetation index (NDVI) trends (‘greening’) in cold arctic tundra (Goetz et al 2005, Verbryla 2008) and semi-arid areas across the globe (Fensholt et al 2012). On the other hand, some regions, including Chilean semi-arid zones, reported a decreased NDVI trend.
(‘browning’, Baldi et al. 2008). In North America such a ‘browning’ phenomenon has been associated with increasing drought stress (Beck and Goetz 2011). This research has also demonstrated a mismatch between the surface climate trends and satellite-based NDVI trends (greening or browning) in some regions. This mismatch could result from human activities, difficulties in extracting a clear satellite-based signal to match climate forcing (White et al. 2005), satellite instrument bias or bias introduced during satellite data corrections (Verbyla 2008, Alcaraz-Segura et al. 2010), different data analysis methods (de Jong et al. 2011), and different ecosystem responses (Goetz et al. 2005, Cleland et al. 2006, Beck and Goetz 2011).

In the northern hemisphere, satellite imagery indicates the SOS has become progressively earlier by 5.4 days and the end of season (EOS) has been delayed by 6.6 days from 1982 to 2008 (Jeong et al. 2011), which is consistent with an overall warming climate over the northern hemisphere. Although significant on hemispheric scales, few studies have been conducted to investigate the cause of SOS mismatch between surface climate and satellite data on a sub-regional scale for the spatial heterogeneity of spring phenology. One study noted, for example, a delayed SOS in the eastern areas of the US High Plains region (in figure 14, White et al. 2009). Another study found that earlier arrivals of SOS slowed down around 40°N latitude and the time of SOS between 35°N and 40°N may have gradually changed from earlier to later during the period from 1982 to 2005 (Zhang et al. 2007). These diverse responses of spring phenology to changes of climatic drivers (Cleland et al. 2006, Zhang et al. 2007, White et al. 2009) motivated us to study the satellite-based SOS trends in the US High Plains, where the land cover is dominated by grasslands and croplands.

The objective of this study is to assess the SOS trends detected by satellite from 1982–2008 in the US High Plains region. For this purpose, we used the satellite biweekly NDVI data to derive the SOS time series. The surface climate observations were then trimmed to the same time series interval for a trend and correlation analysis for climate- and satellite-based phenological indicators in the US High Plains.

2. Data and methods

2.1. Satellite and climate data

The study area extended from −104° to −94.5°W and 37° to 49°N, covering most of the US High Plains region including the states of North Dakota (ND), South Dakota (SD), Nebraska (NE), Kansas (KS), and part of Colorado (CO) (figure 1). The satellite data is the 8 km (64 km² pixels) 15-day composited 1982–2008 NDVI data, obtained from the Global Inventory Modeling and Mapping Studies (GIMMS), Advanced Very High Resolution Radiometer NDVIg dataset (Pinzon et al. 2005). Finer resolution and longer time period (up to current) datasets are also available but, within- and among-sensor corrections (White et al. 2009, Jeong et al. 2011) for robust assessments are a known impediment, rendering the 8 km resolution date product more desirable for accurate analysis and interpretation.

The climate data were obtained from a total of 112 high-quality surface climate stations (figure 1(a)) selected from the US Historical Climatological Network (USHCN) as described in Hubbard and Lin (2006), and Menne and Williams (2009). These data include monthly and daily maximum and minimum temperatures and precipitation. The standardized precipitation index (SPI) was calculated from the monthly USHCN precipitation data according to the procedure developed by Mckee et al. (1993). The daily climate data quality was assured using the following criteria: (1) outliers in daily mean and minimum temperatures were identified as those that were more than 3.5 standard deviations away from the climatological mean temperature for the day (Frich et al. 2002); (2) since the SOS is an annual index, a year was considered missing in a station record if one station contained more than 15 missing daily values (about 4% missing) in a year; and (3) daily homogeneity of temperature observations was visually assessed because the automated detection of daily homogeneity for a station series has met with limited success (Menne and Williams 2009).

The 112 USHCN stations selected are located in nine Level III ecoregions (figure 1(a)) (Omernik 1987). The classification of Level III ecoregion includes Northern Glaciated Plains (ECO46, 17 USHCN stations, hereafter only numbers of stations are described), Northwestern Glaciated Plains (ECO42, 7), Northwestern Great Plains (ECO43, 13), Nebraska Sand Hills (ECO44, 6), Western Corn Belt Plains (ECO47, 17), Central Great Plains (ECO27, 29), High Plains (ECO25, 14), Flint Hills (ECO28, 3), and Central Irregular Plains (ECO40, 6) (figure 1(a)). The MODIS Land Cover product (MOD12Q1) in 2005 was used (Friedl et al 2010) for masking out the cropland for determining SOS trends without croplands. The croplands and grasslands cover 42% and 51% of the US High Plains area in this study, respectively (figure 1(b)).

2.2. Methods

The algorithm for determining satellite-based SOS dates used in our study is the Midpoint_pixel method, which is one of the most reliable of 10 methods for comparing long-term surface phenological data (White et al. 2009). It is found that this method achieved 65% acceptable SOS retrievals, correlations greater than 0.6, low offsets or biases, and regression slope near 1 (White et al. 2009, de Jong et al. 2011). The Midpoint_pixel method is a local threshold method in which the SOS dates are determined as the time at which NDVI exceeds a locally tuned threshold for each pixel. The locally tuned threshold is determined from the annual maximum and minimum NDVIs (NDVI max, NDVI min) in a sub-daily (half-day resolution) time series, obtained from a cubic smoothing spline interpolation (White et al. 2009). The NDVI max and NDVI min are calculated using a 7-day moving average window (i.e. 14 half-day resolution data points). When both NDVI max and NDVI min are determined, the middle point of
NDVI_{max} and NDVI_{min} earlier than NDVI_{max} date is the SOS date (more details in White et al. 2009).

There are a number of approaches for calculating the climate-based SOS (Walther and Linderholm 2006). We selected a ‘5C5D’ method in the calculation (Frich et al. 2002). The 5C5D method defines climate-based SOS as the date when mean air temperatures exceed 5 °C for more than five consecutive days (Frich et al. 2002). We then used an additional requirement for modifying the 5C5D method to incorporate the frost date criterion (5C5DFROST, adapted from Jones et al. 2002). Under this criterion, the five-day period indicative of SOS had to occur after the last frost in spring, where the frost date is defined as the date at which the daily minimum temperature falls below 0 °C.

The satellite-based SOS dates are calculated pixel by pixel and the climate-based SOS dates are calculated station by station. To compare satellite-based with climate-based SOS trends in a spatial domain, the climate-based SOS dates were interpolated from individual station data into 0.5° × 1.0° grids in latitude and longitude. For the SOS trend analysis, the serial autocorrelation remains an issue with the use of linear regression models (de Jong et al. 2011). The linear regression spuriously inflates the power of the significance test (Wilks 2006), making it challenging to delineate statistically significant changes (de Jong et al. 2011). To address this concern and improve the robustness of the analysis, the non-parametric Mann–Kendall method (Wilks 2006) was selected for evaluating the statistical significance of all temporal SOS trends at the 95% confidence level. This method can also accommodate data that are not normally distributed and is not sensitive to outliers. In addition, a Pearson’s correlation measure was used for evaluating correlations at the 95% confidence level.

3. Results and discussion

3.1. SOS profiles

The average SOS profiles calculated from satellite-based and climate-based methods are shown in figure 2. The variations of climate-based SOS dates were smaller than that of satellite-based SOS for both non-croplands (figure 2(a)) and croplands (figure 2(b)). The satellite-based SOS dates were clearly closer to the 5C5DFROST profiles across the study area especially for non-croplands in the US High Plains (figure 2). This is closer agreement than the comparison results from various satellite-based SOS methods reported by White et al. (2009). This finding suggests that the SOS from the Midpoint_{pixel} and 5C5DFROST methods are in reasonable agreement for the US High Plains on a sub-regional scale, especially when masking out croplands.

The standard deviations of satellite-based SOS for non-croplands (i.e. mostly grasslands) were smaller than that of croplands (figure 2). This result suggests that satellite-based SOS dates for croplands have larger longitudinal variations than grasslands. This may be...
attributable to different numbers of spatial samples (figure 1(b)) but it more likely occurs because the native grasslands are relatively homogenous in terms of phenological responses to changes of climatic drivers and soil textural conditions.

Generally, the satellite-based SOS dates were slightly earlier than the SOS dates detected by the 5C5DFROST method in non-croplands (figure 2(a)). However, for croplands only, the satellite-based SOS dates were later than SOS dates by 5C5DFROST except for Kansas (figure 2(b)). The most likely attributions to this inconsistent behavior are differences in changes of land use and cropping systems. For example, winter wheat and pasture in Kansas begin growth initiation and green-up around 4 °C. In contrast, corn or soybean begin growth around 10 °C, with much less vegetative material at planting than over wintering crops and pasture, creating an apparent delay in the SOS calculated from satellite in Nebraska. Since agricultural production in the Dakotas is primarily rainfed summer crops, there was close correspondence between the satellite and the 5C5DFROST SOS dates. Therefore, satellite-based SOS dates in the US High Plains croplands may be due in part to confounding factors such as alterations in cropping systems, production management choices, and land use changes at sub-regional scales.

3.2. Satellite-based SOS trends versus climate-based SOS trends

To examine the trends of phenological changes from 1982 to 2008, statistically significant trends (at 95% confidence levels) from both satellite-based SOS and the 5C5DFROST method are compared (figure 3(a)) (all displayed trends are statistically significant) and; 3(b) (only statistically significant at four stations, indicated by pink boxes)). Our results showed the spatial pattern of SOS trends were similar to those trend patterns observed in White et al 2009, in which a linear regression model was used. Clearly, the satellite-based SOS has trended toward later in most of the ECO46 and ECO47 regions, with the ecoregion averages of 4.9 and 2.5 days decade⁻¹, respectively. It is clear that these satellite-based SOS trends toward later in the season were mostly located in the croplands (figures 3(a) and 1(b)).

Less significant trends toward later SOS on average were observed in the Great Plains ECO43, Nebraska Sandhills EC44, and ecoregions in Kansas (figure 3(a)); all of these ecoregions are mostly covered by grasslands. It should be noted that ecoregion averages may suffer from statistical scaling issue (figure 3(a)) due to a considerable latitudinal gradient. Our results from individual pixel trends support...
Figure 3. (a) All statistically significant satellite-based SOS trends (days per decade) from 1982–2008 for Level III ecoregions and zero or non-significant trends are white. The area-averaged satellite-based SOS trends by ecoregions (indicated by numbers in each region) are: 4.9 (ECO46), 1.5 (ECO42), 0.3 (ECO43), 1.1 (ECO44), 2.5 (ECO27), 1.8 (ECO27), 1.9 (ECO25), 0.28 (ECO28), and 0.1 (ECO40) days per decade. (b) All climate-based SOS trends (days per decade) from 1982–2008 but only four of the stations were statistically significant (pink boxes).

Figure 4. Area-averaged time series of satellite-based SOS (in red) and climate-based SOS by 5C5D_{FROST} method (in black) for (a) non-croplands and (b) croplands in the US High Plains region. The only statistically significant trend of 4.8 days per decade ($p = 0.008$) was detected in the satellite-based SOS time series for croplands among all four area-averaged time series. The $r$ values shown in the right corners along with its $p$ value are correlation coefficients between satellite-based SOS and climate-based SOS by 5C5D_{FROST} method.
findings of average SOS profiles shown in figure 2. Most of the croplands showed a significantly delayed SOS trend (later arrival) by satellite in terms of trend magnitudes. However, the grasslands for the most part showed no significant SOS trends (figure 3(a)).

For the climate-based SOS trends using 5C5D FROST method, the SOS time series showed a statistically significant delay (later arrival) at only four stations across all ecoregions (figure 3(b)). Some stations showed earlier spring arrivals, especially in the eastern areas, but they were not statistically significant in terms of the non-parametric statistics. It should be noted that our 27-year study in the US High Plains region is shorter in length than previous research by Frich et al (2002) and Schwartz et al (2006) for climate-based SOS. Their research demonstrated physical environmental responses towards overall warming trends with an earlier SOS over a larger geographic scale, such as global or hemispherical.

The US High Plains region is unique in terms of satellite-based SOS, with a delayed SOS (figure 3(a)). Figure 4 showed four area-averaged time series of satellite-based SOS and climate-based SOS by 5C5D FROST method for non-croplands (after masking croplands) (figure 4(a)) and croplands (figure 4(b)) from 1982 to 2008. For croplands, only satellite-based SOS time series exhibited a statistically significant delayed trend (later arrival, $p$ value of 0.008) but climate-based SOS time series was not statistically significant. Part of this later arrival of SOS in croplands (figure 4(b)) could be related mainly to changes in cropping systems and land management practices (Mahmood and Hubbard 2002, Mahmood et al 2006). In addition, this ‘delayed spring’ occurred in croplands was not statistically correlated with the climate-based SOS ($r=0.34$ and $p=0.08$) (figure 4(b)). In contrast to croplands’ SOS trends, two area-averaged SOS time series for grasslands showed no statistically significant trends and the correlation ($r=0.37$ and $p=0.05$) between satellite-based SOS and climate-based SOS became statistically significant (figure 4(a)).

3.3. Satellite-based SOS trend related to climatic drivers

Changes in monthly average temperatures, precipitation and drought index from 1982 to 2008 were displayed for each station to examine these climatic drivers in relation to SOS trends and variations (figures 5 and 6). Few stations showed statistically significant warming or cooling trends from January to May (figures 5(a)–(e)). A correlation between the satellite-based SOS and monthly average temperatures showed no significant relationship. Similarly, there were no significant correlations evident between monthly precipitation and satellite-based SOS (figures 5(f)–(j) for trends, correlations not shown). In addition, six-month averages of temperature and precipitation were not significantly correlated with satellite-based SOS (not shown).

To further explore any possible impacts of climatic drivers on the satellite-based SOS, the multi-scale (1–8 month) SPIs were calculated and assessed in relationship to the satellite-based SOS. Unlike the strong correlations between NDVI and three-month SPI in the High Plains region found by Ji and Peters (2003), our results indicate that the six-month SPI (SPI6) had the highest correlation to the satellite-based
SOS (figure 6), although only 14 out of 112 stations showed statistically significant correlations between the two. The SPI6 trends (SPI6 value per decade) indicated a tendency towards increasing dryness from 1982 to 2008 (see the trend histogram in figure 6(a)). Again, these trends were not significant. Negative correlations in figure 6(b) suggest that when SPI6 decreased (became drier), the satellite-based SOS dates were delayed (later spring arrivals).

To further assess the satellite-based SOS trends (figure 3(a)), trends of both annual NDVI\textsubscript{max} and NDVI\textsubscript{min} time series obtained from the Midpoint\textsubscript{pixel} method were examined (figures 7(a) and (b)). The spatial pattern of satellite-based SOS trends (figure 3(a), earlier arrival or later arrival) was similar to the annual NDVI\textsubscript{max} trends (figure 7(b), greening or browning). When the NDVI\textsubscript{max} had a positive trend (greening at timing of NDVI\textsubscript{max} in the season, figure 7(b)), for example in the croplands (or in ECO\textsubscript{46}, Nebraska areas of ECO\textsubscript{17}, and ECO\textsubscript{27}), the satellite-based SOS was trending towards earlier (figure 3(a)). On the other hand, when the NDVI\textsubscript{min} had a positive trend, (greening at timing of NDVI\textsubscript{min} in the season, figure 7(a)), for example in the grasslands (or in ECO\textsubscript{43} and Sandhills ECO\textsubscript{44}), the satellite-based SOS was slightly and sparsely trending toward later or trending earlier (figure 3(a)). This result indicates that the satellite-based SOS trends (either earlier or later) are much better correlated with summertime and wintertime greenness (NDVI values) (figures 7(c) and (d)). The statistically significant correlation coefficients between NDVI\textsubscript{max} or NDVI\textsubscript{min} and satellite-based SOS were higher, up to 0.9, indicating that the summertime NDVI or wintertime NDVI values were primarily related to satellite-based SOS dates detected from 1982–2008 in the US High Plains region.

4. Summary and conclusion

The SOS dates calculated using satellite-based Midpoint\textsubscript{pixel} and the 5C5DFROST methods are in reasonable agreement for the US High Plains region on a statewide scale, especially for areas after masking out the croplands. The SOS difference (earlier or later) between satellite-based and 5C5DFROST on a state-wide scale depends at least in part on confounding factors such as cropping systems and land management. Winter grains green-up as soon as temperatures approach 5 °C. Soybean and corn, however, do not green-up until after planting and emergence (around 10 °C). The vegetative canopy of row crops also take more time to develop and cover the ground because of wider row spacing and less dense plant populations compared to grasses. Use of earlier-maturing varieties and changes of planting dates could further impact the satellite-based SOS. Thus, the satellite-based SOS signals are impacted by land management decisions such as what crops are grown and when they are planted.

The short time period of satellite observations relative to the climate drivers may limit their use in developing realistic and accurate correlations to study long-term warming trends. While more than 100 year climatological records clearly demonstrate long-term warming trends in the US High Plains region, the shorter length of time that satellite observations have provided region-wide NDVI data may lead to some inconsistencies due to spatial heterogeneity for spring pheno-ology (Schwartz et al 2006, Beck and Goetz 2011). This is despite the fact that we used the longest available consistent satellite observation in this study for interpreting anthropogenic warming responses to spring phenology at the Level III ecoregion. Unlike the relationship between satellite NDVI and climatic variables found in previous studies (Ji and Peters 2003, Richardson et al 2013), the satellite-based SOS in our study area did not have a strong relationship with the same period of temperatures and precipitation. The six-month SPI presented the best but still weak correlation with satellite-based SOS among multi-scale SPIs from 1–8 months. The six-month SPI had the highest correlation with the satellite-based SOS for spring owing to impacts of water deficit on the vegetation and the associated lag in the spring phenology. Finally, changes of annual NDVI\textsubscript{max} (mostly in summertime) and NDVI\textsubscript{min} (mostly in wintertime) were correlated to the statistically significant satellite-based SOS trends in the US High Plains regions over 1982–2008. The increase of annual NDVI\textsubscript{max} was positively, spatially, and statistically significantly correlated to satellite-based SOS dates towards later
arrival in our study area for croplands. The satellite-based SOS dates in non-croplands showed positive and significant correlation with changes of annual NDVI\textsubscript{min}. Changes in the integration of precipitation (wet or dry), temperature (warm or cool), irrigation, land use, or land management play important roles in assessing phenological changes in our study area (Mahmood and Hubbard 2002, Adegoke \textit{et al} 2003, Goetz \textit{et al} 2005, Mahmood \textit{et al} 2006, 2008, 2013). These issues will be addressed in our future research to assess the importance of various factors on the observed changes in light of the underlying physical mechanisms (Pielke \textit{et al} 1998, Mahmood \textit{et al} 2004, White \textit{et al} 2005, Schwartz and Hanes 2009, Beck and Goetz 2011, Richardson \textit{et al} 2013). We hope to reassess satellite-based phenological indicator trends when longer-term time series become available.

Acknowledgements

This work was supported by the NOAA, Office of Global Program, Climate Change Data and Detection Element under grant NA06OAR4310110 and the USDA/Agricultural Research Service (Ogallala Aquifer Initiative). The authors thank Dr Mark Schwartz at the University of Wisconsin-Milwaukee, Dr Jesse Brown at the US Geological Survey, and Dr Molly Brown at the NASA Goddard Space Flight Center for their help in obtaining continental GIMMS data.

Figure 7. (a) Statistically significant trends (units: NDVI per decade) for annual NDVI\textsubscript{min}; (c) statistically significant correlations (unitless) between annual NDVI\textsubscript{min} and the satellite-based SOS. The same for (b) and (d) but for the annual NDVI\textsubscript{max}.
from 2007 and 2008. This manuscript is contribution no. 15-101-J from the Kansas Agricultural Experiment Station.

References

Adegoke O A et al 2003 Impact of irrigation on midsummer surface fluxes and temperature under dry synoptic conditions: a regional atmospheric model study of the US High Plains Mon. Weather Rev. 131 556–64
Alcaraz-Segura D et al 2010 Debating the greening versus browning of the North American boreal forest: differences between satellite datasets Glob. Change Biol. 16 760–770
Ault T R et al 2011 Northern hemisphere modes of variability and the timing of spring in Western North America J. Clim. 24 4003–14
Baldi G et al 2008 Long-term satellite NDVI data sets: evaluating their ability to detect ecosystem functional changes in South America Sensors 8 5397–425
Beck P S and Goetz S J 2011 Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences Environ. Res. Lett. 6 045501
Cleland E E et al 2006 Diverse responses of phenology to global changes in a grassland ecosystem Proc. Natl. Acad. Sci. USA 103 13740–4
de Beurs K M and Henenby G M 2008 Northern annular mode effects on the land surface phenologies of Northern Eurasia J. Clim. 21 4257–79
de Jong R et al 2011 Analysis of monotonic greening and browning trends from global NDVI time-series Remote Sens. Environ. 115 692–702
Fensholt R et al 2012 Greenness in semi-arid areas across the globe 1981–2007—an Earth observing satellite based analysis of trends and drivers Remote Sens. Environ. 121 144–58
Frich P L et al 2002 Observed coherent changes in climatic extremes during the second half of the twentieth century Clim. Res. 19 193–212
Friedl M A et al 2010 MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets Remote Sens. Environ. 114 168–82
Goetz S J et al 2005 Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance Proc. Natl. Acad. Sci. 102 13521–5
Hubbard K G and Lin X 2006 Reexamination of the effects of instrument change in the US historical climatology network Geophy. Res. Lett. 33 L15710
Jeong S-J et al 2011 Phenology shifts at start versus end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008 Glob. Change Biol. 17 2385–99
Ji L and Peters A J 2003 Assessing vegetation response to drought in the northern great plains using vegetation and drought indices Remote Sens. Environ. 87 85–98
Jones P D et al 2002 Relationships between circulation strength and the variability of growing-season and cold-season climate in northern and central Europe The Holocene 12 643–56
Linderholm H W 2006 Growing season changes in the last century Agric. Forest Meteorol. 137 1–14
Mahmood R et al 2006 Impacts of irrigation on 20th century temperature in the Northern Great Plains Glob. Planet. Change 54 1–18
Mahmood R and Hubbard K G 2002 Anthropogenic land use change in the North American tall grass-short grass transition and modification of near surface hydrologic cycle Clim. Res. 21 83–90
Mahmood R, Hubbard K G and Carlson C 2004 Modification of growing season surface temperature records in the Northern great plains due to land use transformation: verification of modeling results and implications for global climate change Int. J. Climatol. 24 311–27
Mahmood R, Hubbard K G, Leeper R and Foster S A 2008 Increase in near surface atmospheric moisture content due to land use changes: evidence from the observed dew point temperature data Mon. Weather Rev. 136 1554–61
Mahmood R, Keeling T, Foster S A and Hubbard K G 2013 Did irrigation impact 20th century temperature in the high plains aquifer region? Appl. Geogr. 38 11–21
McKee T B, Doeskin N J and Kleist J K 1993 The relationship of drought frequency and duration to time scales Proc. 8th Conf. on Applied Climatology (17–22 January 1993) (Boston, MA: American Meteorological Society) pp 79–84
Menne M J and Williams C N 2009 Homogenization of temperature series via pairwise comparisons J. Clim. 22 1700–17
Omernick J M 1987 Ecoregions of the conterminous United States Map (scale 1:7 500 000) Ann. Assoc. Am. Geogr. 77 118–25
Piecik R A et al 1998 Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate Glob. Change Biol. 4 461–75
Pinzon J, Brown M E and Tucker C J 2005 EMD correction of orbital drift artifacts in satellite data stream The Hilbert-Huang Transform and its Applications ed N Huang and S Shen (Singapore: World Scientific)
Richardson A D et al 2013 Climate change, phenology, and phenological control of vegetation feedbacks to the climate system Agric. For. Meteorol. 169 156–73
Schwartz M D, Ault T R and Betancourt J L 2013 Spring onset variations and trends in the continental United States: past and regional assessment using temperature-based indices Int. J. Climatol. 33 2917–22
Schwartz M D and Hanes J M 2009 Intercomparing multiple measures of the onset of spring in eastern North America Int. J. Climatol. 30 1614–26
Schwartz M D, Ahas R and Aasa A 2006 Onset of spring starting earlier across the Northern hemisphere Glob. Change Biol. 12 343–51
Verbyla D 2008 The greening and browning of Alaska based on 1982–2003 satellite data Glob. Ecol. Biogeogr. 17 547–55
Walther A and Linderholm H W 2006 A comparison of growing season indices for the greater baltic area Int. J. Biometeorol. 51 107–18
White et al 2005 A global framework for monitoring phenological responses to climate change Geophys. Res. Lett. 32 L04705
White M A et al 2009 Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982 to 2006 Glob. Change Biol. 15 2335–59
Wilks D S 2006 Statistical Methods in the Atmospheric Sciences 2nd edn (International Geophysics Series) (New York: Academic) vol 91
Zhang X, Tarpley D and Sullivan J T 2007 Diverse responses of vegetation phenology to a warming climate Geophys. Res. Lett. 34 L19405