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

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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, Verbyla 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 km^2 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 data 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 (ECO_{46}, 17 USHCN stations, hereafter only numbers of stations are described), Northwestern Glaciated Plains (ECO_{42}, 7), Northwestern Great Plains (ECO_{43}, 13), Nebraska Sand Hills (ECO_{44}, 6), Western Corn Belt Plains (ECO_{47}, 17), Central Great Plains (ECO_{27}, 29), High Plains (ECO_{25}, 14), Flint Hills (ECO_{28}, 3), and Central Irregular Plains (ECO_{40}, 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

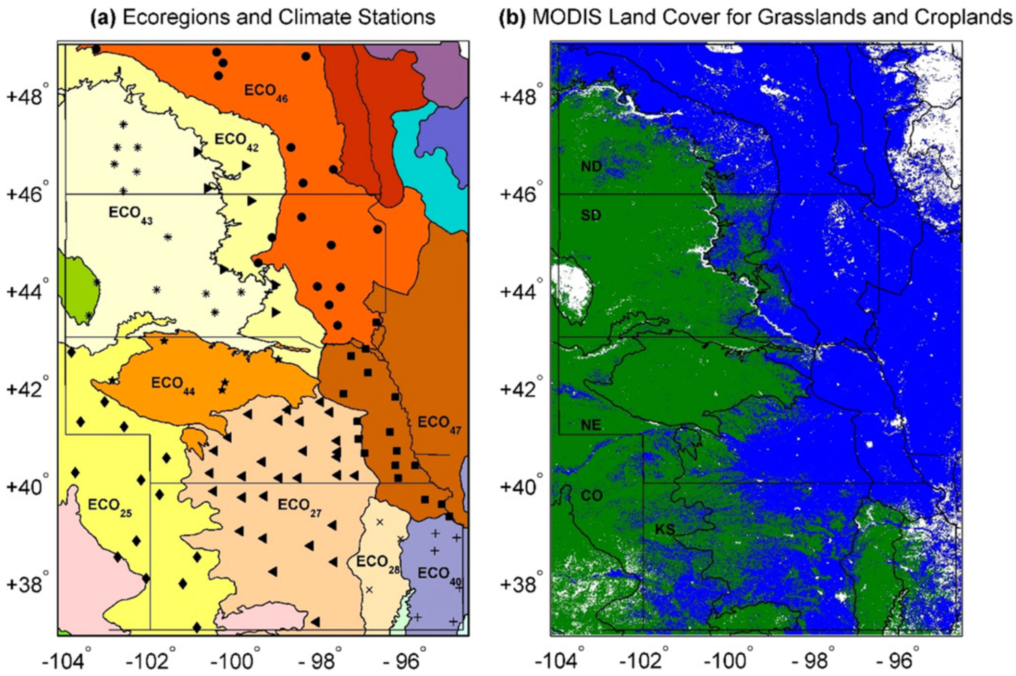

Figure 1. (a) Nine Level III ecoregions (colored areas) and the USHCN stations (black symbols). (b) MODIS land cover map, MOD12Q1 annual data in 2005, for classifications of grasslands (green) and croplands (blue) in the US High Plains region of North Dakota (ND), South Dakota (SD), Nebraska (NE), Kansas (KS), and part of Colorado (CO) State. The colored areas in (a) represent Northern Glaciated Plains (ECO_{46}, 17 USHCN stations), Northwestern Glaciated Plains (ECO_{42}, 7), Northwestern Great Plains (ECO_{43}, 13), Nebraska Sand Hills (ECO_{44}, 6), Western Corn Belt Plains (ECO_{47}, 17), Central Great Plains (ECO_{27}, 29), High Plains (ECO_{25}, 14), Flint Hills (ECO_{28}, 3), and Central Irregular Plains (ECO_{40}, 6).

$NDVI_{max}$ 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 ($5C5D_{FROST}$, 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 $0.5° \times 1.0°$ 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 $5C5D_{FROST}$ 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 $5C5D_{FROST}$ 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). The standard deviations of satellite-based SOS dates were comparable with climate-based SOS method's standard deviations in grasslands. This result suggests that satellite-based SOS dates for croplands have larger longitudinal variations than grasslands. This may be

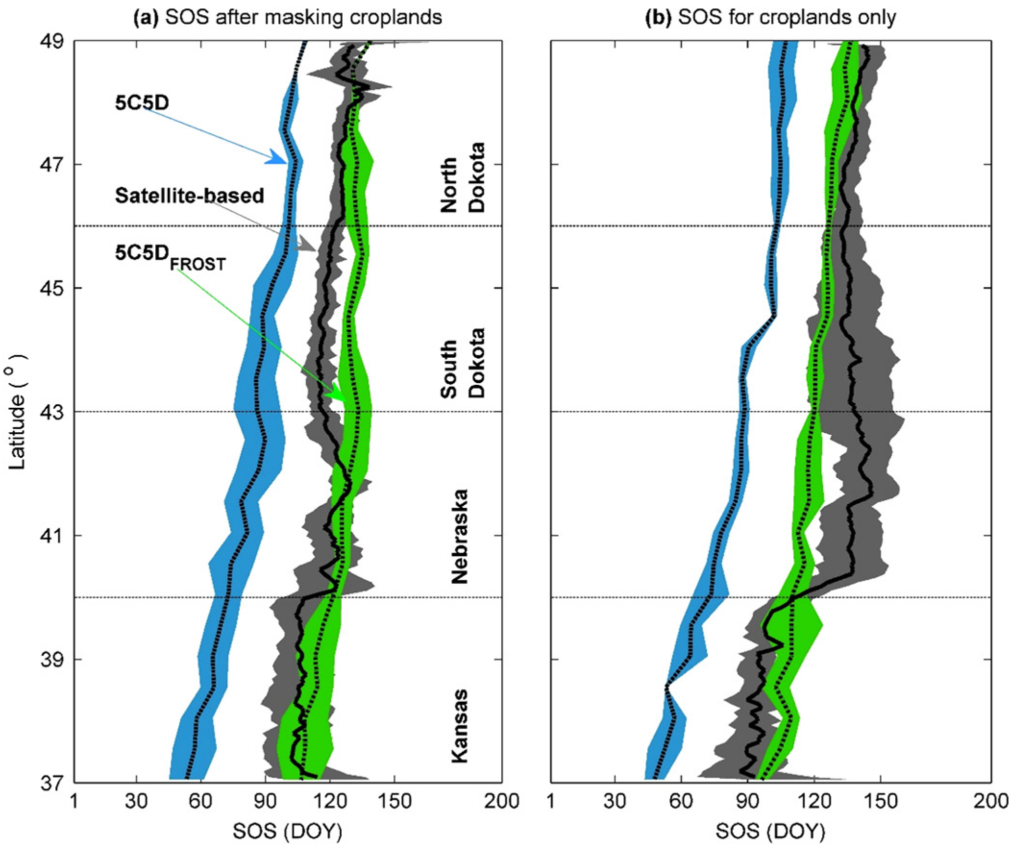

Figure 2. (a) Average SOS profiles by latitude for all non-croplands and (b) average SOS profiles for croplands only in US High Plains region. The SOS dates were averaged over 1982–2008 by satellite-based SOS pixels (solid profile line with gray shade), the 5C5D method (dashed profile lines with blue shade), and the $5C5D_{FROST}$ method (dash-dot profile lines with green shade). Each calculated profile is shown as the average (line) at that latitude plus and minus one standard deviation (shaded area).

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 $5C5D_{FROST}$ method in non-croplands (figure 2(a)). However, for croplands only, the satellite-based SOS dates were later than SOS dates by $5C5D_{FROST}$ 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 $5C5D_{FROST}$ 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 $5C5D_{FROST}$ 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 ECO_{46} and ECO_{47} 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 ECO_{43}, Nebraska Sandhills EC_{44}, 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

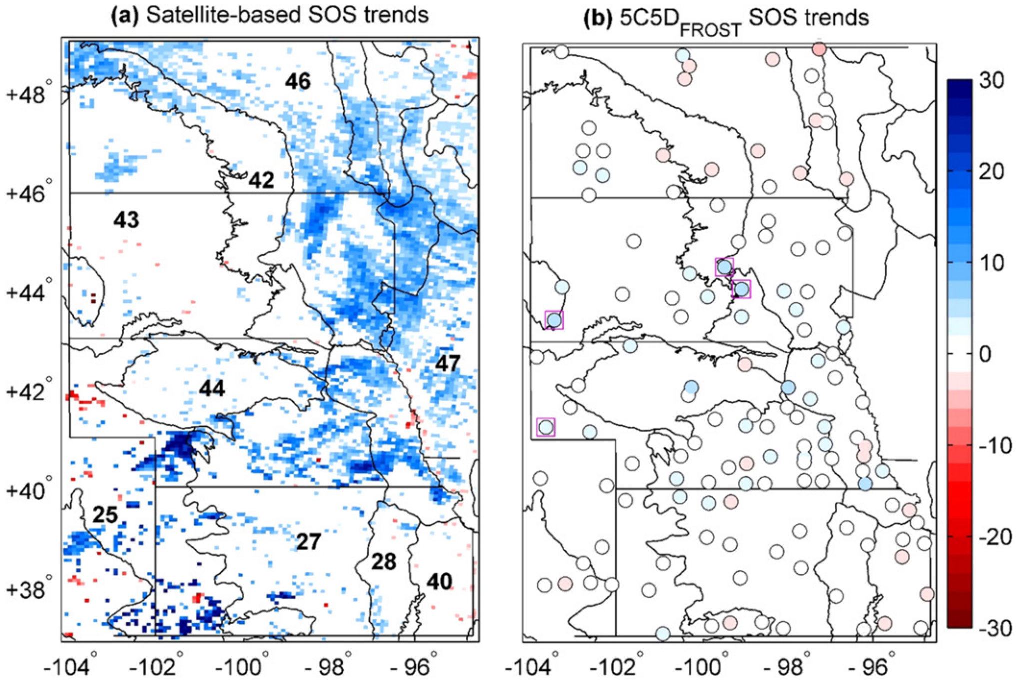

Figure 3. (a) All statistically significant satellite-based SOS trends (days per decade) from 1982–2008 for Level III ecoregions and zero or non-significant trends are white. The area-averaged satellite-based SOS trends by ecoregions (indicated by numbers in each region) are: 4.9 (ECO_{46}), 1.5 (ECO_{42}), 0.3 (ECO_{43}), 1.1 (ECO_{44}), 2.5(ECO_{47}), 1.8 (ECO_{27}), 1.9 (ECO_{25}), 0.28 (ECO_{28}), and 0.1 (ECO_{40}) 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).

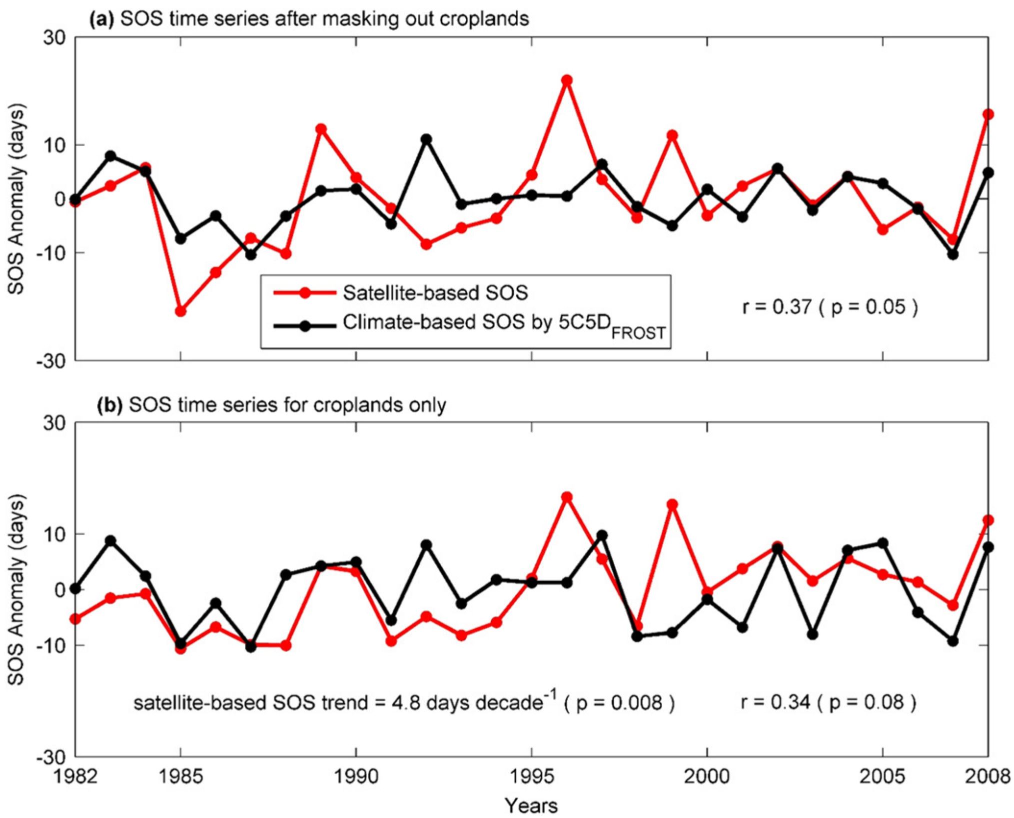

Figure 4. Area-averaged time series of satellite-based SOS (in red) and climate-based SOS by $5C5D_{FROST}$ method (in black) for (a) non-croplands and (b) croplands in the US High Plains region. The only statistically significant trend of 4.8 days per decade ($p = 0.008$) was detected in the satellite-based 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.

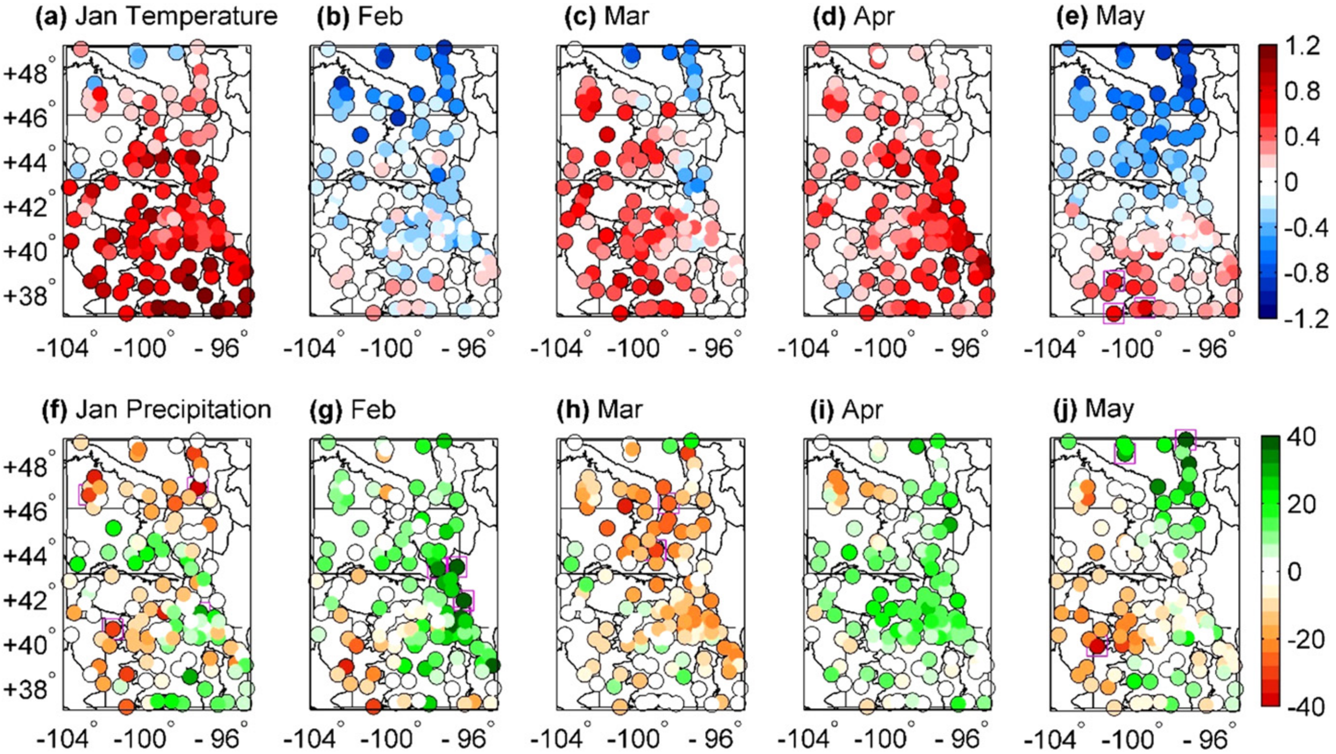

Figure 5. Monthly temperature trends (°C decade^{-1}) (top panel) and monthly precipitation trends (% decade^{-1}) (bottom panel) from January to May from 1982 to 2008. Pink boxes represent the statistically significant trends; otherwise the station trends are not significant.

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

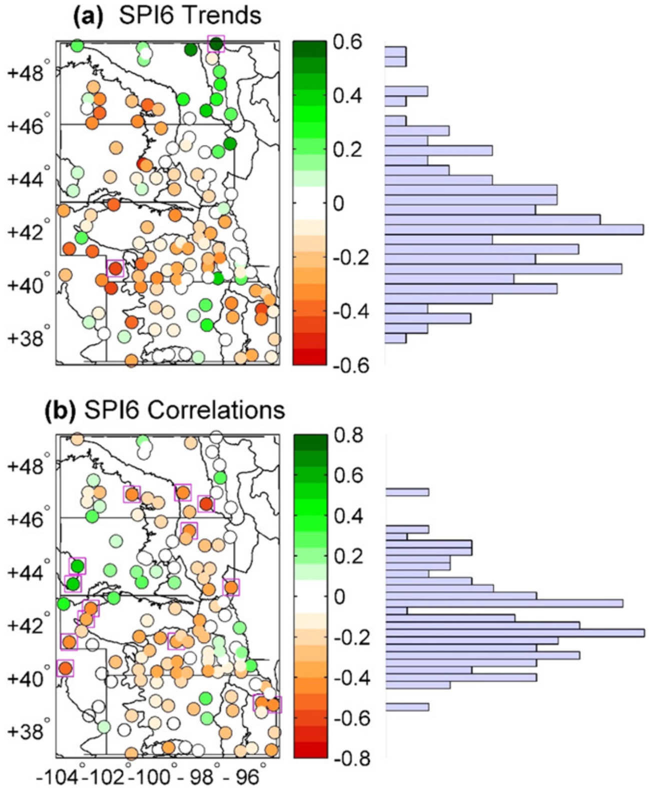

Figure 6. (a) The six-month standard precipitation index (SPI6) trends from 1982 to 2008 (units: SPI value per decade); and (b) the correlations between the satellite-based SOS and SPI6. Both corresponding histograms are presented to the right of each panel. The *x* axis of histogram is the color bar of trends and *y* axis of histogram represents the number of stations having that trend. Stations with statistically significant trends or correlations are highlighted by pink boxes; otherwise, the stations are not statistically significant.

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 $NDVI_{max}$ and $NDVI_{min}$ time series obtained from the $Midpoint_{pixel}$ 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 $NDVI_{max}$ trends (figure 7(b), greening or browning). When the $NDVI_{max}$ had a positive trend (greening at timing of $NDVI_{max}$ in the season, figure 7(b)), for example in the croplands (or in ECO_{46}, Nebraska areas of ECO_{47}, and ECO_{27}), the satellite-based SOS was trending towards later (figure 3(a)). On the other hand, when the $NDVI_{min}$ had a positive trend, (greening at timing of $NDVI_{min}$ in the season, figure 7(a)), for example in the grasslands (or in ECO_{43} and Sandhills ECO_{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 $NDVI_{max}$ or $NDVI_{min}$ 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 $Midpoint_{pixel}$ and the $5C5D_{FROST}$ 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 $5C5D_{FROST}$ 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 phenology (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 $NDVI_{max}$ (mostly in summertime) and $NDVI_{min}$ (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 $NDVI_{max}$ was positively, spatially, and statistically significantly correlated to satellite-based SOS dates towards later

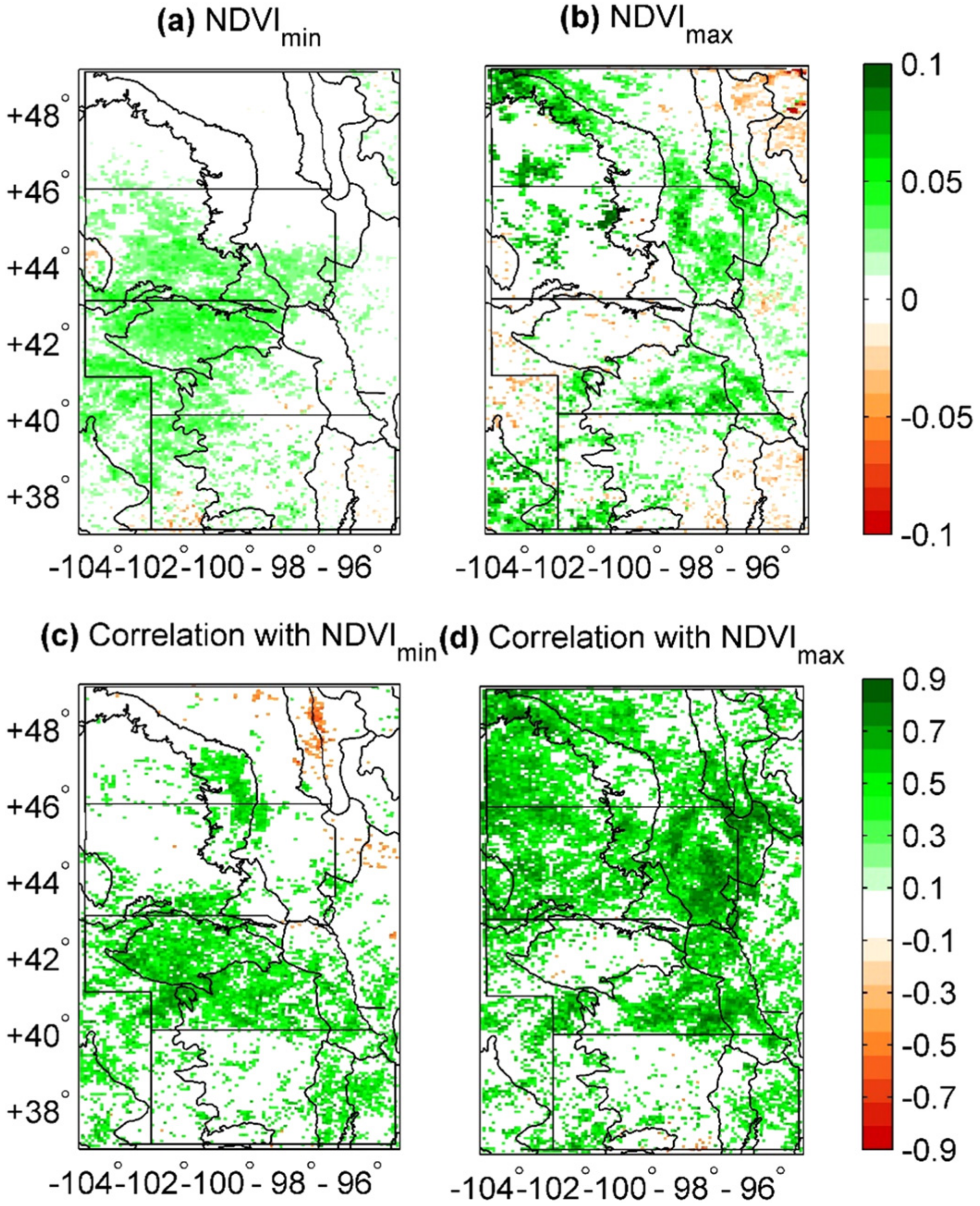

Figure 7. (a) Statistically significant trends (units: NDVI per decade) for annual NDVI$_{min}$; (c) statistically significant correlations (unitless) between annual NDVI$_{min}$ and the satellite-based SOS. The same for (b) and (d) but for the annual NDVI$_{max}$.

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$_{min}$.

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 *et al* 2003, Goetz *et al* 2005, Mahmood *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 *et al* 1998, Mahmood *et al* 2004, White *et al* 2005, Schwartz and Hanes 2009, Beck and Goetz 2011, Richardson *et al* 2013). We hope to reassess satellite-based phenological indicator trends when longer-term time series become available.

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