Spring Onset Variations and Trends in the Continental USA:

Past and Regional Assessment

Using Temperature-Based Indices

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Abstract

Phenological data are simple yet sensitive indicators of the impacts of climate change 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 easily calculated and weather-based algorithms linked to a specific phenological response, for example the seasonal accumulation of growing degree-hours that triggers the onset of leafout/flowering in many plants. The Spring Indices (SI, Schwartz et al. 2006) are one set of 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 have been limited by only producing output in locations where the plants' SI were designed to simulate grow successfully, principally where both the plants' chilling and growing-degree-hour requirements are met. In this paper, we consider an extended form of the Spring Indices (abbreviated SI-x) that can be mapped from polar to subtropical latitudes by ignoring chilling requirements while still retaining the utility and accuracy of the original SI (now abbreviated SI-o). For the continental USA, SI-x variations from 1900-2010 show an abrupt and sustained delay in spring onset of about 4-8 days around 1958 in parts of the Southeast and southern Great Plains, and a comparable advance of 4-8 days in parts of the northern Great Plains and the West. These conspicuous regional patterns are associated with the Pacific North American (PNA) pattern, defined by anomalously high geopotential heights over the Northwest and anomalously low ones in the Southeast. The SI-x are promising metrics for tracking regional variations and trends in spring's onset, relating them to relevant ecological, hydrological and socioeconomic phenomena, and exploring connections between atmospheric drivers and seasonal timing, both in the past and elsewhere in the world.

Introduction

Phenology is the study of plant and animal life cycle events in relation to environmental drivers (especially weather and climate), and phenological data are simple, yet sensitive indicators of the impacts of climate change on ecosystems (IPCC 2007). Phenological measurements are made routinely and extensively in Europe (van Vliet et al. 2003), new national networks were established recently in the USA (Betancourt et al. 2005) and Australia (ClimateWatch 2012), and pleas are being made for developing networks in India and other continents (Kushwaga and Singh 2008). Considerable challenges remain, however, in using phenological data to assess the environmental impacts of climate variability and change across most regions (Schwartz et al. 2006). Chief among these are the lack of: 1) historical and contemporary phenological data in general; 2) long-term and replicated measurements of different populations across the range of the target species; 3) coordination and standardization among existing national phenological networks in terms of species and protocols; and 4) worldwide phenological data sharing agreements.

Given these limitations, many researchers have used available phenological data to first 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, given the greater availability of meteorological data, both currently and in the past. Now it would be fair at this point to ask "Why use phenological models instead of just using the meteorological data alone for such assessments?" In order 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. Let us consider changes in the start of the growing season for plants. Average monthly (or seasonal) temperatures can give a general idea of the expected change at a specific station and of the overall average change over a region. However, monthly values will not be as responsive as a model designed to produce a precise output related to a specific phenological response, for example the initiation of leafing and flowering. 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. 2011). This suite of measures includes several sub-models and associated measures, all of which can be calculated using daily maximum-minimum surface (shelter-height) temperatures and station latitude. SI process weather data into a form comparable to the spring growth of plants that are not water limited and are responsive to temperature increases (Schwartz et al. 2006).

SI 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 Spring Indices (abbreviated SI-x) that retains the utility and accuracy of the original SI (now abbreviated SI-o) while allowing mapping into the subtropics. This permits assessment of spring onset variations and trends in the Southeastern USA, 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., in review).

Data and Methodology

The meteorological stations used in this study came from the over 22,000 observation sites that record standard surface-level (1.5 m above the surface) daily maximum-minimum across the continental (lower-48) United States. The data were obtained from the National Climatic Data Center (NCDC) archives, 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 Spring Indices (SI) model output for at least twenty-five of thirty years over the 1981-2010 (30-year) period.

The methodology for producing the extended SI (SI-x) model output (SI first leaf date and SI first bloom date) are the same as described in McCabe et al. (2011) for the original SI models (SI-o) 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, January 1st, each year. 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 departures-from-normal. These departures were used for all subsequent analyses.

In addition, given the well-document performance of SI-o, SI-x output was compared to SI-o station output at all available stations where both model sets would produce 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-x model and SI-x model accuracy.

The SI-x station departures from normal were accumulated, examined, and plotted over the 1900-2010 period. This initial examination suggested that the time series was different in the Southeastern United States (SEUS), than the rest of the continental USA (REST). Further, it appeared that the decade from 1951-1960 was a pivotal period when broad changes appeared 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 west of 103°W longitude) and REST; and 2) changes in SI-x output values were compared by station between the 1951-1960 and 2001-2010 periods, for all stations that had at least eight years of valid output in both periods.

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 300mb heights from the National Center for Environmental Prediction's (NCEP) reanalysis data (Kalnay et al. 1996). These 300mb 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.

Results

Table 1 shows the results of the comparison of SI-x and SI-o output. Both the first leaf and first bloom models are highly correlated, and the mean bias and mean absolute differences are around 2 days or smaller, with the first bloom models values closer to one day. The comparison of SI-x and SI-o model performance when compared to cloned lilac data are very similar, in terms of both bias and absolute errors. The error differences are 0.25 days or less, well within the 1-day resolution of model predictions.

The temporal trends in SI-x first leaf date are considerably different between the SEUS and REST for the first half of the 20th century (1900-1950), but begin to converge in the late-1950s (Fig. 1). By the 1980s the two regions seems to have come into phase. The spatial coherence across the SEUS is considerable, and well shown by the station comparison between the 1951-1960 and 2001-2010 periods (Fig. 2).

Correlations between SEUS and 300mb heights for January and February are shown in Figure 3. Although correlations are stronger during January (Fig. 3a), the sign and geographic pattern of the correlation fields are very similar for both months. Regions of negative correlation (early SEUS spring with high 300mb heights) occur over the subtropical Pacific and southeastern US, whereas negative correlations occur over northern North America. The pattern during both months is highly reminiscent of the Pacific North American (PNA) stationary wave pattern in mid-tropospheric flow (Wallace and Gutzler 1981). Leathers and Palecki (1992) attributed a sharp increase in the PNA index to the dramatic decline in geopotential heights over SEUS in the late 1950's, which accounts for winter/spring cooling and earlier onset in SEUS.

Discussion

Schwartz et al. (2006) and Parmesan (2007) have documented that SI spring onset and phenological trends for comparable species (shrubs) are both moving earlier at rates of approximately 1.1 to 1.2 days/decade on average at the hemispheric scale. With respect to this hemispheric average, trends in the western USA are anomalously negative, while trends in the southeastern USA are anomalously positive. Biological evidence for the dramatic advance in SI-SEUS around the late 1950's includes delayed seasonal flowering in many Florida plants, inferred from herbarium specimens (Von Holle et al. 2010).

Previous studies have implicated large-scale atmospheric circulation patterns in driving interannual variability and trends in the western USA (Ault et al. 2011; McCabe et al. 2011). 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 southeastern US, were linked to a greater number of warm days earlier in the year and hence earlier spring. This pattern, which resembles the positive phase of the PNA, would also be expected to generate a greater number of outbreaks of cold air in the southeastern USA and consequently delays the onset of spring in that region (Marino et al. 2011). The positive trend in the SEUS time series and the correlation map in Figure 3 both support this explanation. Hence, the anomalous (and opposing) trend in the western USA and southeastern USA are counterbalanced and linked by the same large-scale mechanism.

The geographic pattern of southeastern USA stations where spring has been arriving later is consistent with the well-documented "warming hole" in the southwestern USA (Robinson et al. 2002; Pan et al. 2004; Kunkel et al. 2006; Wang et al. 2009; Meehl et al., in review). Recently, Meehl et al. (in review) have attributed this warming hole to decadal variability in the

Pacific Ocean, which induces atmospheric changes favoring a trough-ridge-trough (positive PNA) structure that brings a greater number of cold outbreaks of air to the southwestern USA. 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., in review). Because the warming hole also evidently impacts seasonality, as shown here, projections of future phenological change should take into account both the forced and natural sources of variability.

Future studies could use the new SI-x product to further explore the patterns of variations and trends and natural low-frequency variability of spring's onset in other parts of the world or over other time domains. For example, the springtime cooling trend in southwest China has been attributed to the teleconnection between the winter North Atlantic Oscillation (NAO) and surface air temperature over the lee side of the Tibetan Plateau (Li et al. 2005).

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, which in turn could be of critical importance to agricultural and natural resource managers alike.

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Table 1: 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 (days)	*Bias difference*	*Absolute difference*
SI-x first leaf date	**-1.4**	**2.5**
SI-x first bloom date	**-0.7**	**1.1**

n of cases = 71,926

Mean Error to Lilac (days)	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**	**0.25**
SI-o first bloom date	**-3.15**	**5.22**	

n of cases = 830

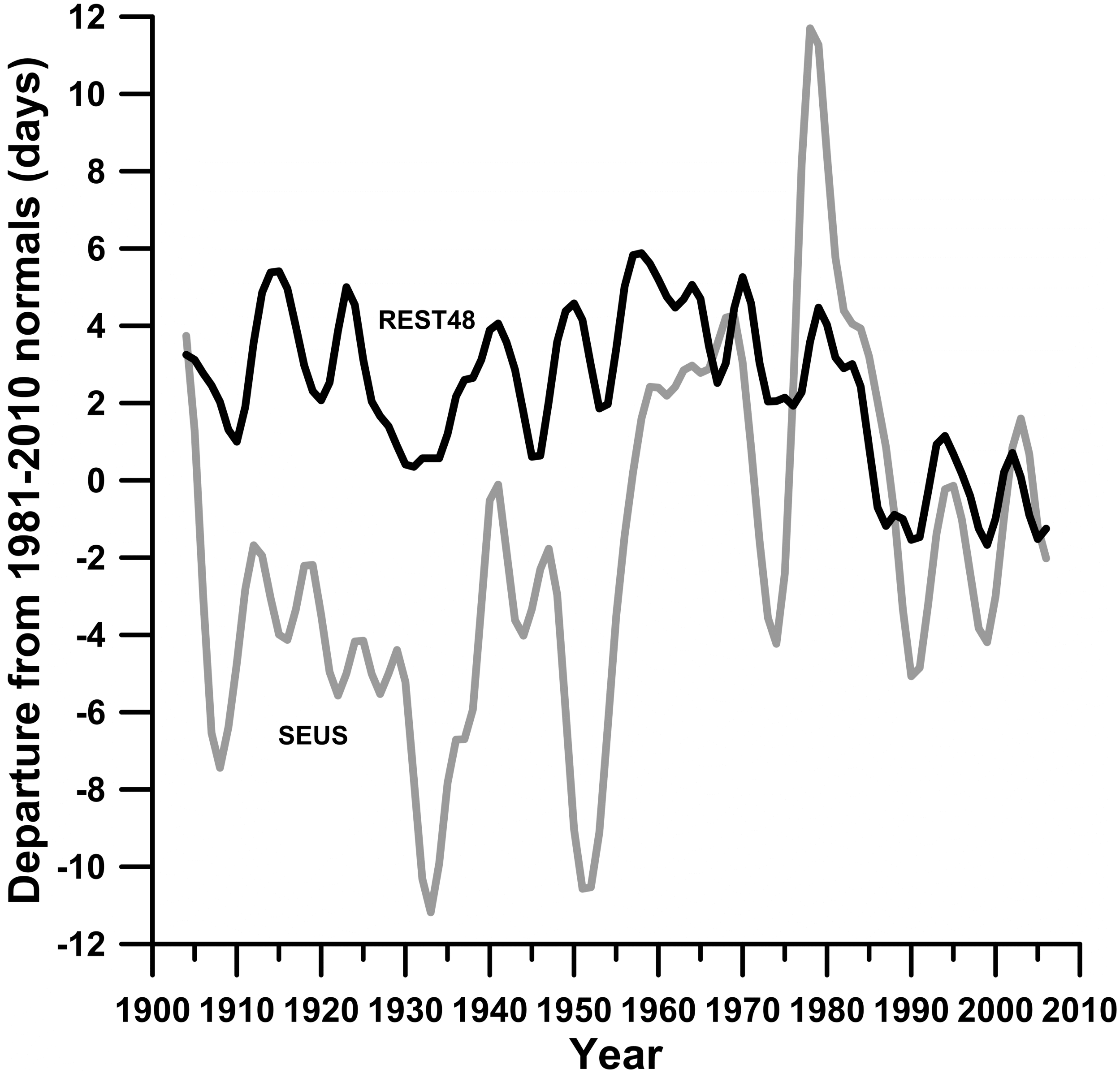

Figure 1: Smoothed (9-point moving average normal curve) SI-x First Leaf Date Departures from 1981-2010 normals in the SEUS compared to rest of the continental USA, 1904-2006.

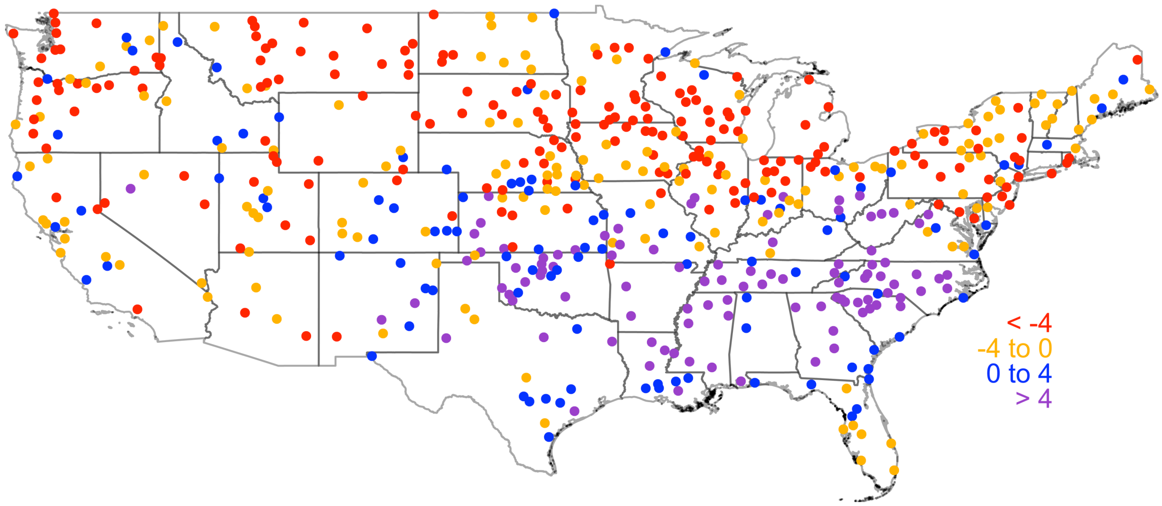

Figure 2: Change in average SI-x first leaf date by station (in days) between 1951-1960 and 2001-2010

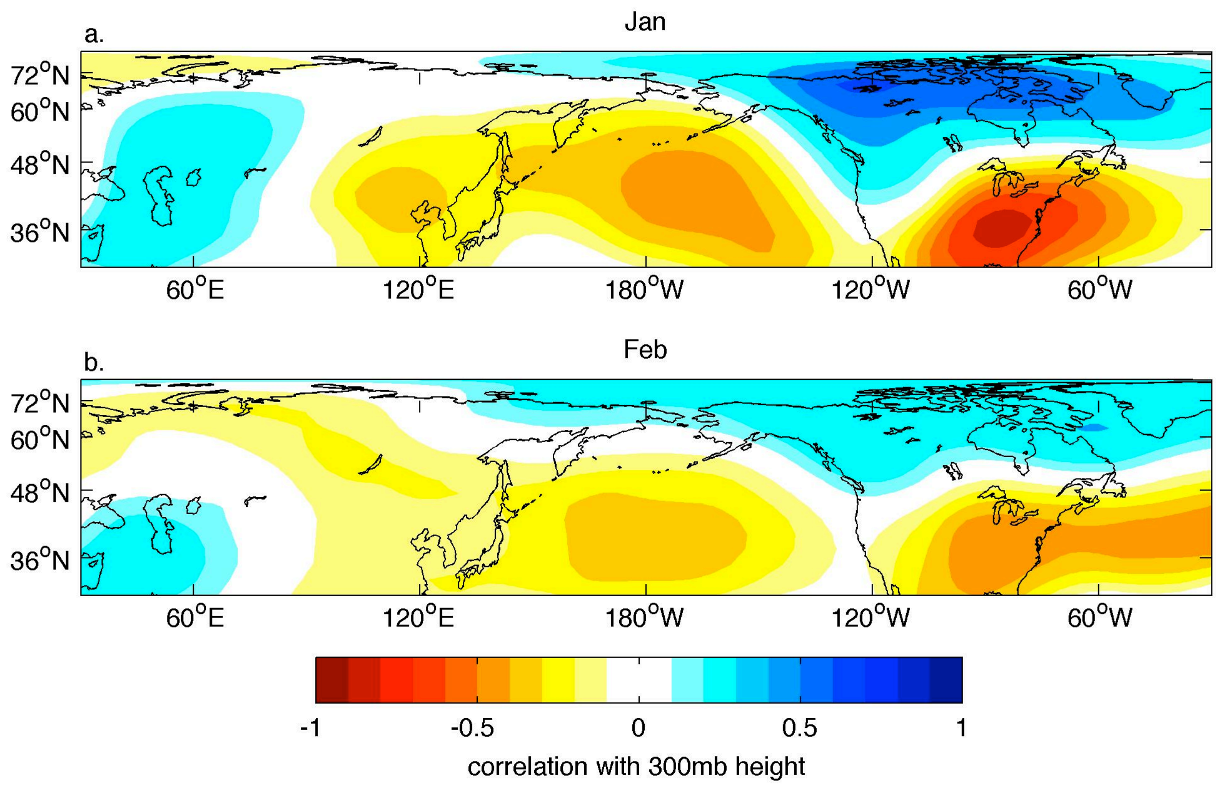

Figure 3: Correlation between the SEUS time series and 300hPa heights during the preceding January and February