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Reconstruction of false spring occurrences over the southeastern United States, 1901–2007: an increasing risk of spring freeze damage?

Garrett P Marino[1,2,3], **Dale P Kaiser**[2,4], **Lianhong Gu**[2] **and Daniel M Ricciuto**[2]

[1] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA
[2] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

E-mail: kaiserdp@ornl.gov

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Abstract
Near-record warmth over much of the United States during March 2007 promoted early growth of crops and vegetation. A widespread arctic air outbreak followed in early April, resulting in extensive agricultural losses over much of the south-central and southeastern US. This 'false spring' event also resulted in widespread damage to newly grown tissues of native deciduous forest species, shown by previous researchers to have had measurable effects on the terrestrial carbon cycle. The current study reconstructed the historical occurrence of false springs over most of the southeastern quarter of the conterminous US (32–39°N; 75–98°W) from 1901 to 2007 using daily maximum and minimum temperature records from 176 stations in the Global Historical Climatology Network database, and enhanced vegetation index (EVI) data derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations. A false spring index was derived that examined the timing of the start of the growing season (SGS), or leaf emergence, relative to the timing of a potentially damaging last hard freeze (minimum temperature $\leqslant -2.2\,°C$). SGS was modeled for the domain by combining EVI data with ground-based temperature 'degree day' calculations reflecting the rate of springtime warming. No significant area-wide, long-term SGS trend was found; however, over much of a contiguous region stretching from Mississippi eastward to the Carolinas, the timing of the last hard freeze was found to occur significantly later, this change occurring along with increased frequency of false springs. Earlier last hard freeze dates and decreased frequency of false springs were found over much of the northwestern part of the study region, including Arkansas and southern Missouri.

Keywords: false spring, start of the growing season (SGS), phenology, minimum temperature, deciduous forest, growing degree days (GDD), last hard freeze, Global Historical Climatology Network (GHCN)

1. Introduction

Persistent warmth engulfed much of the conterminous United States during March 2007, prompting the early growth of vegetation and of many agricultural and horticultural crops. In early April, a shift in the atmospheric flow pattern brought cold arctic air southward into the central and eastern US. This cold air engulfed the region for nearly a week, with temperatures dropping to freezing as far south as the Gulf Coast. Freeze damage was reported in nearly every state from

[3] Present address: Edison Mission Marketing and Trading, Boston, MA, USA.
[4] Author to whom any correspondence should be addressed.

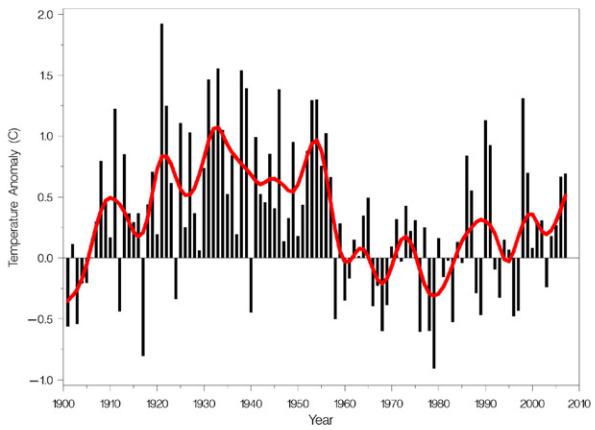

Figure 1. Annual mean temperature anomalies for the southeastern United States (32–39°N; 75–98°W) from 1901 to 2007, computed using the mean of 1961–90 as the base period. The red line is a smoothed five-year central moving average. A simple linear trend analysis over the entire period shows that temperatures have significantly decreased ($-0.36\,^{\circ}$C/century; $p = 0.05$), although over the past 50 years that trend has significantly reversed ($+0.99\,^{\circ}$C/century; $p = 0.03$).

Kansas and Oklahoma eastward to the Carolinas and Georgia, with estimates indicating total agricultural losses of about $2 billion [1]. Commodities affected by the arctic air outbreak included winter wheat, emerged corn, and blooming fruit trees such as apples and peaches. The 2007 'false spring' event also resulted in widespread damage to newly grown tissues of native deciduous forest species. This damage was found to have created both short-term and possible enduring effects on the terrestrial carbon cycle over much of the southeastern US [2].

The false spring of 2007 (hereafter, 2007 FS) should not be considered an isolated event; the literature has documented several similar events over the US (e.g., [3–5]). The 2007 event, however, is a reminder of the concern expressed by plant ecologists over 20 years ago: a warming global climate could actually increase the incidence of false spring freeze damage to temperate deciduous forests [6]. The southeastern US (SEUS) represents an observationally distinct region in which to test this concern. Much of the globe has experienced pronounced warming over the past century, as extensively documented in the Intergovernmental Panel on Climate Change's latest report [7], but analysis of annual mean temperatures (T_{ann}) for our study region shows a statistically significant decrease since 1901 (figure 1; $p = 0.05$) due to a historically unprecedented cool period from the 1960s through the early 1980s [8]. However, a temperature 'break' occurred in the late 1950s [9], and since about 1980 this region has exhibited an increasing temperature trend. (The 2007 FS affected not only the true southeastern states, but also adjacent portions of the south-central states, the lower Ohio Valley, and the mid-Atlantic, which we are including in our 'SEUS' study region.)

Given the character of temperature changes over the SEUS, and poorly understood natural variability and regional climate change feedbacks, has the risk of false spring freeze damage changed over the areas affected by the 2007 FS? To address this question, we develop a model for reconstructing historical trends in false spring occurrence and severity over the SEUS. We diagnose false springs by examining the timing of the start of the growing season, or leaf emergence, relative to the timing of a potentially damaging last hard freeze (minimum temperature (T_{min}) $\leqslant -2.2\,^{\circ}$C ($28\,^{\circ}$F)). Timing of leaf-out signals the beginning of the photosynthetic season and influences subsequent carbon cycling and productivity [10]. Regional long-term networks of phenology, i.e., the study of annually recurring events such as leaf-out, are currently sparse and temporally limited [11]. Therefore, we generate an empirical phenology model that integrates remotely sensed phenology from satellite data with surface weather records. This approach offers improvements over recent attempts in the meteorological literature to define the start of the growing season [12–14]. The model, although imperfect, offers an attractive advantage: it allows for reconstructions of phenology (and consequently false springs) back through the instrumental climate record, providing a context for the more recent and limited satellite data.

2. Methods

2.1. Meteorological data

A common limitation of studies examining extreme meteorological events (such as false springs) is their use of data beginning during the mid-twentieth century (e.g., [15]), mainly due to the absence of digitally available daily data. Recent efforts to digitize and quality assure surface weather records stretching back to the nineteenth century [16, 17] have resulted in an enhanced set of daily temperature data for many regions of the globe. For this study, daily maximum and minimum temperature observations from 1901 to 2007 for 309 stations over the SEUS (32–39°N; 75–98°W) were extracted from the Global Historical Climatology Network (GHCN) database [18], compiled and quality checked at the National Climatic Data Center (NCDC). The spatial domain was chosen to include the forested and agricultural areas most affected by the 2007 FS; it does not extend to the Gulf Coast or to Florida where impacts were far fewer [1]. To ensure the highest data quality, station records were analyzed for temporal gaps, missing data, and NCDC-assigned quality flags. Stations were kept if fewer than 20 years over 1901–2007 exhibited missing data or quality problems, with no more than five consecutive years allowed to be missing at any point. Individual data values having potential issues indicated by quality flags were set to missing. These selection criteria decreased the number of stations analyzed to 176.

2.2. The model for the start of the growing season (SGS)

The occurrence and severity of false springs depends on the timing of the start of the growing season (SGS), or leaf emergence, relative to the timing of a potentially damaging last hard freeze ($T_{\mathrm{min}} \leqslant -2.2\,^{\circ}$C). We introduce a false spring index (FSI) that considers these two events, and resembles indices mentioned in the literature [12, 19]. A positive FSI

Table 1. MODIS subset sites and locations of nearby weather stations with their T_{ann}.

MODIS subset location	Nearby weather station	Weather station T_{ann} (°C)[a]
Penn State SURFRAD Station, PA	State College, PA	9.4
Oak Openings, OH	Toledo Express Airport, OH	9.6
Morgan Monroe State Forest, IN	Bloomington Indiana University, IN	11.9
Missouri Ozark Site, MO	Columbia Regional Airport, MO	12.3
Asheville 8 SSW—North Carolina Arboretum (Beirbaum Site), NC	Asheville Regional Airport, NC	13.2
Bowling Green 21 NNE—Mammoth Cave National Park, KY	Bowling Green—Warren County Regional Airport, KY	13.9
Walker Branch Watershed, TN	Oak Ridge, TN	14.2
Duke Forest—Hardwoods, NC	Raleigh-Durham Intl. Airport, NC	15.3
Goodwin Creek, MS	Batesville 2 SW, MS	16.6[b]
Watkinsville 5 SSE—USDA/ARS (Colham Ferry Site), GA	Athens Airport, GA	16.7
Monroe 26N—Upper Ouachita National Wildlife Refuge, LA	Monroe Regional Airport, LA	18.4
Selma 13 WNW—Auburn, AL	Selma, AL	18.6

[a] Based on 1971–2000 data. [b] T_{ann} from nearby Charleston, MS.

value indicates a likely false spring, with damage to crops and vegetation.

$$\mathrm{FSI} = \text{Day of year (last hard freeze)} - \text{Day of year (SGS)}. \quad (1)$$

Determining SGS in the index requires an empirical model because extensive multi-species phenological data are currently limited for the United States, and therefore no direct measurement of SGS can be implemented back to 1901. Here, a simple model of the approximate timing of leaf-out is employed to reconstruct SGS over the period 1901–2007. The model combines enhanced vegetation index (EVI) data derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations with a ground-based temperature 'degree day' approach reflecting the rate of springtime warming. Remote sensing products like EVI have been used to monitor plant growth stages [20], and are related to the column integral of chlorophyll in the canopy [21]. Twelve deciduous forest sites in or near the domain were selected for the model (see table 1), and available EVI data from 2000 to 2008 for these locations were extracted from the MODIS land subsets online interface [22] and the MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN grid V005 (MOD13Q1) product [23]. The locations were selected on the basis of several considerations, and represent a range of forest species: the subset location must have a discernible annual EVI cycle, be within 25 miles of a meteorological reporting station of similar elevation ($<$250 ft elevation difference), and contribute to a good spatial coverage of the domain (no stations within 50 miles of one another). The two coldest sites in Pennsylvania and Ohio were selected, despite being outside of the domain, to ensure that the phenology model could be extended to the coldest sites in our GHCN subset (5 of 176 GHCN sites have a T_{ann} between 9.6 and 12.0 °C). The T_{ann} range for all of our GHCN stations was 9.3 °C (9.6–18.9 °C).

Deciduous forest sites were chosen because they comprise the majority of the domain [20], with agricultural areas (mainly winter wheat) concentrated in the western regions. SGS was then defined as the date in late winter or early spring when the site's EVI pixel value exceeded four standard deviations of its December-to-early-February winter baseline, corresponding to about two standard deviations above uncertainties associated with a larger 7 pixel × 7 pixel grid centered at the point considered. Due to the small sampling frequency of the available satellite data (one EVI value for each period of 16 days), and inherent EVI measurement error, the uncertainty associated with the satellite-derived SGS was about one week for most cases. To determine SGS, a linear interpolation was used between sequential EVI values. An assumption of the SGS definition is that the majority of crops will be vulnerable to hard freezes after the SGS, which is reasonable considering the damage caused by the 2007 FS. The SGS definition thus provides an approximate measure of both vegetative and agricultural development.

After SGS was established at the MODIS subset locations, local climatological data [24] from nearby surface weather stations were extracted and growing degree day (GDD) units were accumulated from a beginning base date (March 1) to the satellite-derived SGS date for each site-year. A base daily mean temperature for the GDD calculations was set at 10 °C, a typical value used in the literature [25]. That is, if a daily mean temperature exceeded 10 °C, then the difference between the actual and base temperatures was taken as the GDD contribution from that day. This method enabled GDD thresholds to be implemented on the historical GHCN data to reconstruct SGS over the domain for 1901–2007.

3. Results

3.1. The start of the growing season (SGS)

We first plotted the average MODIS-derived SGS for each of the 12 subset sites versus their respective T_{ann}, and found a strong linear relationship ($r^2 = 0.91$). This result suggests that temperature may explain a large portion of SGS variance,

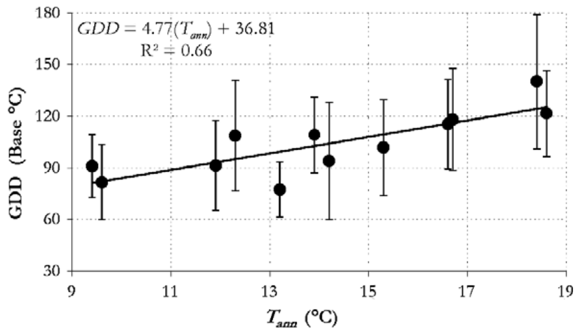

Figure 2. GDD threshold for each MODIS subset site. Shown are the average GDD for each site (filled circle), along with the $\pm 1\sigma$ variability (bars). This linear best-fit relationship between SGS and T_{ann} is used to reconstruct SGS from 1901 to 2007.

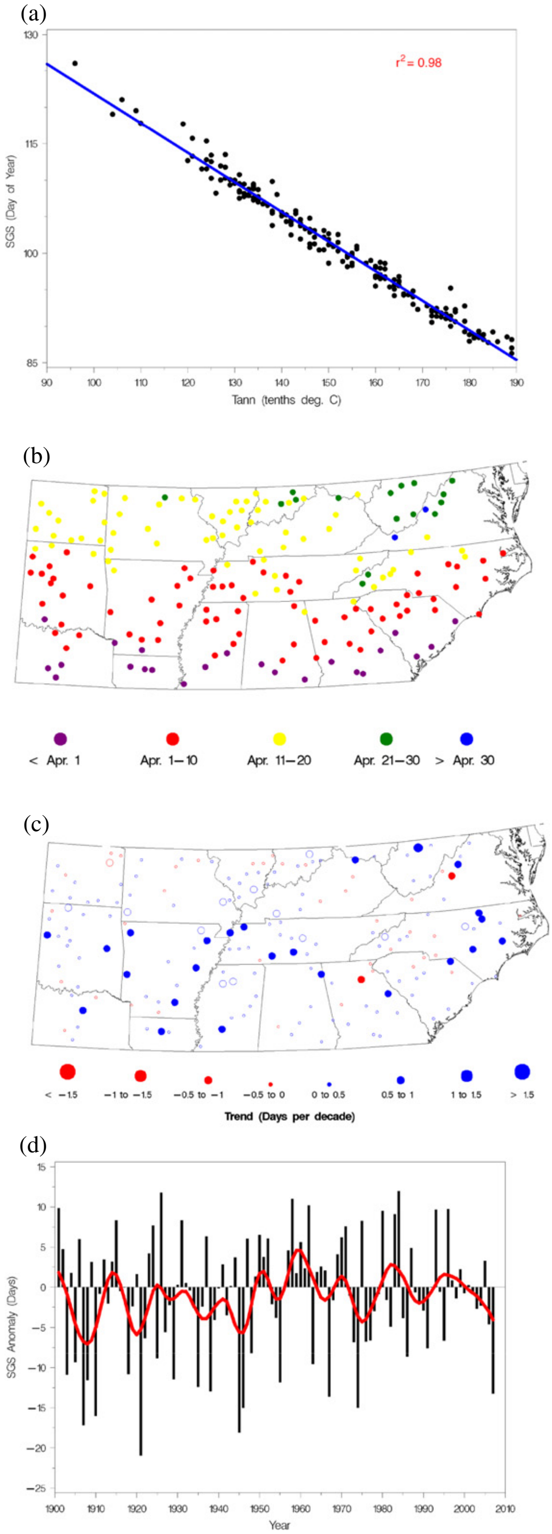

Figure 3. SGS results: (a) relationship between average date of SGS and T_{ann} for the 176 stations (Day of year = 162.44 − 4.05 (T_{ann}); $r^2 = 0.98$); (b) average date ranges of SGS for the 176 stations, 1901–2007; (c) linear trends in SGS, 1901–2007. Blue symbols indicate later SGS, with dots indicating trends significant at the 95% confidence level; (d) domain-averaged SGS annual anomalies, 1901–2007, relative to the 1961–1990 average date (April 12). Positive SGS anomalies indicate later SGS, and the red line indicates a five-year central moving average.

and supports the use of GDD thresholds to define SGS. The average GDD threshold for each subset site is given in figure 2, along with $\pm 1\sigma$ variability. A linear best-fit relationship with T_{ann} explains 66% of the variance in GDD, and generally works well for all the sites:

$$\mathrm{GDD} = 4.77(T_{\mathrm{ann}}) + 36.81. \qquad (2)$$

Furthermore, this best-fit model predicts SGS dates only 0.2 (±5.0) days later than the satellite observations, with a range of −12 to +10 days for all site-years. Equation (2) is used to reconstruct SGS back to 1901. A station's T_{ann} is the only parameter needed to define the GDD threshold, and consequently SGS for each year and location across the domain.

Upon applying (2) to the GHCN station data, we find that T_{ann} accounts for 98% of the variance in the average date of the SGS over the study area (figure 3(a)), which reflects the simple latitudinal gradient in temperature over the eastern US. The strong linear relationship found here also falls within the 95% confidence interval of a similar model derived from surface tower observations of ecosystem CO_2 exchanges [10, figure 3].

Figure 3(b) shows ranges of average SGS date for SEUS stations. SGS trends for each station spanning 1901–2007 are shown in figure 3(c), and a time series of the domain-averaged SGS annual anomalies is given in figure 3(d). Results indicate that despite the large interannual variability of the modeled SGS, no significant long-term trend exists for the SEUS as a whole (+0.2 days later/decade, $p = 0.3$); however, a few dozen stations over the study region (about half concentrated in the southwest) do show small but significant trends toward later SGS.

3.2. The timing of the last hard freeze

The timing of the last hard freeze ($T_{\min} \leqslant -2.2\,^{\circ}\mathrm{C}$) represents the second part of the FSI as expressed in (1). Ranges of the average date of the last hard freeze for all stations are depicted in figure 4(a). About 92% of the variance in the last hard freeze date can be accounted for by T_{ann} (figure 4(b)), further evidence that T_{ann} is the dominant factor, on average, determining

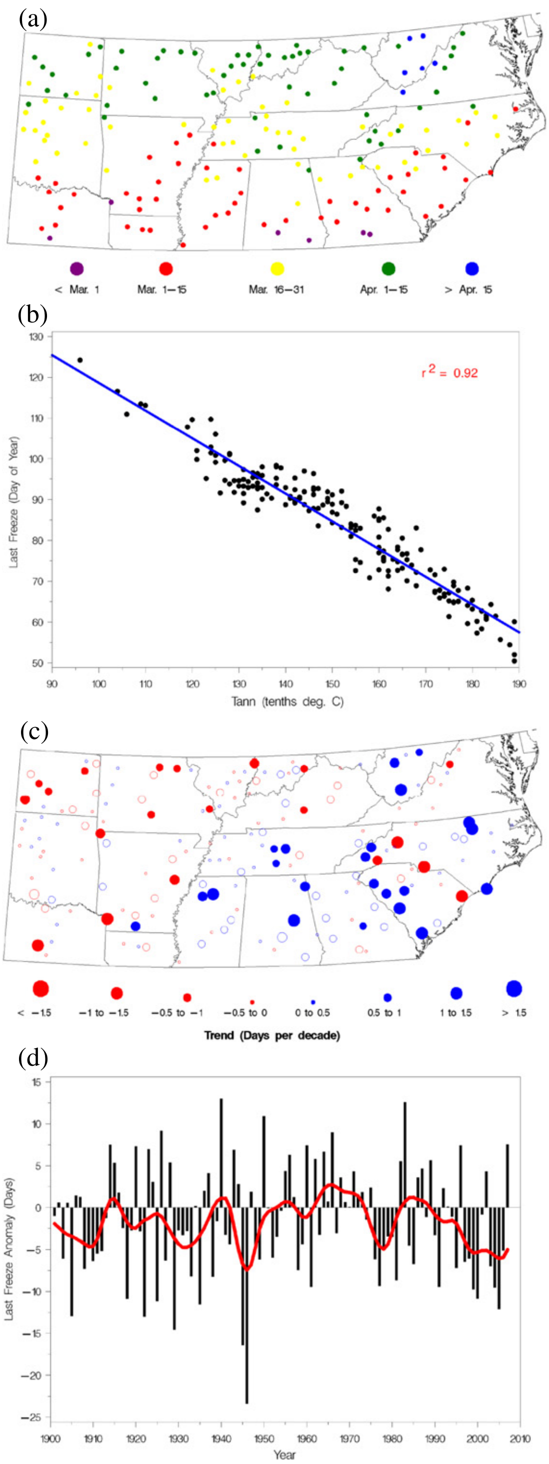

Figure 4. Timing of the potentially damaging last hard freeze ($T_{\min} \leqslant -2.2\,^{\circ}$C) over the SEUS: (a) average date ranges of last hard freeze for the 176 stations, 1901–2007; (b) relationship between average date of last hard freeze and T_{ann} for the 176 stations (day of year $= 186.49 - 6.79$ (T_{ann}); $r^2 = 0.92$); (c) linear trends in date of last hard freeze, 1901–2007. Blue symbols indicate later dates, with dots indicating trends significant at the 95% confidence level; (d) SEUS-averaged last freeze date annual anomalies, 1901–2007, relative to the 1961–1990 average date (March 25). Positive anomalies indicate later last freeze dates, and the red line indicates a five-year central moving average.

annually recurring events such as SGS and the last hard freeze date. Figure 4(c) shows that for 1901–2007 the last hard freeze occurred significantly later (>1 day/decade) over much of a contiguous region stretching from Mississippi eastward to the Carolinas, while areas to the northwest largely exhibited the opposite trend. This regional distinction is important, as the SEUS-averaged time series of last hard freeze date anomalies (figure 4(d)) by itself shows no evidence of century-scale trends; however, an interesting trend toward earlier last hard freezes is hinted at over about the past 25 years.

3.3. The false spring index (FSI)

The FSI considers the timing of SGS relative to the last potentially damaging hard freeze. No SEUS-averaged FSI trend is apparent over the period of record (figure 5(a)). The FSI captures the false spring of 2007 as the most extreme domain-wide event over the period of record, and figure 5(a) also suggests several similar widespread events over the past century (e.g., 1907, 1921, and 1955). The choice of a −5 day reference FSI value in figure 5(a) is made to better highlight these years. Other weaker false spring events (covering at least some portion of the SEUS) may have taken place in years with more moderate negative values, whereas more extreme negative FSI values likely indicate years without false springs. Spatial trends (figure 5(b)) reveal some evidence of an area from Mississippi eastward to western South Carolina exhibiting increasing risk of false spring (on the order of +1 day/decade), while areas in the west have generally experienced fewer false spring occurrences. A literature search revealed that the FSI accurately identifies false spring events dating back to 1907 ([5, 26, 27]). Figures 5(c) and (d) reveal a potential shortcoming of the index when applied to cool locations. The coldest stations have average FSI values of only around −5 days. Either the model does not work well for these locations, or, more likely, the damaging threshold temperature at these locations is below $-2.2\,^{\circ}$C.

Given the suspect average FSI values at the coldest stations, an alternative to using FSI trends and time series to identify likely false spring events may be to consider the lowest $T_{\min}$ ($LT_{\min}$) attained after SGS. Such an analysis yields results (figures 6(a) and (b)) largely consistent with those found using the FSI. $LT_{\min}$ after SGS has been generally decreasing from Mississippi to western South Carolina and increasing over essentially the northwestern quarter of the study area. To examine trends over the southernmost states (Mississippi, Alabama, Georgia, and South Carolina) more carefully, we computed $LT_{\min}$ after SGS for just those states. A somewhat different time series emerges (figure 7) in comparison to the FSI series (figure 5(a)). We clearly see evidence of the 2007 false spring, but now 1955 stands out with extreme cold temperatures $4\,^{\circ}$C lower than in 2007. An overview of the synoptic situation leading to this damaging cold snap is given in [5]. When looking back at the original FSI time series (figure 5(a)), we note that 2007 still appears as a greater anomaly than 1955. This could arise from either the model not accurately predicting SGS across a large portion of the domain during March 1955, or, perhaps more likely, the SGS being just

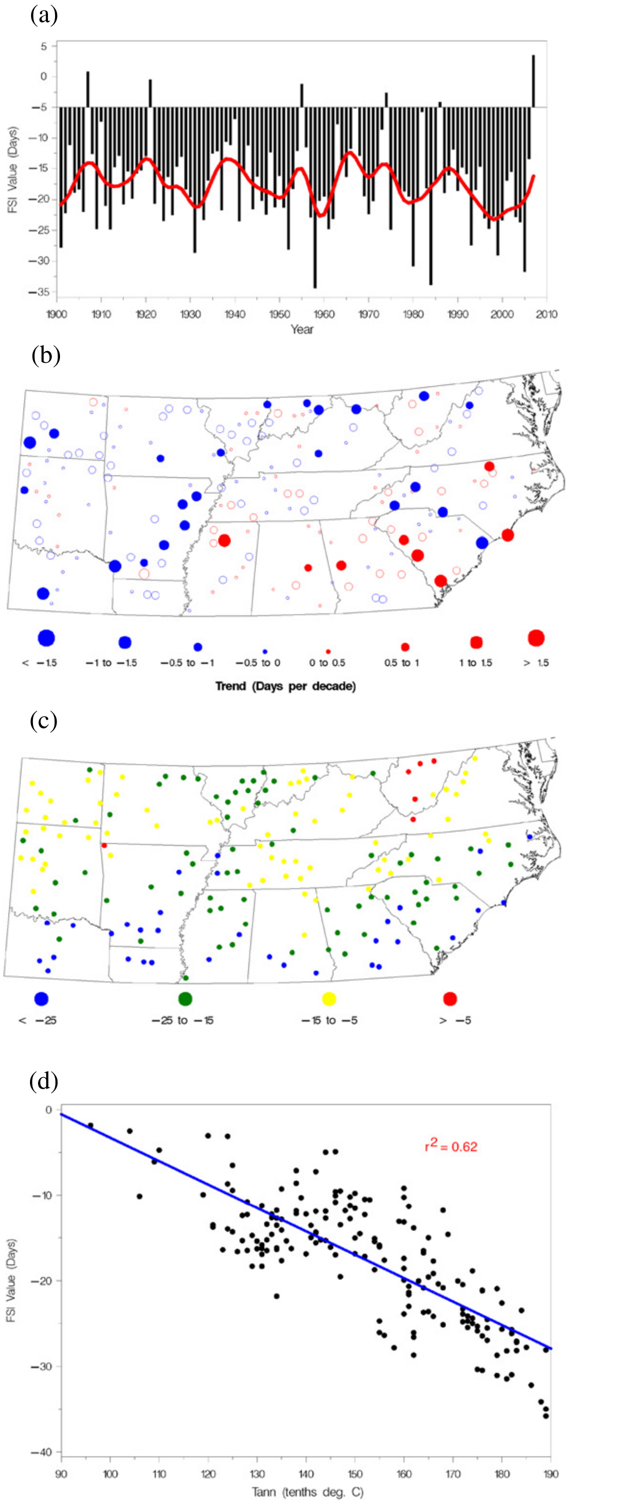

Figure 5. FSI results: (a) domain-averaged anomaly time series with five-year central moving average (positive values indicate high risk of false spring; note that the 2007 event has the largest FSI value over the period of record); (b) 1901–2007 linear trends at the 176 stations (red indicates increasing risk); (c) average FSI values for the 176 stations, 1901–2007; (d) relationship between average FSI and T_{ann} for the 176 stations (FSI $= 24.05 - 2.74$ (T_{ann}); $r^2 = 0.62$).

barely reached over the southern states when the extreme cold wave occurred, and therefore damage being confined to this region.

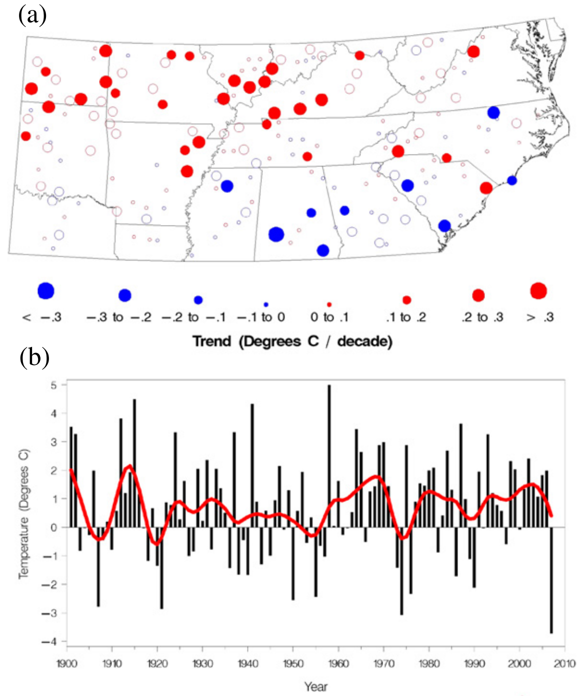

Figure 6. Lowest T_{min} after SGS: (a) 1901–2007 linear trends at all stations (blue indicates decreasing temperature);
(b) domain-averaged LT_{min} anomaly time series with five-year central moving average. Note that 2007 has the most negative LT_{min} anomaly.

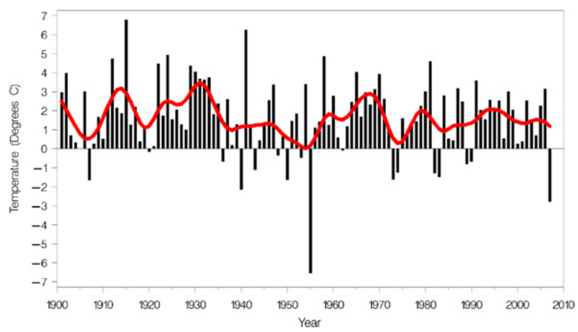

Figure 7. Lowest T_{min} after SGS averaged over Mississippi, Alabama, Georgia, and South Carolina. Note the extreme cold associated with the 1955 false spring.

4. Discussion and conclusions

The historical occurrence and severity of false springs over the southeastern United States from 1901 to 2007 was diagnosed by examining the timing of the start of the growing season (SGS), or leaf emergence, relative to the timing of a potentially damaging last hard freeze ($T_{\mathrm{min}} \leqslant -2.2\,^{\circ}$C), and deriving a false spring index (FSI). SGS was accurately reconstructed for the domain by integrating surface temperature records with enhanced vegetation index data derived from MODIS satellite observations. Other studies (e.g. [30]) fail to find a parameterization for their phenology (SGS) models; domain and station number/density differences may explain why the same conclusions do not extend to this work. If MODIS subset data were analyzed for every station in the domain, a larger variability would likely exist than for the 12 sites considered here. However, since we are concerned with long-term trends, results suggest that the SGS model is adequately calibrated by the sites examined in this study. We found that the interannual variability of the modeled SGS was large, and no significant area-wide, long-term trend existed. While SGS has been arriving earlier over a large portion of the globe in recent decades (e.g., [28, 29]), much of the southeastern US represents an observationally distinct land area not following global trends for many climatic variables.

The timing of the last hard freeze was also unchanged over the domain on average, although regionally, an area stretching from Mississippi eastward to much of the Carolinas experienced a significantly later last hard freeze, while areas to the north and west exhibited a trend toward earlier dates. Again, the behavior of these far-southeastern states with respect to this variable does not match that of other regions [31]. The FSI shows that the risk of false spring has increased over the far-southeastern states, while a southeast-averaged trend showed no significant change in FSI since 1901 due to the balancing effect of decreasing risk over the region's western and northern areas. Continued employment of the FSI for the southeastern US would be useful in monitoring trends and changes in risk.

The findings illustrate the complexity of observed climate change over the last century. In a generally warming world, the character of temperature changes in some regions does not result in decreasing risk of false spring, and may in fact pose increased risk if occurring during vulnerable plant growth stages. This work stresses the important need for climate change research to further examine sensitivity of ecosystems to small changes in spring climate, and to better understand large-scale atmospheric circulation modes that may drive regional temperature anomalies and climatic variability. Climate change is likely to not only increase globally averaged temperature, but may also increase temperature variance [32].

Vegetation development may be sensitive to these larger intra-annual temperature fluctuations, and these fluctuations will influence false spring occurrence. Global-scale plant phenology networks should also be expanded to strengthen understanding of phenological dependence on environmental factors. Ultimately, a SGS model should assimilate these phenology records with satellite and surface weather observations for maximum effectiveness.

Acknowledgments

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