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Onset of spring starting earlier across the Northern Hemisphere

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Abstract

Recent warming of Northern Hemisphere (NH) land is well documented and typically greater in winter/spring than other seasons. Physical environment responses to warming have been reported, but not details of large-area temperate growing season impacts, or consequences for ecosystems and agriculture. To date, hemispheric-scale measurements of biospheric changes have been confined to remote sensing. However, these studies did not provide detailed data needed for many investigations. Here, we show that a suite of modeled and derived measures (produced from daily maximum–minimum temperatures) linking plant development (phenology) with its basic climatic drivers provide a reliable and spatially extensive method for monitoring general impacts of global warming on the start of the growing season. Results are consistent with prior smaller area studies, confirming a nearly universal quicker onset of early spring warmth (spring indices (SI) first leaf date, -1.2 days decade^{-1}), late spring warmth (SI first bloom date, -1.0 days decade^{-1}; last spring day below 5 °C, -1.4 days decade^{-1}), and last spring freeze date (-1.5 days decade^{-1}) across most temperate NH land regions over the 1955–2002 period.

However, dynamics differ among major continental areas with North American first leaf and last freeze date changes displaying a complex spatial relationship. Europe presents a spatial pattern of change, with western continental areas showing last freeze dates getting earlier faster, some central areas having last freeze and first leaf dates progressing at about the same pace, while in portions of Northern and Eastern Europe first leaf dates are getting earlier faster than last freeze dates. Across East Asia last freeze dates are getting earlier faster than first leaf dates.

Keywords: climate change, freeze dates, global warming, growing season, Northern Hemisphere, phenology, spring

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Introduction

The pronounced warming of Northern Hemisphere (NH) land in recent decades is well documented (IPCC, 2001). Analyses of seasonal average temperatures reveal that across many temperate areas, for example, warming is typically greater in winter and spring than in the other seasons (Bonsol *et al*., 2001; Robeson, 2004). Responses to warming in the physical environment, such as changes in ice breakup dates on lakes and rivers have also been reported (Magnuson *et al*., 2000). However, such climatological/physical studies are not designed to probe the impacts of these temperature changes on the biosphere.

Plants respond to the cumulative effects of daily weather over an extended period, so their development stages are effective integrators of climate data. One specific measure, first appearance of spring foliage, is particularly important because it often shows the strongest response to temperature change, and is crucial for accurate assessment of processes related to start and duration of the growing season (White *et al*., 1997; Cayan *et al*., 2001; Chuine & Beaubien, 2001; Fitzjarrald *et al*., 2001; Schwartz & Crawford, 2001). Changing temperatures can force adjustments in crop production, and produce ‘ripple effects’ in natural ecosystems. For example, if plants bloom earlier, then insects must try to adjust

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their life cycles, as well as, other animals that use insects for food. Further, some species can probably respond better, thus gaining an evolutionary advantage. Given such grave consequences, understanding more about interactions during spring 'greening' is crucial to improve models, monitor growing season variations, and calculate the carbon budget precisely (White *et al.*, 1999; Wilson & Baldocchi, 2000; Chmielewski & Rötzer, 2002).

Studies of changes in plant and animal life-stage events, driven by environmental change (phenology) have revealed important impacts in selected regions with sufficiently long data series (e.g. Menzel & Fabian, 1999; Schwartz & Reiter, 2000; Peñuelas & Filella, 2001; Ahas *et al.*, 2002; Sparks & Menzel, 2002; Parmesan & Yohe, 2003; Root *et al.*, 2003). Notably, summaries of these findings show that many spring events (plant leafing and blooming, insect hatching, and arrival of migrating birds) are occurring earlier in response to warming, especially since the mid-1950s (Walther, 2003; Badeck *et al.*, 2004). However, as the distribution of these regional studies is uneven (most are in Europe) and none are based on a global-scale phenology network (utilizing similar species and observational methods) their ability to represent change across the entire NH (or even for their various results to be precisely compared) is limited.

Satellite-derived information is playing an important role in development of global biospheric databases, as it has shown what appears to be a fairly consistent response of spring vegetation growth starting earlier in response to recent warmer temperatures (Myneni *et al.*, 1997; Zhou *et al.*, 2001). However, these data are available only since the 1980s, and typically do not provide precise interpretations of changing plant responses and climate conditions at the local scale (Schwartz, 1998; Schwartz *et al.*, 2002; Badeck *et al.*, 2004). In this study, we bridge the approaches employed in dispersed regional phenological studies and hemisphere-wide remote sensing analyses by integrating daily maximum and minimum temperatures into a suite of modeled and derived measures that link plant phenology with its basic climatic drivers, and can be used to monitor general impacts of warming on the start of the growing season either at individual stations, or aggregated up to hemispheric spatial-scale and century time-scale (Schwartz, 1994; Schwartz & Reiter, 2000). Such measures provide consistent and spatially extensive information that facilitates evaluation and linkage of regional phenological studies across all temperate regions of the NH.

Materials and methods

We gathered daily maximum–minimum temperature data (these will serve as input for producing the suite of modeled and derived measures) from stations covering all temperate portions of the NH, over the longest possible time. The National Climatic Data Center (United States) provided most of these data. Specific sources included the Historical Climatological Network, TD3200 Daily Summary of the Day, Global Daily Climatological Network, and DatSav (daily data generated from hourly and three-hourly synoptic reports worldwide). In addition, we obtained supplemental datasets for specific countries and regions from the Carbon Dioxide Information and Analysis Center at Oak Ridge, TN, Chinese Academy of Meteorological Sciences, Environment Canada, European Climate Assessment, German Weather Service, and Instytut Meteorologii I Gospodarki Wodnej (Poland).

Most of these daily maximum–minimum temperature values were already evaluated and cleaned to remove questionable values as part of their source development, but all were additionally checked to ensure that no daily minimum temperature value was larger than the corresponding daily maximum temperature value. Station data were used rather than gridded values primarily because of the undesirable homogenizing effect that widely available coarse-resolution grid point data can have on spatial differences, resulting in artificial uniformity of processed outputs. Output products that preserve individual stations results were considered superior for proper interpretation of often spatially heterogeneous growing season-related measurements (Schwartz & Reiter, 2000; Schwartz & Chen, 2002; Menzel *et al.*, 2003).

We based station selection for inclusion in the database on these criteria: (1) provide for the best temporal and spatial coverage possible; (2) have at least 25 of 30 years during the 1961–1990 period with no 30-day periods missing more than 10 days of data; (3) have sufficient wintertime chilling and spring-summer warmth to generate valid Spring indices (SI) model output (Schwartz, 1997; Schwartz & Reiter, 2000; Schwartz & Chen, 2002); and (4) have at least 30 of 40 years during the 1961–2000 period with valid SI model output available to compute linear trends. These criteria resulted in a database that included 1417 stations (Fig. 1).

This information served as input for calculating a set of variables related to onset of the growing season from several perspectives, including plant development and temperature climatology (Schwartz, 1997; Jaagus & Ahas, 2000; Schwartz & Reiter, 2000). Although widely cited as a general concept, definitions of the growing season will differ by plant species (including specific constraints), and can be calculated in various ways (plant phenology, days above temperature thresholds, days between freezes, etc.). So the applicability and precise impact of any particular measure of the growing

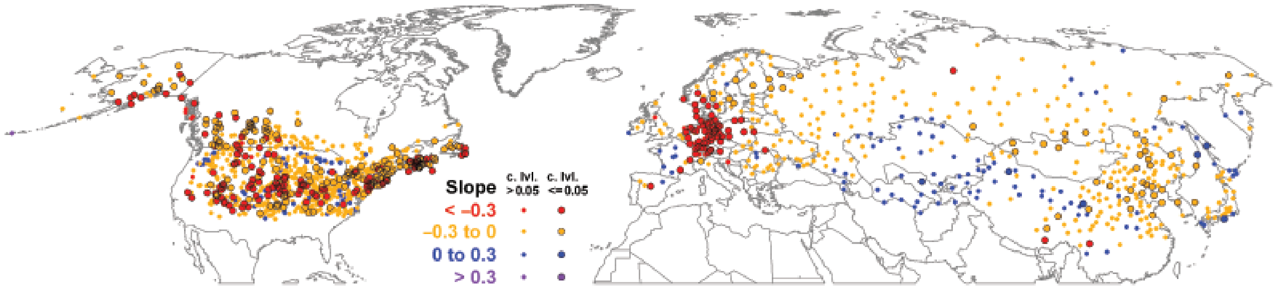

Fig. 1 Spring indices (SI) first leaf date 1961–2000 trend by station. Trend values are in days per year and colors show categories. Stations with trends significant at the 0.05 level or better are shown with larger symbols outlined in black.

Table 1 Spring Indices (SI) first bloom model performance (model output compared with lilac bloom data in selected regions)

Region (*lilac* species)	Total n of cases/ n of sites within region	Bias error (days) *shows values after adjustment by a constant value for better absolute model fit (see note in text)	Absolute error (days)	Pearson's *r* value
Eastern USA (*Syringa chinensis* clones)	2152/178	+ 0.09*	4.11	0.92
Western USA (*Syringa vulgaris*)	1293/126	−0.42	4.65	0.91
China (*Syringa oblata*)	325/27	−0.07*	3.81	0.96
Estonia (*Syringa vulgaris*)	85/2	−0.25*	3.35	0.80
Germany (*Syringa vulgaris*)	1115/45	−0.26*	4.39	0.87

season on specific plant species should be carefully considered. In this study, SI phenology models that simulate the phenology of representative cloned shrubs (lilac and honeysuckle) are the core measurements. They have been thoroughly tested at 378 sites across Germany, Estonia, China, and the USA, and show a consistent response in these varied regions (Table 1). It is important to emphasize that the 'bias error' variations reported in Table 1 are mostly the result of different lilac species, nonclonal plants, and somewhat different definitions of the first bloom phenological event being used in the listed regions. These factors slightly affect the absolute output values of the models, but in no way hinder their ability to detect trends in a reliable way across the regions (as shown by the consistent absolute error and correlation values). They also serve to highlight two of the greatest advantages of using SI models for evaluating basic phenological trends: (1) as the SI models can be generated at any location that has daily maximum–minimum temperature time series, they can be produced and evaluated over much larger geographic areas than any currently available conventional phenological data; and (2) the model output is consistent over all areas, which may not be true for conventional data for the reasons listed above (different species and event definitions), as well as, human observation variations.

The models also have a demonstrated potential to represent seasonally integrated changes in temperature that plant species which are temperature responsive and not water limited in spring will react to. Thus, they are most applicable to selected forest trees and shrubs (those whose phenology is temperature responsive) and agricultural crops planted in temperate regions with adequate rainfall, or in temperate dry regions where irrigation is used. The models show valid output in all areas that the lilac and honeysuckle plants would receive sufficient chilling in the cold season and sufficient heat in the warm season to theoretically survive (survival is theoretical because the models do not address potential summer water stress or winter cold mortality).

As an example of this potential, spatially averaged yearly departure-from-normal values of first bloom SI dates for Europe (at 136 climate stations, 15°W to 30°E longitude), over the 1959–1993 period, were very highly correlated ($r = 0.928$, significance level 0.0005) with comparable International Phenological Gardens (IPG) data (representing bud-burst values averaged across a wide variety of tree and shrub species at approximately 80 sites across the continent, IPG departure data were provided by A. Menzel (personal communication), and are described in Menzel & Fabian (1999) and Menzel (2000). Similar tests in north-eastern China (at seven stations in the area ranging from 32°N to 53.5°N latitude and 106°E to 135°E longitude) over the 1982–1996 period, showed that first leaf SI dates were highly correlated ($r = 0.687$, significance level 0.005) with onset of spring growth dates averaged across many tree and shrub species (data provided by X. Chen, personal communication). Lastly, annual comparisons of the first bloom SI against multiple-native-species-averaged tree and shrub data at the Harvard Forest, MA, USA (42.53°N, 72.17°W) over the 1990–1999 period and similar comparisons at Wauseon, OH, USA (41.30°N, 84.10°W) over the 1884–1899 period showed a high correlation ($r = 0.818$, significance level 0.007, Schwartz *et al.*, 2002; and $r = 0.796$, significance level 0.0005, Schwartz, 1997,respectively).

Thus, these SI allow an assessment of the change in seasonally integrated temperatures occurring at climate-monitoring sites (many more available than phenological sites) in a consistent way across regions (because of the use of clonal plants) that the aforementioned vegetation categories will most likely be responsive to. While not reproducing all the details of multispecies phenology data at any site, or the specific phenology of some types of plants, these models process weather data into indices directly related to growth and development of many plants. As such, they provide baseline assessment of each location's general phenological response (with the above noted limitations) over a standard period, supplying a needed context for evaluating and comparing regional or local-scale studies (Badeck *et al.*, 2004).

We generated the SI 'suite of measures' for all available station years of data. The suite includes eight model-related measures that facilitate an analysis of temperature-related climate variations and their impact on spring plant development, as outlined in previous work (Schwartz & Reiter, 2000; Schwartz & Chen, 2002):

1. first −2.2 °C freeze date in autumn,
2. composite chill date – average date when winter cold requirements among the three indicator plants (lilac and two honeysuckle species) have been satisfied, meaning they are ready to respond to spring warmth. (The requirement for the lilac is 1375 chill hours, and 1250 chill hours for the two honeysuckles, base 7.2 °C),
3. SI first leaf date – 'early spring' average date among the three indicator plants that leaves grow beyond their winter bud tips, related to a general onset of growth in grasses and shrubs,
4. SI first bloom date – 'late spring' average date among the three indicator plants that flowers start to open, related to a general onset of growth in dominant forest vegetation,
5. last −2.2 °C freeze date in spring,
6. freeze period, the number of days from first freeze date in autumn to last freeze date in spring,
7. damage index value, the difference in days between the SI first leaf date and last −2.2 °C freeze date, indicative of the relative internal timing of spring and potential for plant damage in a given year (Schwartz, 1993),
8. average annual temperature, and all four average seasonal (December–February = winter, etc.) temperatures for comparative purposes (this is a modification from the earlier referenced studies where monthly average temperatures were generated).

Other indicators of climatic seasons were calculated at the same stations for comparison. For these measures, temperature thresholds determine seasonal timing, such as when the daily mean temperature permanently increases above and falls below 0°, 5°, and 13 °C (Jaagus & Ahas, 2000). The period above 0 °C is called the 'warm season', above 5 °C the 'growing season' and above 13 °C 'summer.'

Next, we calculated 30-year averages for the 1961–1990 period for all measures at each station, and determined yearly departures-from-normal to facilitate compositing of results. For each individual station, linear trends were now determined for each measure over the 1961–2000 period, with particular attention paid to the trend of temporal change, and its statistical significance. Station trend results were mapped for each measure, with special highlighting applied (in the graphical results) to those stations with trend values significant at the $\alpha = 0.05$ level or better.

North America and parts of Europe were overly represented both temporally and spatially among the stations, so we needed to apply adjustments before hemisphere-wide average values could be calculated for all measures each year. This was accomplished temporally by narrowing the period of study to those years with data from at least 70% of the total stations, and no regions with large spatial gaps compared with the full network, which resulted in an available period of 1955–2002.

In order to deal with the uneven spatial distribution, we averaged all station outputs for each measure to a single value within every 5° × 5° grid box each year. These grid-cell values (with appropriate weighting adjustment for their varying size with latitude) were then used to calculate the hemispheric mean and standard error for every measure in each year. Hemispheric trends were calculated from these time series, and also evaluated to an equinox-adjusted time scale (this step was not applied to the individual station time series because its small effect was not deemed crucial to those analyses) as recommended by Sagarin (2001). Lastly, we graphed results from all variables for visual evaluation.

Results and discussion

We evaluated variables based on their trend (slope of linear change with time) at all stations over the 1961–2000 period (Schwartz, 1994, 1997, 1998; Schwartz & Reiter, 2000). Average annual and seasonal temperatures are described first to provide a link to other climate change studies, and a general context for remaining results. While many previous studies produced selected results also reported in this study, most were for other periods, and so are not directly comparable. In the following discussion, comparable results are cited as appropriate. Average annual temperatures are getting warmer across nearly all temperate land areas in the NH (Jones & Moberg, 2003). Most stations in Europe, East Asia, and Alaska have significant trends of $+0.3\,^{\circ}\mathrm{C\,decade}^{-1}$ or greater. The rest of North America exhibits a more complex pattern with much warming but some cooling, especially in the east. Central Asia is the only area that does not show strong warming.

Seasonal average temperatures show that annual warming is clearly being caused primarily by the winter and spring seasons (Klein Tank *et al*., 2002; Robeson, 2004). Winter (December–February) temperatures are broadly similar to the annual, except that warming is less intense in Western Europe and western North America, but more intense in eastern North America (trends of $+0.6\,^{\circ}\mathrm{C\,decade}^{-1}$ or greater).

In spring (March–May), warming is considerably reduced but still present in Europe and East Asia (Jones & Moberg, 2003). Across North America, the pattern is the reverse of winter, with a mixed signal of cooling areas in the east, but strong warming in the west (including Alaska). Summer (June–August) warming is weaker everywhere (few trends of $+0.6\,^{\circ}\mathrm{C\,decade}^{-1}$ or more). Nevertheless, most areas still show significant warming (but mixed with pockets of cooling in central and western North America). Few areas (only East Asia and far Western Europe) show significant warming in autumn (September–November), and much of Eastern Europe, Central Asia, and North America show weak warming or cooling (Jones & Moberg, 2003; Robeson, 2004). Large portions of central and eastern North America show significant cooling – some stations displaying trends of less than $-0.6\,^{\circ}\mathrm{C\,decade}^{-1}$.

SI first leaf dates, measuring change in the start of 'early spring' (roughly the time of shrub budburst and lawn first greening), are getting earlier in nearly all parts of the NH (Fig. 1). This change is strongest in Central Europe and North America, and weaker (but still present) in East Asia, Eastern Europe, and part of Western Europe. Central Asia is the only sizeable area without a trend. The average rate of change over the 1955–2002 period is approximately $-1.2\,\mathrm{days\,decade}^{-1}$ (Fig. 2). SI first bloom dates, representing change in 'late spring' (roughly when dominant trees show budburst in deciduous forest biomes), exhibit more diversity across the hemisphere, with small portions of central North America even showing later dates. Overall, however, most areas are getting earlier, at an overall average rate of approximately $-1.0\,\mathrm{days\,decade}^{-1}$.

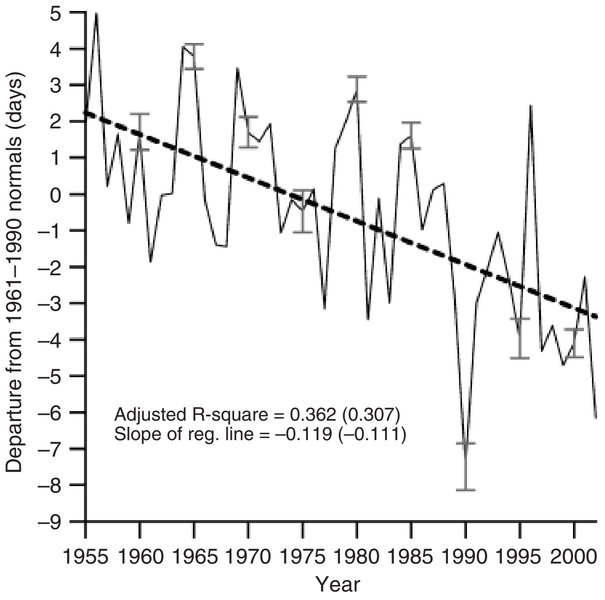

Fig. 2 Spring indices (SI) first leaf date departures by year across the Northern Hemisphere, 1955–2002. Standard error values (± 1) are shown by symbols at 5 year intervals. Linear regression trend shown with a heavy black dashed line. Statistics for the regression line as shown, with values in parentheses calculated after equinox date adjustment (Sagarin, 2001).

Other important climatological measures we assessed are: (1) modifications to dates of last and first freeze events, related to plant growth because of their lethal effects on many (especially garden) plants, and (2) date of the 'permanent' crossing of temperature thresholds in spring and autumn (time after which daily mean temperatures do not fall below the threshold in spring, or rise above it in autumn), as well as, the length of the period between. The length of the $-2.2\,^{\circ}\mathrm{C}$ freeze period (number of days between the first autumn freeze and last spring freeze) is decreasing (freeze-free period is increasing, see Kunkel *et al*., 2004), with the most dramatic change in East Asia, and weaker change in Europe and central North America. This appears to correspond with earlier findings of trends toward fewer numbers of annual freeze days (Frich *et al*., 2002; Kiktev

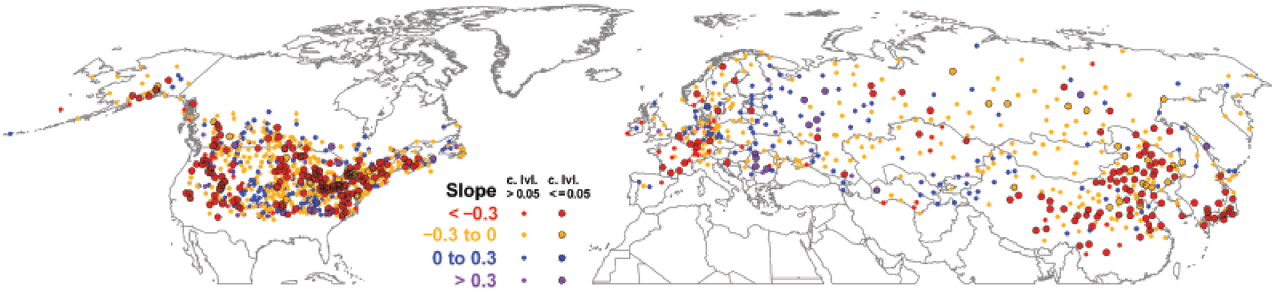

Fig. 3 Last spring −2.2 °C freeze date 1961–2000 trend by station. Details as in Fig. 1.

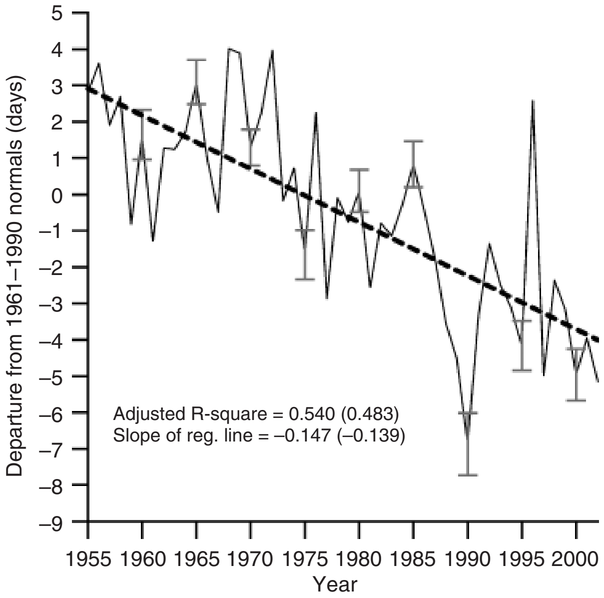

Fig. 4 Last spring −2.2 °C freeze date departures by year across the Northern Hemisphere, 1955–2002. Details as in Fig. 2.

et al., 2003). While first freeze dates in autumn are getting somewhat later, this decrease in the freeze period is being driven primarily by earlier spring last freeze dates (Heino *et al.*, 1999; Robeson, 2002; Menzel *et al.*, 2003; Meehl *et al.*, 2004; Feng & Hu, 2004) our results show these getting earlier on average at a rate of −1.5 days decade^{-1}, Figs 3 and 4,). Likewise, length of the period spent with no average daily temperatures below 5 °C, is increasing in most regions (Frich *et al.*, 2002; Menzel *et al.*, 2003) at an average rate of 1.6 days decade^{-1}, with the permanent crossing date in spring contributing most, by getting earlier at a rate of −1.4 days decade^{-1}.

The differing rates of change of last freeze date and onset of plant growth across various regions of the NH (measured as SI first leaf date minus last freeze date, and termed the damage index) offer diverse possibilities for impacts on plant development (Schwartz, 1993). Usually, when the time between the onset of plant growth and subsequent last spring freeze grows larger, the potential for damage increases, as plants are in a more advanced stage of development. A shortening period should have the opposite impact. In North America, although both are getting earlier, the relative rates of change of SI first leaf and last spring freeze date are spatially heterogeneous, so assessment of freeze damage risk variations are complex (Schwartz & Reiter, 2000). However, the onset of plant growth to last freeze date period is shortening in East Asia (last freeze dates getting earlier much faster than SI first leaf dates) which may suggest a lessening of the potential for plant freeze damage in this region (Schwartz & Chen, 2002; Zhai & Pan, 2003).

Scheifinger *et al.* (2003) did an extensive examination of the relative rates of change of last spring freeze events compared with 13 phenological phases over the 1951–1997 period, in a small region that included Switzerland, Austria, and primarily the southern portion of Germany. Their results showed that except for some of the earliest phenological events (these were progressing slightly faster or at the same rate as last freeze dates), last freeze dates were getting earlier at a faster rate than phenological events in that region. They also correctly caution that the timing difference between last freeze date and phenological event date will not be the same for all phenological events, so results from a single comparison (such as our damage index) need to be interpreted with caution.

Nevertheless, given that SI first leaf dates are most closely correlated with early spring phenological events, our results are consistent with those of Scheifinger *et al.* (2003), but reveal a larger pattern of change for the relationship between last freeze dates and first leaf dates across the European continent (Fig. 5). In western continental areas (primarily France) last freeze dates are getting earlier at a faster rate than SI first leaf dates. In the Scheifinger *et al.* (2003) study area (Central Europe) last freeze dates and SI first leaf dates are getting earlier at about the same pace, while in European areas further to the north and east, SI first leaf dates show a tendency for getting earlier faster than last

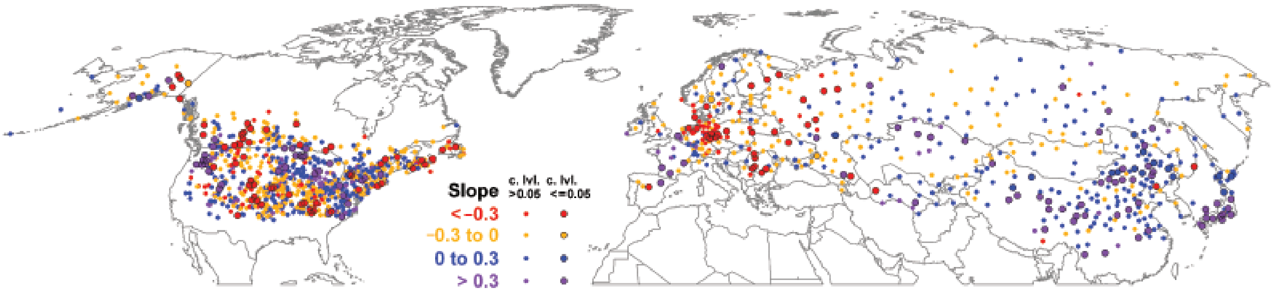

Fig. 5 Damage index value 1961–2000 trend by station. Details as in Fig. 1.

freeze dates (including some places in Russia and Eastern Europe where last freeze dates are actually getting later).

A final variable we examined is date of winter chilling satisfaction (SI winter chill date is when approximately 1375 chill hours, base 7.2 °C have accumulated). This is when deciduous plants have completed their winter rest, and can respond to springtime warmth. In many areas with strong winter/spring warming (East Asia and Western Europe) these dates are getting much later, meaning stress because of inadequate chilling may be causing inconsistent responses in some plants. Interestingly, in North America, the previously mentioned autumn cooling in the center and east are apparently supporting a strong trend toward earlier chilling satisfaction (despite significant winter warming in these same areas). Thus, plants here may have increasing capacity to continue responding to additional springtime warmth.

Conclusions

Two recent review articles provide an excellent context for evaluating our study and understanding its advantages and importance (Walther, 2003; Badeck *et al.*, 2004). Walther (2003) points out the difficulty posed by combining results from studies that deal with different species and areas in order to deduce common quantitatively comparable trends across different taxa, tropic levels, and geographic regions. Badeck *et al.* (2004) adds concerns about comparing studies with different time-series lengths. Our analyses produce a common and consistent set of measures related to temperature-driven plant development evaluated across the entire temperate portion of the NH over a standard period (which effectively addresses both Walther's and Badeck's concerns). Further, the spatial coverage of our trend analyses is much more extensive than most previous studies. Our results also provide a consistent and convenient framework within which to compare the results of many regional and local-scale phenology studies (which are affected by the use of different species, event definitions, and observer variations). By showing the basic climatic drivers of phenological change in various regions (with noted limitations in areas where temperature is not the major driver and/or precipitation is important), our measures will allow a first approximation of basic impacts on plant growth, potential for ripple/species competition effects in selected ecosystems, and agricultural impacts caused by global warming.

Indeed, if we look just in Europe (15°W–30°E longitude), average change in SI first leaf onset ($-2.2\,\text{days decade}^{-1}$) compares well with the $-2.3\,\text{days decade}^{-1}$ advancement rate of spring phenological events reported by Parmesan & Yohe (2003, data from 172 species combined in this study were almost exclusively from Europe). This close match in one continent supports the probable accuracy of the $-1.2\,\text{days decade}^{-1}$ trend we report for the entire NH (Fig. 2). Further, other previously reported features such as earlier spring events changing faster than later events (Sparks & Menzel, 2002), growing season length extending about 7 days since the 1960s (Walther, 2003), and last spring 0 °C freeze date in the USA changing by $-1.3\,\text{days decade}^{-1}$ (Easterling, 2002), are consistent with our results.

Lacking a global phenology network, basic impacts of global warming on the growing season in many different regions and (with noted limitations) the hemisphere as a whole, can be effectively monitored by using measures such as those reported here. Yet more phenological monitoring is needed. Badeck *et al.* (2004) emphasizes the need to keep current ground phenology observation networks in operation and expand them whenever possible, given their low cost/high value, the coarse nature of satellite-derived data, and the difficulties in comparing ground and satellite measures of phenology. Additional research is needed to understand how we can compare these two complimentary sources of phenological data more effectively and realize their synergistic benefits.

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