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The False Spring of 2012, Earliest in North American Record

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Phenology—the study of recurring plant and animal life cycle stages, especially their timing and relationships with weather and climate—is becoming an essential tool for documenting, communicating, and anticipating the consequences of climate variability and change. For example, March 2012 broke numerous records for warm temperatures and early flowering in the United States [*Karl et al.*, 2012; *Elwood et al.*, 2013]. Many regions experienced a "false spring," a period of weather in late winter or early spring sufficiently mild and long to bring vegetation out of dormancy prematurely, rendering it vulnerable to late frost and drought.

As global climate warms, increasingly warmer springs may combine with the random climatological occurrence of advective freezes, which result from cold air moving from one region to another, to dramatically increase the future risk of false springs, with profound ecological and economic consequences [e.g., *Gu et al.*, 2008; *Marino et al.*, 2011; *Augspurger*, 2013]. For example, in the false spring of 2012, an event embedded in long-term trends toward earlier spring [e.g., *Schwartz et al.*, 2006], the frost damage to fruit trees totaled half a billion dollars in Michigan alone, prompting the federal government to declare the state a disaster area [*Knudson*, 2012].

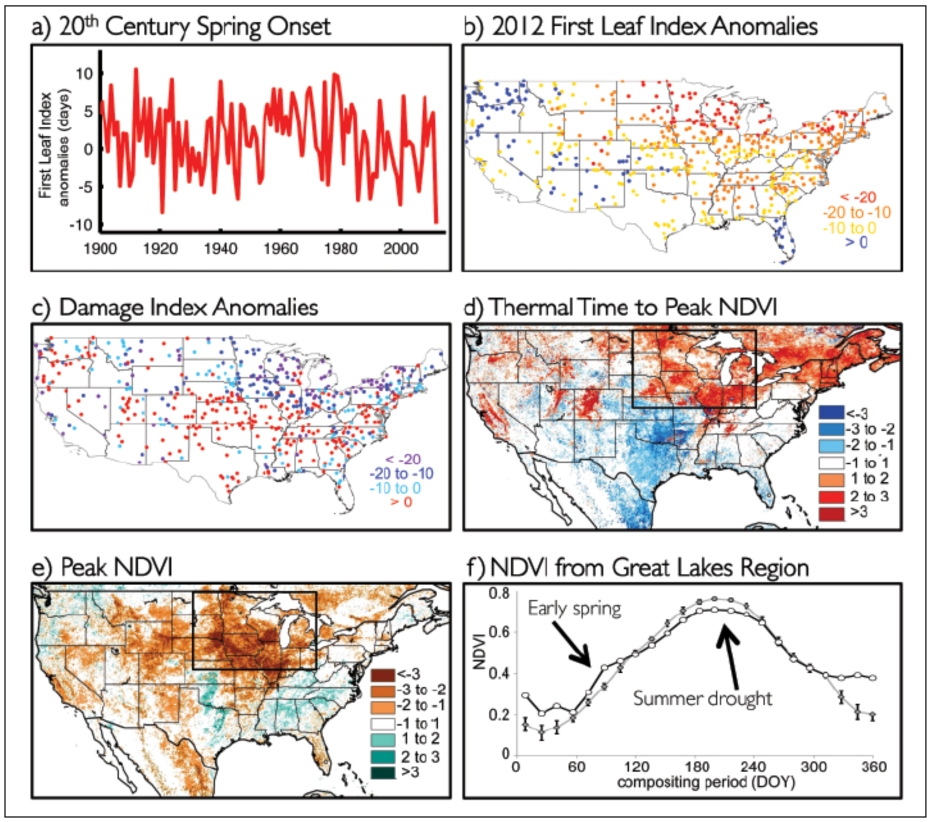

Fig. 1. Metrics of phenology during the spring and summer of 2012. (a) Time series of station-based extended spring index anomalies with respect to the 1981–2010 climatology from 1900 through 2012 and averaged over the conterminous United States (the first leaf index described in Schwartz et al. *[2006] and* Schwartz et al. *[2013]). (b) Map of first leaf index anomalies (in days) with respect to the 1981–2010 climatology. (c) Values of the damage index with respect to the 1981–2010 climatology (also described in* Schwartz et al. *[2006]), which measures the anomalous number of days between the last freeze event date and the first leaf index date (with high negative numbers indicative of a long period of potential plant growth followed by a freeze event). (d) Normalized anomalies, with respect to the 2001–2011 baseline, of the thermal time to peak normalized difference vegetation index (NDVI; a metric of heat accumulated prior to peak spring greenness [cf.* de Beurs and Henebry, *2005, 2008, 2010]). (e) Normalized anomalies in modeled peak NDVI (again, with respect to 2001–2011), indicating significantly lower values during the summer. (f) The NDVI time averaged across the Corn Belt and around the western Great Lakes, shown by the box in Figures 1d and 1e (in days from 1 January onward). The gray line in Figure 1f shows the 2001–2011 climatology, and the black line shows the 2012 anomalies. Observational data used to create Figures 1a–1c were obtained from the National Oceanic and Atmospheric Administration Global Historical Climate Network archive of daily temperature records (http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/), and Moderate Resolution Imaging Spectroradiometer (MODIS) products MCD43C4 and MOD11C2, used to create Figures 1d–1f, was obtained from the U.S. Geological Survey Land Processes Distributed Archive Center (https://lpdaac.usgs.gov).*

Phenological Forecasting: Predicting False Springs a Season or Two in Advance?

Robust phenological forecasts at seasonal time scales would enable governments and private entities alike to anticipate certain climate risks (e.g., frost damage, wildfires, and drought). Despite uncertainties associated with seasonal forecasts [*National Research Council,* 2010], some aspects of the circulation anomalies that drove the 2012 early spring may have been predictable

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several weeks, perhaps even a season, in advance (http://www.esrl.noaa.gov/psd/csi/events/2012/marchheatwave/anticipation.html).

Although phenological forecasting on comparable time scales is still in its infancy, several recent applications of phenological metrics, called phenometrics, are beginning to lay the groundwork for relating spring variations in the atmosphere to large-scale ecological effects [e.g., *Cayan et al*., 2001; *Russell and Wallace*, 2004; *de Beurs and Henebry*, 2008; *Ault et al*., 2011; *McCabe et al*., 2012; *Schwartz et al*., 2013]. These studies suggest that hemispheric patterns of variability in the atmosphere and ocean—which are sometimes predictable—play a fundamental role in governing the timing of spring throughout North America and elsewhere. Although the ecological relevance of these findings may still be elusive in regions lacking long-term phenological observations, there is considerable promise for successful phenological forecasting through continued modeling and observational endeavors.

Historical Phenological Monitoring in the United States

Systematic efforts at continental-scale phenological monitoring did not begin in the United States until the mid–twentieth century, although phenological observations appear in the notebooks and writings of Aldo Leopold, Henry David Thoreau, and even Thomas Jefferson. In the 1950s, Joe Caprio of Montana State University recruited hundreds of volunteers from 12 western states to plant common lilac and, later, cloned honeysuckle and then record the date on which their leaves and flowers first appeared each spring (similar data from cloned plants were also collected in several eastern U.S. projects).

These observations now span more than 60 years, and the use of cloned plants reveals how weather and climate, as opposed to biological factors alone, govern their phenology [*Schwartz et al*., 2012]. This relationship enables empirical phenological models to be optimized for application at continental scales by using historical weather data [*Schwartz et al*., 2006]. Most important, however, these models capture the timing of a major transition into spring growth shared by many plant species whose leaf-out and flowering vary primarily with temperature. Such "spring indices" (SIs) have been used to characterize spring onset through time and across a wide range of geographies [*Schwartz et al*., 2006; *Schwartz et al*., 2013]. Essentially, these phenometrics allow scientists to model what the Caprio network of observations would look like if it included every site where daily meteorological data are available from the last century.

Phenometrics for the Early Spring of 2012

SIs for 2012 show that it was the earliest spring recorded since 1900 across the United States, and this large anomaly affected agriculture and ecosystems. Figure 1a shows the average spring onset anomaly (with respect to the 1981–2010 baseline) from 537 stations across 48 states. Much of the central and eastern parts of the domain experienced spring onset as much as 20 or 30 days ahead of their climatological expectations (Figure 1b). For states in which farmers planted crops early, the unusually warm spring led to early corn silking and reduced crop yields (http://usda01.library.cornell.edu/usda/nass/CropProd//2010s/2012/CropProd-09-12-2012.pdf). Unusually early blooming in fruiting trees (e.g., cherries, apples, peaches, and pears) was followed by a damaging but climatically normal hard freeze in April. The anomalous amount of time between the first leaf index date and last freeze (–2.2°C) event for sites across the United States is shown in Figure 1c (the damage index [*Schwartz et al*., 2006]). This map pinpoints the Great Lakes and the northeast as regions that were particularly vulnerable to the 2012 false spring.

Another class of widely used phenometrics is derived from satellite data and includes products such as the normalized difference vegetation index (NDVI), which provides a measure of the "greenness" of an area. These tools provide insight into growing season dynamics at high spatial resolution (e.g., <10 kilometers) across hemispheric scales. Simple parametric models can be used to link the seasonal progression of NDVI to "thermal time," a variable that weights the progression of time by the amount of warmth above a certain threshold [*de Beurs and Henebry*, 2005].

Phenometrics derived from these models highlight key points in the development of terrestrial vegetation: In 2012, normalized anomalies of thermal time to peak NDVI (calculated from the Moderate Resolution Imaging Spectroradiometer (MODIS) nadir bidirectional reflectance distribution function (BRDF) adjusted reflectance (NBAR) product and the MODIS Land Surface Temperature and Emissivity Product) show that the cumulative effects of anomalous early spring warmth were most pronounced across the Corn Belt, around the western Great Lakes region, and into the northeastern United States (Figure 1d). However, peak NDVI values were significantly lower than average due to drought conditions that set in during June, cutting short the growing season across the Corn Belt and around the western Great Lakes (Figure 1e). The effects of the early spring/summer drought sequence can be clearly seen in Figure 1f, which compares the anomalies of 2012 to NDVI climatology for the Great Lakes region (similar findings are reported for Illinois in *Karl et al.* [2012]).

Large-Scale Ocean and Atmospheric Variations Contribute to Phenological Effects

Continental-scale variations in phenometrics occur on interannual to decadal time scales as responses to organized structures of variability in the ocean and atmosphere [*Cayan et al*., 2001; *Russell and Wallace*, 2004; *de Beurs and Henebry*, 2008; *Ault et al*., 2011; *McCabe et al*., 2012; *Schwartz et al*., 2013]. For example, twentieth century trends toward earlier spring in western North America (1.5 to 3 days per decade [*Schwartz et al*., 2006; *Ault et al*., 2011]) outpaced global averages (~1.2 days per decade [*Schwartz et al*., 2006]), while trends in the southeastern United States were toward later spring onset dates [*Schwartz et al*., 2013].

In terms of the time-averaged structure of the atmosphere, these findings make sense because the two regions are dynamically linked. When a relative low-pressure zone emerges over the North Pacific Ocean, it creates a ripple effect downstream, with a relative high above western Canada and a trough over the southeastern United States. Such a configuration favors warm air mass intrusions and early spring onset across much of western North America, while concomitantly allowing cold air masses to move into the southeast and protracting spring in that region.

The historically early spring of 2012 was driven primarily by a strong, stable high-pressure system that set up over much of the northeast during March and caused record-setting high temperatures during that month [*Karl et al*., 2012]. From a phenological perspective, the timing of this atmospheric ridge in March was as important as its magnitude. It triggered a large number of early spring plant responses such as the appearance of first leaf, bud growth, and green-up (Figure 1f). The subsequent freeze events in the Great Lakes region and northeast therefore had a more deleterious effect on annual productivity. Notably, the northwestern United States (Oregon and Washington) as well as southern Florida saw abnormally late spring onset in 2012 (Figure 1b). This emphasizes the role of large-scale waves in the atmosphere in modulating spring onset differently at continental scales.

Given the critical role of large-scale circulation structures in governing spring onset, understanding the predictability of the atmospheric ridge that drove early spring in 2012 may facilitate phenological forecasting. Developing these products will necessarily require extensive vetting and validation by using a wide range of phenometrics as well as other observational data sets, particularly those being collected at continental scales as part of the USA National Phenology Network (http://www.usanpn.org). If successful, however, phenological forecasts could produce short- and medium-term climate predictions in near real time, thereby allowing a wide range of resource managers to better anticipate and mitigate the effects of a changing climate.

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