

Short Communication

Spring onset variations and trends in the continental United States: past and regional assessment using temperature-based indices

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ABSTRACT: Phenological data are simple yet sensitive indicators of climate change impacts on ecosystems, but observations have not been made routinely or extensively enough to evaluate spatial and temporal patterns across most continents, including North America. As an alternative, many studies use weather-based algorithms to simulate specific phenological responses. Spring Indices (SI) are a set of complex phenological models that have been successfully applied to evaluate variations and trends in the onset of spring across the Northern Hemisphere's temperate regions. To date, SI models have been limited by only producing output in locations where both the plants' chilling and warmth requirements are met. Here, we develop an extended form of the SI (abbreviated SI-x) that expands their application into the subtropics by ignoring chilling requirements while still retaining the utility and accuracy of the original SI (now abbreviated SI-o).

The validity of the new indices is tested, and regional SI anomalies are explored across the data-rich continental United States. SI-x variations from 1900 to 2010 show an abrupt and sustained delay in spring onset of about 4–8 d (around 1958) in parts of the Southeast and southern Great Plains, and a comparable advance of 4–8 d (around 1984) in parts of the northern Great Plains and the West. Atmospheric circulation anomalies, linked to large-scale modes of variability, exert modest but significant roles in the timing of spring onset across the United States on interannual and longer timescales. The SI-x are promising metrics for tracking spring onset variations and trends in mid-latitudes, relating them to relevant ecological, hydrological, and socioeconomic phenomena, and exploring connections between atmospheric drivers and seasonal timing. Copyright © 2012 Royal Meteorological Society

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1. Introduction

Phenology is the study of plant and animal life cycle events in relation to environmental drivers such as weather and climate. Over time, phenological observations can track simple, yet critical, impacts of climate change on ecosystems (IPCC, 2007). Such observations are made routinely and extensively in Europe (van Vliet *et al.*, 2003), North America (Schwartz *et al.*, 2012), and Australia (ClimateWatch web page, 2012), while new networks are being proposed in India and other continents (Kushwaga and Singh, 2008). Notwithstanding the value of these monitoring networks, building capacity to use phenological observations to track regional climate change impacts faces considerable challenges (Schwartz *et al.*, 2006). For example, historical and

contemporary phenological data are generally sparse, and long-term, replicated measurements of different populations across a wide range of target species are uncommon. Furthermore, international efforts are not coordinated with each other, and consequently differ in their protocols for monitoring, measuring, and reporting phenological events. Similarly, phenological data sharing agreements among countries are weak or non-existent.

Given the limitations of working directly with synoptic and long-term phenological observations to track climate change impacts, many researchers have instead used available weather and phenological data to develop biologically relevant algorithms for simulating 'spring's onset', typically driven by daily surface maximum/minimum air temperatures. Once tested and calibrated, such models extend the possible spatial coverage and temporal range of phenological assessments of environmental change due to the greater availability of current and long-term meteorological data. So why use phenological models instead of just the meteorological

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data alone for such assessments? To answer this question, one must consider that, when measuring environmental change, there are various levels of precision related to the type of measure used, the length of time addressed, and the degree of spatial aggregation. Consider changes in the start of the growing season for plants. Average monthly (or seasonal) temperatures give a general idea of the expected change at a specific station, and the average change over a region. Monthly averages, however, lack the information to discern important phenoclimatic processes that occur at the scale of days to weeks and initiate specific phenological responses (e.g. leafing and flowering) that in turn change the structure of the atmosphere and drive ecosystem food-web dynamics (e.g. insect pollination, etc.). Also, if the phenological event ranges over a broad geographic area, or can be triggered by a brief period of extreme temperatures, this may be poorly represented in general measures like average monthly or seasonal temperature.

One set of phenological models that have been successfully applied to assess the impact of environmental change on the onset of the spring season across temperate regions around the Northern Hemisphere are the Spring Indices (SI, Schwartz *et al.*, 2006; Ault *et al.*, 2011; McCabe *et al.*, 2012). This suite of metrics includes several sub-models and associated measures, all of which can be calculated using daily maximum/minimum surface temperatures and station latitude. SI models process weather data into a form mimicking the spring growth of plants that are not water limited, and are responsive to temperature increases (Schwartz *et al.*, 2006).

SI models were initially designed to simulate the growth of specific plants. As such, earlier versions of SI do not produce output in locations where these plants do not grow successfully, most specifically in areas where warm winter weather provides inadequate chilling (Schwartz *et al.*, 2006). Here, we explore development of an extended form of the SI (abbreviated SI-x) that retains the utility and accuracy of the original SI (now abbreviated SI-o) while allowing mapping further south into the subtropics. This permits assessment of spring onset variations and trends in the southeastern United States (SEUS), particularly in reference to this region constituting a 'warming hole', where the secular trend during the past century has been towards later hard freezes (Marino *et al.*, 2011) and generally cooler springs and summers (Robinson *et al.*, 2002; Pan *et al.*, 2004; Kunkel *et al.*, 2006; Wang *et al.*, 2009; Meehl *et al.*, 2012).

2. Data and methodology

The meteorological stations used in this study came from more than 22 000 observation sites that record standard surface-level (1.5 m above the surface) daily maximum/minimum temperature across the continental (lower-48) United States. The data were obtained from the National Climatic Data Center, covering the period of record for these stations through 2010. The final 716

station locations selected for inclusion in the analyses were those that had sufficient data to produce valid SI model outputs for at least 25 of 30 years over the 1981–2010 (30-year) period.

The methodology for producing the SI-x model output (SI first leaf date and SI first bloom date) are the same as described in McCabe *et al.* (2012) for the SI-o models with the following exception. For SI-x first leaf calculation, no chilling hours are accumulated, rather energy accumulation starts for all stations from the same fixed day each year – 1st January. For the selected stations, SI-x first leaf and first bloom model dates were first calculated for the station period of record. Next, from these yearly values, 30-year averages ('normals') were calculated for the 1981–2010 period, and these normals were subsequently used to turn the yearly SI-x output into anomalies. These anomalies were used for all subsequent analyses.

In addition, given the well-documented performance of SI-o, SI-x output was compared with SI-o station output at all available stations where both model sets would produce the output. The comparisons included Pearson's correlation, mean bias, and mean absolute differences. Lastly, for stations where cloned lilac (*Syringa chinensis* 'Red Rothomagensis' data – the main type of plants used in the original development of SI) were also available, these data were used to compare SI-o model and SI-x model accuracy.

The SI-x station anomalies were accumulated, examined, and plotted over the 1900–2010 period. This initial examination suggested that the time series was different in the SEUS, than the rest of the continental United States (REST48). Further, it appeared that the decade from 1951 to 1960 was a pivotal period when broad changes seemed to be taking place in the previous trends. To further explore these changes: (1) the temporal trends were accumulated in two regions, the SEUS (defined as the area south of 37°N latitude and east of 103°W longitude) and REST48 and (2) changes in average SI-x first leaf date were compared by station between the 1951–1960 and 2001–2010 periods, for all stations that had at least 8 years of valid output in both periods.

Although the suite of SI-x indices were calibrated and validated using lilacs and honeysuckles, they also are relevant for the phenology of many temperature-sensitive crop and native species (Wolfe *et al.*, 2005; Schwartz *et al.*, 2006). We performed correlation analyses and constructed a composite graphic comparing state or area-wide average time series of SI-x first bloom dates and 80% bloom dates for anjou pears in southwest Oregon (unpublished), dogwood average bloom time in South Carolina from herbarium data (unpublished, but using methodology reported in Park, 2012), peach full bloom dates in South Carolina (Schwartz *et al.*, 1997), and winter (Kharkov) wheat heading dates in the Great Plains (Hu *et al.*, 2005). All these time series were converted to *z*-scores (standard deviation units) for better visual comparison.

To assess the role of large-scale circulation anomalies on the timing of spring in the SEUS time series, we correlated it with January and February 300 hPa heights from the National Center for Environmental Prediction's (NCEP) reanalysis data (Kalnay *et al.*, 1996). Variability during these months contains the most relevant information for subsequent large-scale variations in the onset of the early spring (late-February and March) growing season (Ault *et al.*, 2011). The 300 hPa fields were computed using a numerical model of climate constrained by observational data from 1950 through 2010, and hence provide insight into the dynamical mechanisms responsible for interannual variability in SI-x. We also correlated the SEUS time series with January and February indices of the Pacific North American pattern (PNA) and Northern Annular mode (NAM). Again, the indices were derived from NCEP reanalysis data. In this case they are the first (PNA) and second (NAM) principal component time series of NCEP sea level pressure.

3. Results

Table I shows the results of the comparison of SI-x and SI-o output. Both the first leaf and first bloom models are highly correlated between versions and the mean bias and mean absolute differences between versions are around 2 d or smaller, with the first bloom models values closer to 1 day. The comparison of SI-x and SI-o model performance when compared with cloned lilac data are very similar, in terms of both bias and absolute errors. The error differences are 0.24 d or less, well within the 1-d resolution of model predictions.

Figure 1 shows the comparisons of the three crops and one native species time series to SI first bloom dates. All the paired Pearson's correlations are significant at the $\alpha = 0.005$ level or better. Rendered as levels of explained

Table I. Comparison of original Spring Indices (SI-o) to extended Spring Indices (SI-x) and both to lilac phenological data.

Pearson's correlation	SI-x first leaf date	SI-x first bloom date	
SI-o first leaf date	0.975	–	
SI-o first bloom date	–	0.995	
Mean difference (d)	Bias difference	Absolute difference	
SI-x first leaf date	–1.4	2.5	
SI-x first bloom date	–0.7	1.1	
<i>n</i> of cases = 71 926			
Mean error to lilac (d)	Bias error	Absolute error	Error difference
SI-x first leaf date	–2.47	6.57	0.14
SI-o first leaf date	–1.78	6.43	–
SI-x first bloom date	–3.66	5.46	0.24
SI-o first bloom date	–3.15	5.22	–
<i>n</i> of cases = 830			

variance (r^2) these are 92% for the South Carolina peach (Figure 1(c)), 72% for the Oregon pear (Figure 1(a)), 32% for the Great Plains wheat (Figure 1(d)), and 20% for the South Carolina dogwood (Figure 1(b)).

The temporal trends in SI-x first leaf date are considerably different between the SEUS and REST48 for the first half of the 20th century (1900–1950), but begin to converge in the late-1950s (Figure 2). By the 1980s the two regions seems to have come into phase. The spatial coherence across the SEUS is considerable, and shown by the station comparison between the 1951–1960 and 2001–2010 periods (Figure 3).

Correlations between SEUS and 300 hPa heights for January and February are shown in Figure 4. Although correlations are stronger during January (Figure 4(a)), the sign and geographic pattern of the correlation fields are very similar for both months. Regions of negative correlation (early SEUS spring with high 300 hPa heights) occur over the subtropical Pacific and SEUS, whereas positive correlations occur over northern North America. Although the pattern during both months is highly reminiscent of the PNA stationary wave pattern in mid-tropospheric flow (Wallace and Gutzler, 1981), the correlation with the PNA index is modest (0.31) in January and non-significant in February. On the other hand the correlation with the NAM is slightly stronger (–0.40) for both months. These findings imply that spring onset in the SEUS is governed almost equally by both patterns of variability.

4. Discussion

Comparisons between time series of SI-x first bloom date and 80% bloom dates for anjou pears in southwest Oregon (Figure 4(a)), *Cornus florida* (dogwood) average bloom from South Carolina herbaria data (Figure 4(b)), peach full bloom in South Carolina (Figure 4(c)), and winter (Kharkov) wheat heading in the Great Plains (Figure 4(d)), suggest that SI-x can explain moderate to very high levels of the year-to-year and decadal variance depending on species and region. The highest levels were for the fruit trees, which is expected given that 80% bloom (Figure 4(a)) and full bloom (Figure 4(c)) are well-defined phenological events which appear to be strongly driven by temperature alone (Schwartz *et al.*, 1997). The levels for wheat heading (Figure 4(d)) are understandably lower, specifically in the dry 1930s and 1940s, because phenological development in this non-irrigated crop is influenced by moisture conditions in addition to temperature (Hu *et al.*, 2005). The relatively low variance explained for dogwood average bloom (Figure 4(b)) likely reflect the broader and less precise nature of the measure (average time that any individuals across the entire state of *S. Carolina* were found to be in bloom extracted from herbaria data, Park, 2012).

Averaged over the continental United States, SI-x trends are consistent with averages from other phenological data in the Northern Hemisphere. Schwartz *et al.*

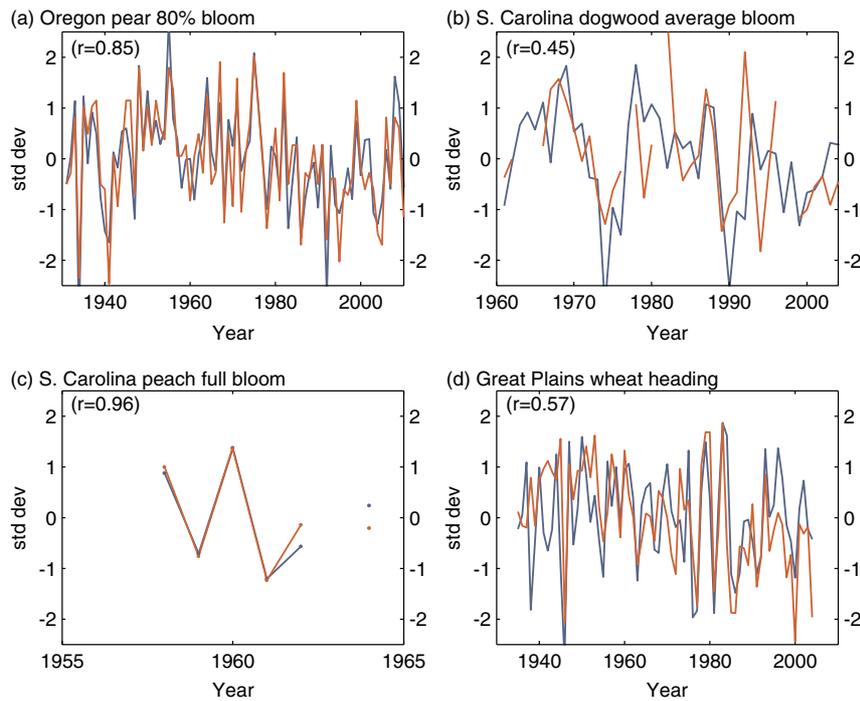


Figure 1. Comparison of SI-x first bloom date (blue) with three crops and one native species phenological time series (red). All are displayed as z -scores (standard deviation units) for better visual comparison, and the Pearson's correlation for each pair is shown in the upper left corner. (a) Average SI-x first bloom dates across the state of Oregon (from 23 weather station sites) and anjou pear 80% bloom dates in the Rogue Valley of southwestern Oregon (Medford, Ashland, Grants Pass, near the California border) from 1931 to 2010 (G. Jones, unpublished pear data). (b) Average SI-x first bloom dates across the state of South Carolina (from 14 weather station sites) and average *Cornus florida* (dogwood) flowering time, derived from herbaria records, partial years from 1961 to 2007 (I. Park, unpublished dogwood data, compiled using methodology in Park, 2012). (c) Average SI-x first bloom dates (as in Figure 4(b)) and average peach full bloom dates among three varieties (Dixired, Elberta, and Red Haven) at two station sites from 1958 to 1962, and 1964 (peach data from Schwartz *et al.*, 1997). (d) Average SI-x first bloom dates in the United States region north of 35° N latitude and between 90° and 100° W longitude (from 153 weather station sites) and winter wheat (Kharkof cultivar) heading dates at six sites from 1935 to 2004 (wheat data from Hu *et al.*, 2005).

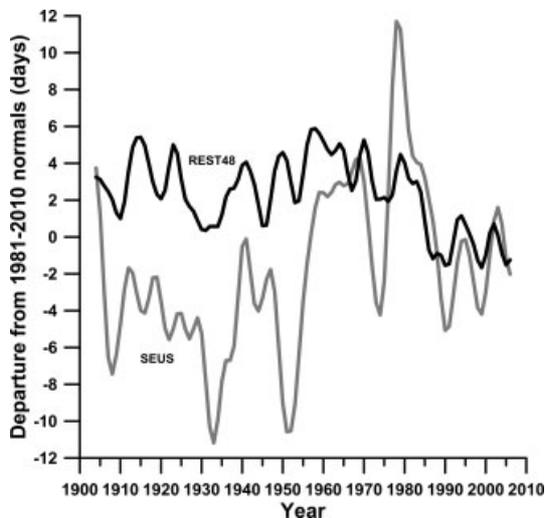


Figure 2. Smoothed (nine-point moving average normal curve) SI-x first leaf date departures from 1981 to 2010 normals in the SEUS compared to rest of the continental United States (REST48), 1904–2006.

(2006) and Parmesan (2007) have documented that SI spring onset and phenological trends for comparable species (shrubs) are both shifting earlier at rates of approximately 1.1–1.2 d per decade on average at the

hemispheric scale over the last half of the 20th century. With respect to this hemispheric average, trends in the western United States are anomalously negative (4–8 d earlier after 1984), while trends in the SEUS are anomalously positive (4–8 d later after 1958).

Previous studies have implicated large-scale atmospheric circulation patterns in driving interannual variability and trends across the western United States (Ault *et al.*, 2011; McCabe *et al.*, 2012). In particular, Ault *et al.* (2011) argued that the atmospheric trends towards an enhanced ridge over western North America, with troughs over the subtropical Pacific and SEUS, were linked to a greater number of warm days earlier in the year and hence earlier spring. Likewise, the negative correlations with the NAM associate its negative phase (e.g. a more northward, zonal jet) with fewer outbreaks of cold air and hence warmer temperatures and early spring onset (Thompson and Wallace, 2001).

The trough–ridge–trough structure, which resembles the positive phase of the PNA, would be expected to generate a greater number of outbreaks of cold air in the SEUS and consequently delays the onset of spring in that region (Marino *et al.*, 2011). Biological evidence for the dramatic advance in SI-SEUS around the late 1950s includes delayed seasonal flowering in many Florida plants, inferred from herbarium specimens (Von



Figure 3. Change in average SI-x first leaf date by station (in days) between 1951–1960 and 2001–2010.

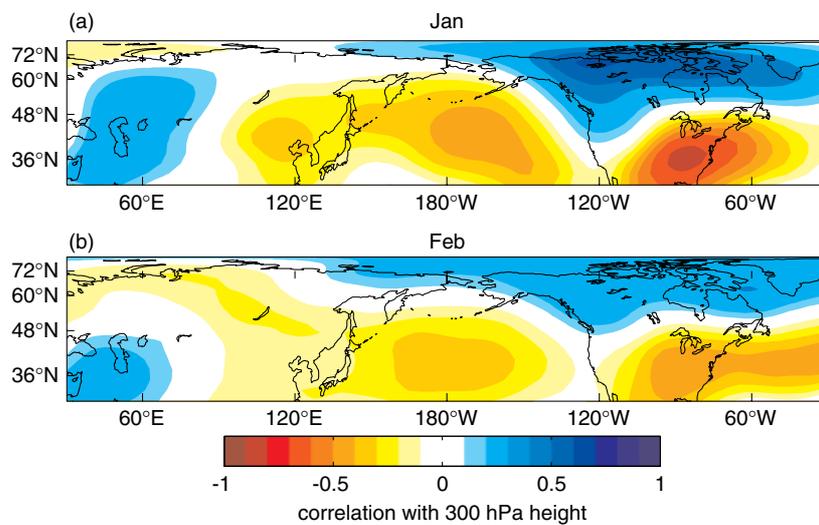


Figure 4. Correlation between the SEUS time series and 300 hPa heights during the preceding January (a) and February (b).

Holle *et al.*, 2010). The geographic pattern of SEUS stations where spring has been arriving later is consistent with the well-documented ‘warming hole’ in the SEUS (Robinson *et al.*, 2002; Pan *et al.*, 2004; Kunkel *et al.*, 2006; Wang *et al.*, 2009; Meehl *et al.*, 2012). This ‘warming hole’ anchors one end of a broad arc of cooling in boreal winter stretching from the eastern United States across northern Eurasia that is associated with a negative trend in the arctic oscillation (AO).

Recently, Meehl *et al.* (2012) attributed the SEUS warming hole to decadal variability in the Pacific Ocean, which induces atmospheric changes favouring a trough–ridge–trough (positive PNA) structure that brings a greater number of cold outbreaks of air to the SEUS. Using a coupled global climate model (GCM), the study further documents that the pattern of Pacific decadal variability responsible for the warming hole in North America may be internally generated, and therefore not directly linked to climate change (Meehl *et al.*, 2012). Alternatively, Cohen *et al.* (2012) suggest that the cooling trends in the eastern United States and northern Eurasia over the last few decades may belie dynamical interactions between greater Eurasian snow cover extent

in the fall and negative winter AO. In other parts of the NH, including the leeside of the Tibetan Plateau, complicated interactions across seasons may explain delayed springs (Li *et al.*, 2005). Because warming holes also evidently impact seasonality, as shown here, projections of future phenological change should take into account both the forced and natural sources of variability.

We emphasize that the calculation of SI-x only require daily maximum/minimum temperatures as input, and so they could be calculated from daily reanalysis data and GCM output to develop a more refined dynamical explanation for the sources of spring onset variability on interannual to centennial timescales. Such efforts would provide insight into the sources of spring onset predictability.

The prominent correlation between atmospheric circulation in previous months and spring onset has been found not only in North America (Ault *et al.*, 2011), but also in northern China (Qian *et al.*, 2011), suggesting seasonal predictability may be possible in many temperate regions. The SI-x product could be used to further explore predictability in other temperate areas of the world or at decadal timescales. Long-lead forecasting of SI-x, if it

becomes feasible and operational, could inform myriad applications, including agriculture, health, recreation, and natural resource management.

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