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Examining the onset of spring in China

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ABSTRACT: The onset of spring is a critical time in mid-latitude atmosphere-biosphere interactions. Deciduous plants resume growth after winter dormancy, and their activities cause land surfaces to become more active agents in energy and mass exchanges. The progress of spring plant development driving these changes can be conveniently monitored by observation of plant life-stage (phenological) events. Thus, phenological data can play a crucial role in understanding and monitoring springtime vegetation and climate dynamics, especially about potential changes over time. Although global-scale phenological monitoring is not yet possible, alternative strategies are available to assess these impacts. In this paper, a simple phenological model, driven by surface-level daily maximum-minimum temperatures is employed as a surrogate measure of the onset of spring in China. Contrasting with results from similar studies in North America and Europe, the onset of spring plant growth in China has no apparent change over 1959–1993. However, during the same period, last spring frost (–2.2°C) dates have become markedly earlier (by 6 d), with the greatest change occurring in the northeast portions of the country. First autumn frost dates have also become later (by 4 d), especially in north-central China. Combining these 2 changes, the frost period has decreased by 10 d over many northern regions of the country. A shorting frost period is consistent with decreasing diurnal temperature ranges and day-to-day temperature differences during spring and autumn in China, reported by previous research.

KEY WORDS: Phenology · Climate change · Global change · Spring · China · Modeling

1. INTRODUCTION

The onset of spring in mid-latitudes is a time of rapid change in the lower atmosphere. Deciduous plant growth resumes after winter dormancy, and these changes influence energy and mass exchange, as well as albedo of the surface. While the passage of synoptic weather systems can dilute and obscure these effects in particular places and during certain years, the modal pattern of plant growth processes is to produce a rapid and discernable change in the nature of lower atmospheric energy and mass balance (Schwartz 1996, Bounoua et al. 2000, Hogg & Price 2000, Durre & Wallace 2001, Freedman et al. 2001). In particular, sensible heat diminishes and latent heat rises, while carbon dioxide is rapidly drawn from and moisture infused into the surface layer by photosynthesis and transpiration, respectively (Wilson & Baldocchi 2000, Fitzjarrald et al. 2001, Schwartz & Crawford 2001). These modifications can be measured by meteorological instrumentation, but the number of stations so equipped is extremely small.

The timing of the onset of plant growth and associated change connected to the beginning of the growing season (last frost events, soil temperature thresholds, etc.) are of equal interest to the lower atmospheric changes mentioned above, as they are important indicators for the greening of land vegetation, and in the long-term will affect the distribution and hardiness of native plant species. Thus, effective means to assess and compare the timing of these changes over large regions would be useful (Myneni et al. 1997, White et al. 1997, Botta et al. 2000, Zhou et al. 2001). Phenology is the study of life-stage events in plants

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and animals driven by environmental factors. Appropriate phenological data can be of immense assistance in measuring the onset of spring activity and the associated lower atmospheric changes (Schwartz 1994, 1998, Menzel & Fabian 1999). Unfortunately, these valuable data are not widely recorded, and except for a few regions, such as western Europe, systematic collection of comparable phenological data over continental areas has not occurred (Schwartz & Reiter 2000). Thus, for the time being an alternative strategy must be employed.

2. SPRING INDICES DESCRIPTION

While many plants have not been observed, extensive observations have been made in eastern North America (ENA) on 1 type of cloned lilac (*Syringa chinensis* 'Red Rothomagensis') and 2 varieties of cloned honeysuckle (*Lonicera tatarica* 'Arnold Red' and *L. korolkowii* 'Zabeli'). Although few individual station records extend beyond 5 to 10 yr, the total volume of observations in the ENA network (over 2000), the overall period covered (1961–1994), and the geographic extent of the data (from approximately 35 to 49° N and 52 to 104° W) made for an ideal set of information to build phenological models capable of accurately simulating diverse events on a continental scale. A comparable lilac-honeysuckle database (but using common lilac plants, *Syringa vulgaris*) is also available in the western USA from 1957–1994 (Cayan et al. 2001).

Such models have been constructed and refined using a multiple regression methodology, and are called collectively 'Spring Indices' (SI, Schwartz 1997). The only input variables required to compute these SI for a selected location are daily maximum-minimum temperatures and latitude (for day length determination). There are 3 individual SI (model outputs): (1) *composite chill date*—the date when the winter cold requirement for the plant has been satisfied, meaning that it is ready to respond to spring warmth; (2) *first leaf date*—'early spring' date that lilac/honeysuckle leaves grow beyond their winter bud tips, related to a general onset of vegetative growth in grasses and shrubs; and (3) *first bloom date* – 'late spring' date that lilac/honeysuckle flowers start to open, related to a general onset of vegetative growth in dominant forest vegetation. Each of these SI is computed by averaging the dates produced by sub-models developed for the 3 plant varietals (1 lilac and 2 honeysuckles) listed above.

Several other variables that can be computed from daily maximum-minimum temperatures are produced with the SI because of their usefulness in interpreting plant-climate interactions, and the whole group is called the SI 'suite of measures' (Schwartz & Reiter 2000). These other variables include: (1) *first –2.2°C frost date* in autumn; (2) *last –2.2°C frost date* in spring; (3) *frost period*—the number of days from first frost date in autumn to last frost date in spring; (4) *damage index value*—first leaf date minus last frost date, indicative of the relative internal timing of spring and potential for plant frost damage in a given year [values becoming more positive indicate decreasing plant frost damage potential, as that corresponds to either (a) when last frost date occurs after first leaf date (most common situation) it moves closer in time to first leaf date, and plants are less sensitive to frost since they are not in as advanced a stage of development, or (b) when last frost date occurs before first leaf date, the time between the 2 dates is increasing, which again reduces the risk of frost damage]; and (5) *average annual temperature*, plus all 12 *average monthly temperatures* for comparative purposes.

The SI have been extensively tested and found to be reliable indicators of lower atmospheric changes and native species phenology in ENA (Table 1; Schwartz 1996, 1997, 1998). Noting why SI first leaf and first bloom dates are negatively biased 2 and 3 d, respectively, relative to *Syringa chinensis* (lilac) event dates is important. This is because phenological events for both honeysuckle species occur earlier than lilac events, and the SI are simple averages of the 3 plant-varietal sub-models. SI lilac sub-models are unbiased on average, relative to *S. chinensis* event dates, and have other error values similar to those reported for the 3-plant composite SI (Table 1).

Given the lack of global-scale phenological data, but the desirability of having some reasonable way to as-

Table 1. Comparison of lilac phenology and Spring Index (SI) model output in Eastern North America. n = 2323 for first leaf variables and n = 2152 for first bloom variables. SIFLD/SIFBD: SI first leaf/bloom date. DOY: day of year (January 1 = 1)

Variable	Minimum	Maximum	Mean	SD (d)
Syringa chinensis first leaf date (DOY)	28	152	104.1	17.4
SIFLD (DOY)	43	142	101.9	16.0
SIFLD + 2 d (DOY)	45	144	103.9	16.0
Bias error of SIFLD + 2 d (d)	–41	37	–0.3	8.8
Abs. error of SIFLD + 2 d (d)	0	41	6.6	5.8
S. chinensis first bloom date (DOY)	65	190	133.8	14.8
SIFBD (DOY)	62	182	130.9	14.0
SIFBD + 3 d (DOY)	65	185	133.9	14.0
Bias error of SIFBD + 3 d (d)	–29	50	0.1	5.8
Abs. error SIFBD + 3 d (d)	0	50	4.1	4.1

sess the onset of spring on a global scale, judging the applicability of the SI to other mid-latitude areas is important (Schwartz & Reiter 2000). Thus, the first objective of this paper is to assess the reliability of the SI in China, primarily through comparison with lilac phenological observations available in that country. If the models are adequate, then a second objective, development of a preliminary sketch of the trends and geographical patterns associated with any changes in these proxy measures, can be accomplished. These products will also permit comparisons to changes in the onset of spring already reported for Europe and North America (Menzel & Fabian 1999, Schwartz & Reiter 2000).

3. DATA

Chinese phenological data used in this study are for lilac *Syringa oblata* first leaf and first bloom dates observed at 31 locations across the country (primarily in the northeast and north-central regions) from 1963–1993 (Institute of Geography at Chinese Academy of Science 1965, 1977a,b, 1982, 1986a,b, 1988a,b, 1989a,b, 1992, Fig. 1). The Chinese national phenological network was established in 1961 and discontinued in 1996. Observations started in 1963 with 41 stations and the lilac *S. oblata* was chosen as the 'common observation species.' The Institute of Geography at the Chinese Academy of Science took responsibility for collecting the phenological data and publishing them. We acquired our lilac data from these yearbooks and from an unpublished data set (1989–1993). Because of alterations to the station network over the years, the data are spatially and temporally inhomogeneous. For example, in 1964 there were 69 stations, whereas during 1969 and 1972 there were only 4 to 6 stations.

Statistical analysis in central Beijing shows that the flowering dates of lilac correlates highly (Pearson's r, 0.01 significance level) with the flowering dates of other species such as David peach *Prunus davidiana* (r = 0.75), apricot *Prunus armeniaca* (r = 0.83) and black locust *Robinia pseudoacacia* (r = 0.73) over the 1950–1998 period. Further, an obvious downward trend (becoming earlier) has been observed in the flowering date time series of lilac, David peach, and black locust (Chen & Zhang 2001). This local trend is associated with urban development creating warmer temperatures in the Beijing metropolitan area, and it is not representative of other parts of the country. However, it demonstrates that lilac phenology responds to temperature changes in a fashion similar to some native tree species. Therefore, based on the following, it appears reasonable to conclude that lilac phenology can serve as a useful indicator of spring plant development for some portion of the deciduous native species in China: (1) the use of the lilac as a common observation species in the Chinese national network; (2) the favorable comparisons of lilac events to spring phenology of other species in Beijing; and (3) previous evidence of useful connections of lilac to native species phenology in ENA. Thus, the SI can be appropriately applied as proxy measures of the onset of spring, if the models prove accurate.

Daily maximum-minimum temperature data from 147 selected stations (as input for the SI models) over the 1952–1994 period, provided by the China Meteorological Administration to the US Department of Energy's Carbon Dioxide Information and Analysis Center (CDIAC, Oak Ridge, TN), are most of the climate data used in this study. Additional temperature data for 1995–2000 were kindly provided by the China Meteorological Administration. Climate stations were included in the study only if they had maximum-minimum temperature data available for at least 25 yr during the 1961–1990 period (this ensures that a representative 30 yr normal is available for use in annual departure-from-normal calculations, see Schwartz & Reiter 2000). Lastly, stations with either insufficient winter chilling (less than 1375 chill hours, base 7.2°C) or inadequate summer warmth for proper indicator plant (lilac-honeysuckle) development (roughly less than 48 500 growing-degree hours, base 0.6°C) during more than 5 yr, 1961–1990, as determined by model calculations, were also excluded (Schwartz 1997).

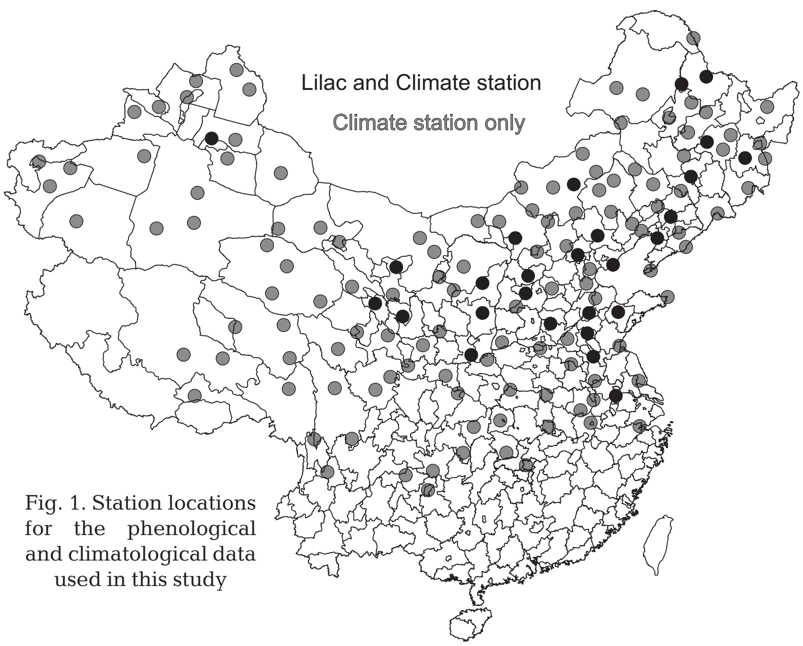

Fig. 1. Station locations for the phenological and climatological data used in this study

4. TESTING SPRING INDICES IN CHINA

The first research task was to verify the applicability of the SI to China. Initially, we needed to match phenological stations to climate stations, in order to compare lilac phenological first leaf and first bloom event dates with model dates generated from daily maximum-minimum temperatures. In a few cases, both types of data were recorded at the same site, but most often they were not. After an inspection of the available locations, we decided to include phenology/climate station pairs in the comparison that were either (1) within 0.5° of latitude and longitude of each other or (2) more than 0.5° but less than 1° of latitude and longitude from each other. Twenty-two site pairs met the first criteria, and 8 others met the second, for a total of 31 sets. However, 4 climate stations were matched to 2 phenology stations, so there were actually only 27 climate stations included in the comparison (Fig. 1).

One limitation of this approach is that no phenology/climate station pairings were available at elevations above 650 m, while the full 147 climate station network had 40 % of the stations above 900 m and 10 % above 3000 m. No biases were apparent in the highest phenology/climate station pairing results (above 500 m) compared to lower elevations, but the reliability of the SI at higher elevations (above 650 m) in China cannot be directly evaluated at this time. Tests of the SI in western North America showed no biases at station elevations up to 2400 m (Schwartz & Reiter 2000).

The overall error statistics and other results of the comparison are mostly similar to the values previously reported for ENA (Table 2). Absolute errors are actually smaller than in ENA, but this is likely related to the much smaller number of cases in China. Generally, the first leaf and first bloom SI both predict the corresponding lilac events in a linear fashion over the entire range of the data (Figs. 2 & 3). At the extremes, however, very early dates are slightly overpredicted (too late) and very late dates are slightly underpredicted (too early). These small biases are caused by nonlinear aspects of the lilac's temperature responses, which are not being fully simulated by the models. Similar biases are present in the ENA SI, and they represent a limitation of linear multiple-regression-based techniques.

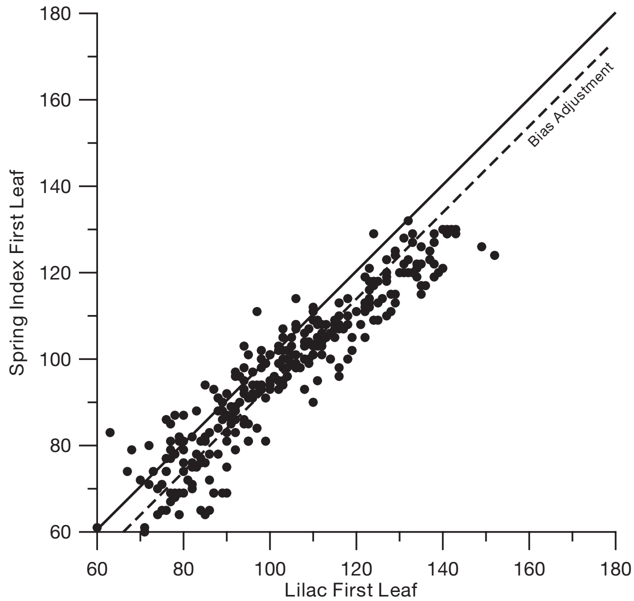

Fig. 2. Scatter plot of lilac first leaf date vs Spring Index (SI) first leaf date in China

Larger and different global biases occur in the Chinese SI than those observed in ENA. SI first leaf is biased 6 d early, and SI first bloom is biased 7 d late (Figs. 2 & 3, Table 2). These biases are not a concern for using the SI as indicators of the onset of spring, because (1) comparisons are made using departures from the 30 yr normal, rather than raw values; and (2) correlations between the lilac events and SI in China are comparable to the high levels observed in ENA (Table 3). Nevertheless, exploring reasons for these different model biases would be useful. Some possibilities include (1) the lilacs observed in China are a different species (*Syringa oblata*) than those observed in ENA (*S. chinensis*) — *S. chinensis* clones have been planted in Beijing for comparative study, but the plants are not yet mature enough to be observed, and (2) the event definitions are different in China than those in ENA.

First leaf in ENA is defined as the date when 'the widest part of the new leaf has pushed past the brown winter bud tips,' which will occur earlier than the Chinese first leaf date when 'the first 10 % of small leaves began to unfold' (transla-

Table 2. Comparison of lilac phenology and SI model output in China. n = 292 for first leaf variables and n = 325 for first bloom variables. Abbreviations as in Table 1

Variable	Minimum	Maximum	Mean	SD (d)
Syringa oblata first leaf date (DOY)	60	152	104.0	19.5
SIFLD (DOY)	60	132	97.7	17.3
SIFLD + 6 d (DOY)	66	138	103.7	17.3
Bias error of SIFLD + 6 d (d)	–22	26	–0.3	7.0
Abs. error of SIFLD + 6 d (d)	0	26	5.4	4.4
S. oblata first bloom date (DOY)	78	161	114.4	17.3
SIFBD (DOY)	87	154	121.3	15.9
SIFBD – 7 d (DOY)	80	147	114.4	15.9
Bias error of SIFBD – 7 d (d)	–25	14	–0.1	5.1
Abs. error SIFBD – 7 d (d)	0	25	3.8	3.3

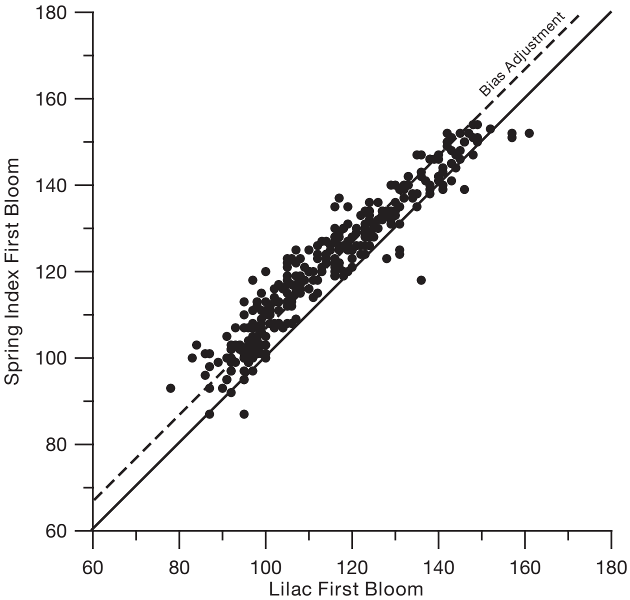

Fig. 3. Scatter plot of lilac first bloom date vs SI first bloom date in China

tion; Institute of Geography at Chinese Academy of Science 1965). These differing event definitions are consistent with the greater negative bias of SI first leaf relative to Chinese first leaf. Likewise, first bloom in China is defined as the date when 'several flowers are fully open' (translation; Institute of Geography at Chinese Academy of Science 1965) which will occur earlier than the ENA first bloom date when 'at least half of the flower clusters on the plant have at least 1 open flower.' Again, this would be compatible with the greater positive bias of SI first bloom relative to Chinese first bloom. In summary, the balance of evidence shows that the SI perform with similar accuracy in China as they do in ENA and can thus be appropriately used there.

5. METHODS

The SI suite of measures (previously defined: composite chill date, first leaf date, first bloom date, first –2.2°C frost date, last –2.2°C frost date, frost period, damage index, and annual-monthly average temperatures) were next computed at all 147 climate stations over the entire research period (1952–2000) and evaluated (along with the lilac first leaf and first bloom data) for significant linear trends over the 1959–1993 period (regression analysis, *F*-test, 0.05) as in comparable European and North American studies (Menzel & Fabian 1999, Schwartz & Reiter 2000). As in those 2 previous studies, station records were only included in the trend analysis if they had at least 20 yr of valid data within the 1959–1993 period. All variables were also transformed into departures from the applicable 1961–1990 station normals and then averaged by year to produce annual countrywide departures over the full period of record.

6. RESULTS

Neither SI composite chill date, SI first leaf date, nor SI first bloom date show linear trends over the 1959–1993 period. In contrast, last frost date in spring is becoming earlier, especially in northeastern China (Fig. 4), together with first frost date in autumn trending toward later dates in the north-central and northwestern portions of the country (Fig. 5). The combined effects of these changes in spring and autumn frost dates are leading to a shortened frost period across much of northern China. Twenty-nine of the 42 stations with shortening frost period also have increasing average annual temperature, indicating a strong spatial connection between these 2 variables (Figs. 4 & 6).

Significant linear trends (0.05) over the 1959–1993 period for the 147 climate station network (average departures from 1961–1990 normals) were detected for last frost date (–0.17 d yr^{-1}, equivalent to an advance of 6.0 d toward earlier arrival over the period, Fig. 7), similar to the 4.5 d advance over the same period in North America (Schwartz & Reiter 2000); first frost date (+0.11 d yr^{-1}, equivalent to a retreat of 3.9 d toward later arrival over the period, Fig. 8); frost period (–0.28 d yr^{-1}, equivalent to a shortening of 9.8 d over the period); damage index value (+0.17 d yr^{-1}, equivalent to a positive increase of 6.0 d over the period); and average annual temperature (+0.014°C yr^{-1}, equivalent to a warming of 0.49°C over the period). No significant trends over the 147 climate station network were present over this period in the SI composite chill, SI first leaf date (Fig. 9), SI first bloom date (Fig. 10), lilac first leaf date, or lilac first bloom date (no lilac data available before 1963).

Table 3. Pearson's r correlations of lilac phenology and SI model output in China and Eastern North America (ENA) (all significant at the 2-tailed 0.01 level)

	First leaf (China)	First bloom (China)	First leaf (ENA)	First bloom (ENA)
SI first leaf (China)	0.94			
SI first bloom (China)		0.96		
SI first leaf (ENA)			0.87	
SI first bloom (ENA)				0.92

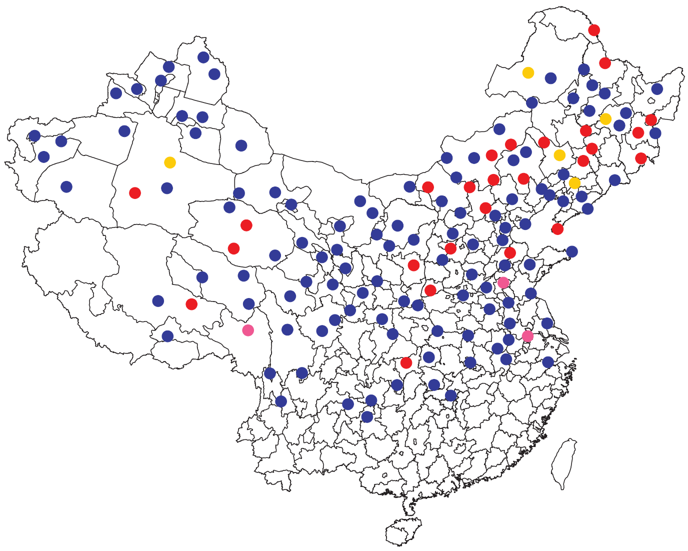

Fig. 4. Last −2.2°C frost date linear trends. Data are from stations with long data series (20 yr or more) during the 1959–1993 period. Red dots: significant at the 5% level and trends <−0.3 d yr^{-1}; yellow dots: significant at the 5% level and trends between −0.3 and 0 d yr^{-1}; pink dots: significant at the 5% level and trends greater than 0 d yr^{-1}; blue dots: not significant at the 5% level (*F*-test)

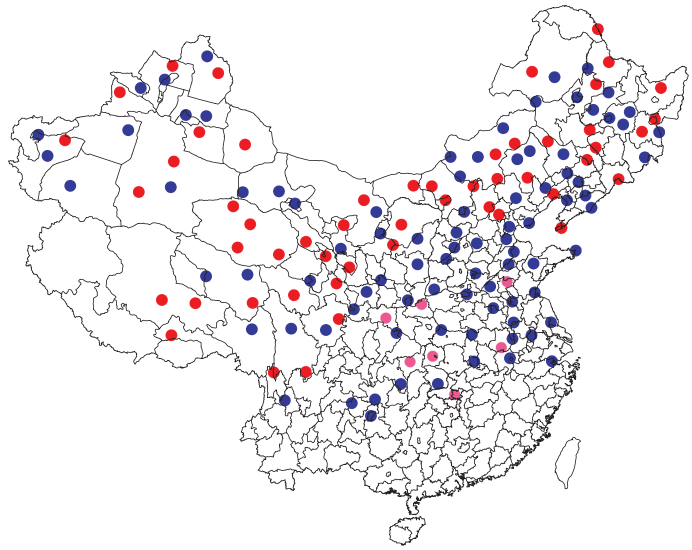

Fig. 6. Annual average temperature linear trends. Data period as in Fig. 4. Red dots: significant at the 5% level and trends greater than 0°C yr^{-1}; pink dots: significant at the 5% level and trends less than 0°C yr^{-1}; blue dots: not significant at the 5% level (*F*-test)

7. DISCUSSION

These overall results correspond with a previous analysis of the departure of area-average annual temperature for 8 large geographic regions in China between 1951 and 1995 (Chen et al. 1998) and a more recent analysis of annual mean temperature trends based on full-day data for 1951–1994 in China (Wang & Gaffen 2001). Both these studies also showed the most significant increases in annual mean temperature located in northeast China and north China. However, an examination of the 12 monthly average temperatures (not shown) suggests that the decreasing frost

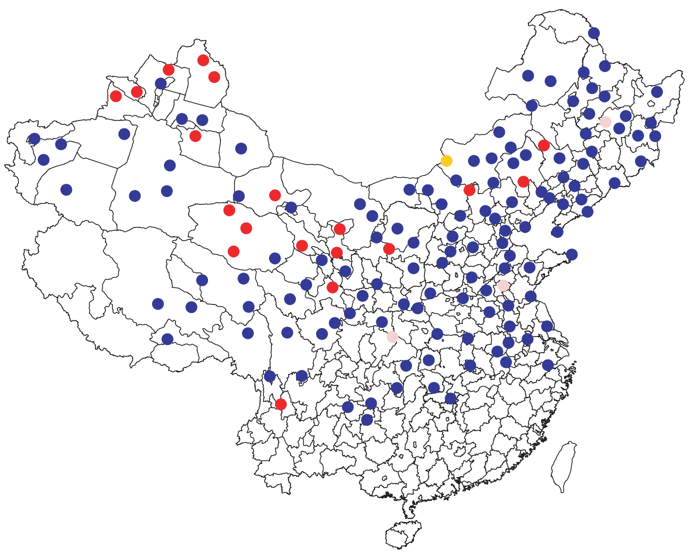

Fig. 5. First −2.2°C frost date linear trends. Data period as in Fig. 4. Red dots: significant at the 5% level and trends >0.3 d yr^{-1}; yellow dots: significant at the 5% level and trends between 0 and 0.3 d yr^{-1}; pink dots: significant at the 5% level and trends less than 0 d yr^{-1}; blue dots: not significant at the 5% level (*F*-test)

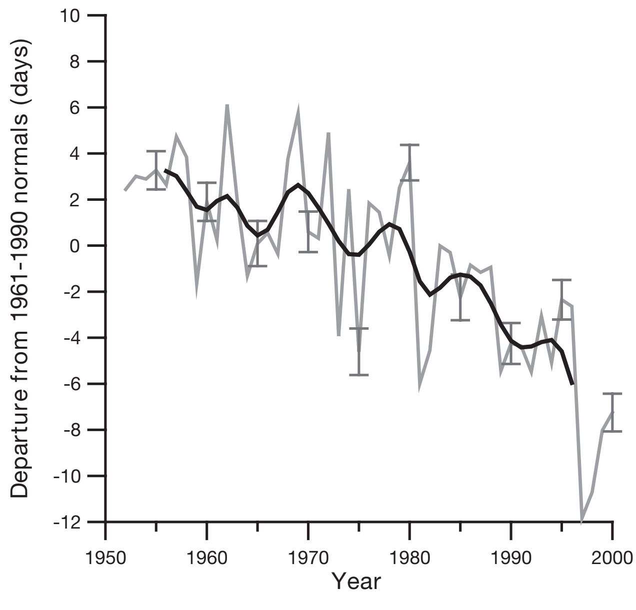

Fig. 7. 147 meteorological station average departures from the mean of last −2.2°C frost date, 1952–2000, with ±1 SE bars, and smoothed trend produced by a 9 yr moving average normal curve filter (heavy solid line)

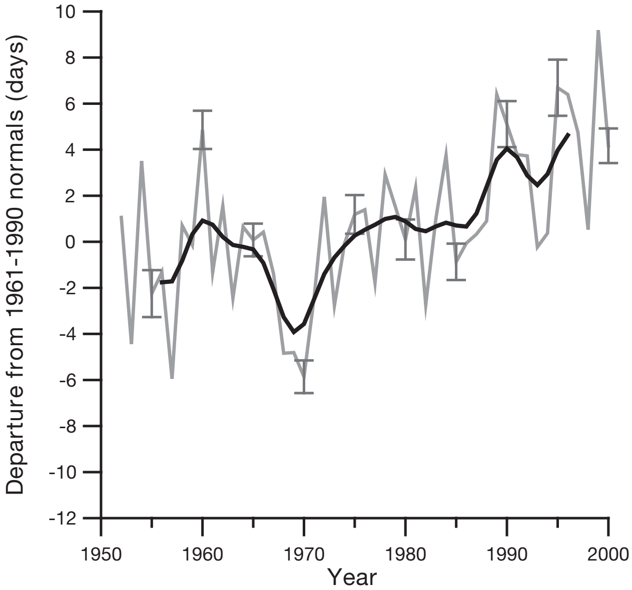

Fig. 8. 147 meteorological station average departures from the mean of first −2.2°C frost date, 1952–2000

period in the north is not related to general warming in spring or autumn, and appears to be spatially related to warming in December and January (February showed little change). None of the spring months (March, April, May) show any regional warming patterns in the north, and September actually shows cooling in some north-central locations. Other autumn months (October and November) had fewer than 10 stations each with any significant trends in temperature). In summer months (June, July, August) east-central China (between the Yangtze River and the Huaihe River) shows an anomalous area of mild warming, which contrasts with the overall pattern of cooling at some stations in that region.

In China there is no evidence of overall warming during spring (MAM) or autumn (SON), and the onset of spring vegetation growth is not changing, yet last spring frost dates are occurring earlier and first autumn frost dates are occurring later. This is in contrast to North America, where strong overall warming is occurring during spring and both the onset of spring vegetation growth and last spring frost dates are occurring earlier (Schwartz & Reiter 2000).

Interpretation of the causes of these regional differences is possible through examination of the seasonal patterns of change in diurnal temperature range (DTR) and day-to-day temperature (DDT) differences in the 2 locations.

Karl et al. (1993, 1995) provided regional assessments of daily maximum temperature, daily minimum temperature, DTR, and DDT difference changes for each season in China and the USA/Canada over roughly the same period as our study that are suitable for this purpose. Their results show that in the USA/Canada both daily maximum and daily minimum temperatures are increasing during spring, which corresponds to little change in DTR and is consistent with the earlier onset of spring vegetative growth and last frost dates reported by Schwartz & Reiter (2000). Likewise, Karl et al. (1993, 1995) describe spring and autumn daily maximum temperature decreases cou-

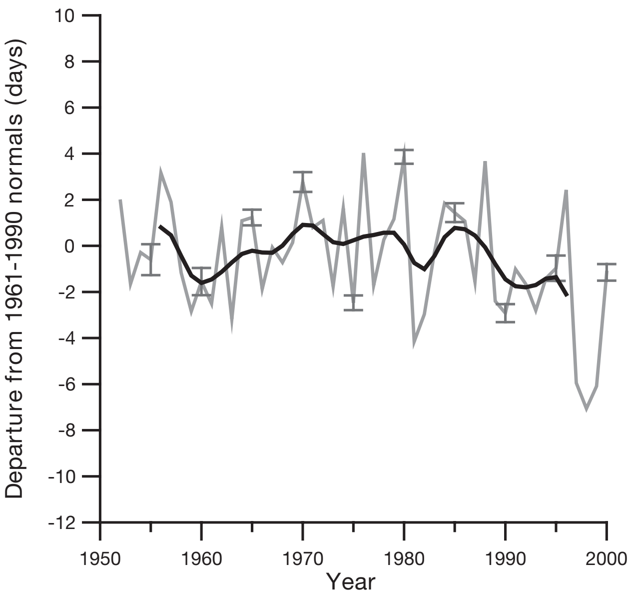

Fig. 9. 147 meteorological station average departures from the mean of SI first leaf date, 1952–2000

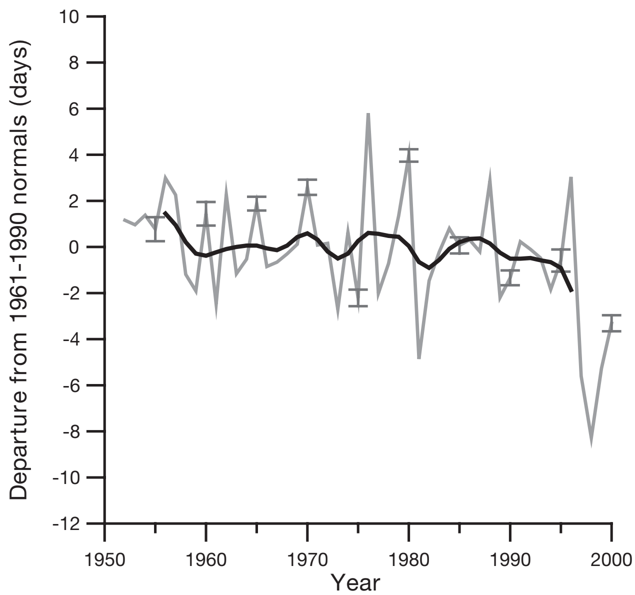

Fig. 10. 147 meteorological station average departures from the mean of SI first bloom date, 1952–2000

pled with daily minimum temperature increases in China that result in decreasing DTR during these 2 seasons, as well as decreased DDT differences, especially in spring. These changes in daily and day-to-day temperature variability in China provide a reasonable explanation of how last spring frost dates can be occurring earlier and first autumn frost dates later (as reported in this study), while the overall average temperatures of these seasons and the corresponding onset of spring vegetative growth remain unchanged.

Generally speaking, decreasing DTR and DDT differences across the Northern Hemisphere are consistent with model projections of a warmer world (Karl et al. 1995). Thus, a shortened frost period in China, resulting from these changes, is an expected climate change response. A lengthening of the frost-free period (shortened frost period) would be beneficial for enhancing the potential for multiple cropping and the total yield of some crops. Further, more positive damage index values (last frost dates occurring earlier, while first leaf dates—representing the onset of spring vegetative growth—remain constant) could mean crops will suffer frost injuries less frequently. However, considering the annual variability of the damage index values within the trends, careful field management in spring and autumn will still be crucial for obtaining the highest and most stable yields.

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