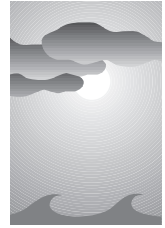


Changes in the Onset of Spring in the Western United States



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Joseph M. Caprio,[@] and David H. Peterson[&]

ABSTRACT

Fluctuations in spring climate in the western United States over the last 4–5 decades are described by examining changes in the blooming of plants and the timing of snowmelt–runoff pulses. The two measures of spring’s onset that are employed are the timing of first bloom of lilac and honeysuckle bushes from a long-term cooperative phenological network, and the timing of the first major pulse of snowmelt recorded from high-elevation streams. Both measures contain year-to-year fluctuations, with typical year-to-year fluctuations at a given site of one to three weeks. These fluctuations are spatially coherent, forming regional patterns that cover most of the west. Fluctuations in lilac first bloom dates are highly correlated to those of honeysuckle, and both are significantly correlated with those of the spring snowmelt pulse. Each of these measures, then, probably respond to a common mechanism. Various analyses indicate that anomalous temperature exerts the greatest influence upon both interannual and secular changes in the onset of spring in these networks. Earlier spring onsets since the late 1970s are a remarkable feature of the records, and reflect the unusual spell of warmer-than-normal springs in western North America during this period. The warm episodes are clearly related to larger-scale atmospheric conditions across North America and the North Pacific, but whether this is predominantly an expression of natural variability or also a symptom of global warming is not certain.

1. Introduction

Since the late 1940s, annual average temperatures over the northwestern part of North America have increased by approximately 1° – 2°C , with most pronounced warming in winter and spring (Karl et al. 1993; Dettinger et al. 1995; Lettenmaier et al. 1994; Vincent et al. 1999). Largest increases occurred in March over western Canada and the interior Northwest of the United States (Fig. 1). While this is similar to the winter pattern, the spring temperature trend is dis-

tinguished by the extension of the core of warm anomalies southward into the western United States. During winter, that core was located farther to the north in Canada. In a comparative sense, the spring trend is more impressive than that in winter, because it expresses the same magnitude of change, but occurs during a period of the year when the atmosphere’s variability is not as large as in winter. In the central Canadian Rockies, Luckman (1998) finds that “tree-ring based temperature reconstruction indicates summer and spring temperatures in the last half of the twentieth century are higher than any equivalent period over the last 900 years.” Although the ultimate cause of this warming is uncertain, much of it has a dynamic origin, involving changes in the pattern, frequency, or intensity of storms and other large-scale features of the atmospheric circulation (Wallace et al. 1996). Groisman et al. (1994) describe an impressive retreat of Northern Hemisphere snow cover extent by approximately 10%, and found that it was tied to increases in spring temperature and asserted that a positive feedback in the surface radiation balance was involved. The warming of western North America

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during winter months since the mid-1970s was associated with a long-term shift in atmospheric circulation from the weaker to the stronger phase of the Aleutian low, called the Pacific Decadal oscillation (Mantua et al. 1997) or the North Pacific oscillation (Gershunov et al. 1999). While wintertime effects of this interdecadal variability are strong and have received much attention, impacts during the other seasons are not as well appreciated.

Seasonal to interdecadal climate variability in the western United States has great practical significance, impacting a wide spectrum of sectors such as water resources, agriculture, energy consumption and production, and recreation. At the downwind edge of the North Pacific, the region is impacted by the El Niño–Southern Oscillation and also by longer period decadal variability (Ebbesmeyer et al. 1991; Miller et al. 1994; Trenberth 1990; Trenberth and Hurrell 1994; Latif and Barnett 1994; Mantua et al. 1997; Gershunov et al. 1999). Climate fluctuations in the eastern North Pacific Ocean and the adjacent western margin of North America often vary synchronously as one link in a hemispheric chain of atmospheric pressure and surface temperature anomalies (Miller et al. 1994; McGowan et al. 1998; Mantua et al. 1997). Since the mid-1970s, the region has undergone marked warming of coastal ocean temperatures (Roemmich and McGowan 1995; McGowan et al. 1998). Along with this, warmer winter and spring nighttime temperatures and increased humidity of the air near the surface have been observed in California and are thought to have

increased the quantity and improved the quality of central California wine grapes (Nemani et al. 2000, manuscript submitted to *Climate Res.*). Hydrologic consequences of the changes included a southward shift in the location of anomalously heavy mountain snow accumulation in western North America (Changnon et al. 1993; Moore and McKendry 1996; Cayan 1996) and retreat or diminished mass balance of glaciers (Walters and Meier 1989; McCabe and Fountain 1995; Hodge et al. 1998; McCabe et al. 2000; Luckman 1998; Bitz and Battisti 1999). In many high-elevation streams in the western United States, the last three decades have seen a reduction in the portion of annual river discharge during spring and early summer; that is, the fraction of annual discharge attributable to spring snowmelt has diminished (Roos 1991; Wahl 1991; Aguado et al. 1992; Dettinger and Cayan 1995).

Such changes in North American climate have likely caused significant changes in terrestrial ecosystems and, especially, vegetative growth and development. The relationship between seasonal changes in vegetative development and the environment, known as phenology, has been studied for decades as an agricultural predictor (Caprio 1957; 1993a,b), as well as a means of measuring ecosystem response and meteorological and climate characteristics (Schwartz 1992, 1994; Menzel and Fabian 1999; White et al. 2000). Markers that have been monitored in the Western Regional Phenological Network (WRPN) include specific annual phases of plant development that allow quantification of the timing and rates of spring green up and autumn degradation in a given setting (Caprio et al. 1970). Variations of vegetation phases with weather and climate reflect strong links to spring temperature and insolation, and year-to-year phenological variations have been successfully modeled using these elements (Caprio 1967, 1993c; Schwartz 1994). As early as 1984, Caprio reported that lilacs were tending to bloom at earlier dates during recent years in the northern part of North America. Recent analyses of first bloom dates from three species (*Populus tremuloides*, *Amelanchier almitulia*, *Prunus virginiana*) in Edmonton, Alberta, Canada (Beaubien and Johnson 1994), provide evidence for a foreshortening of spring development by 8 days since the 1930s. A

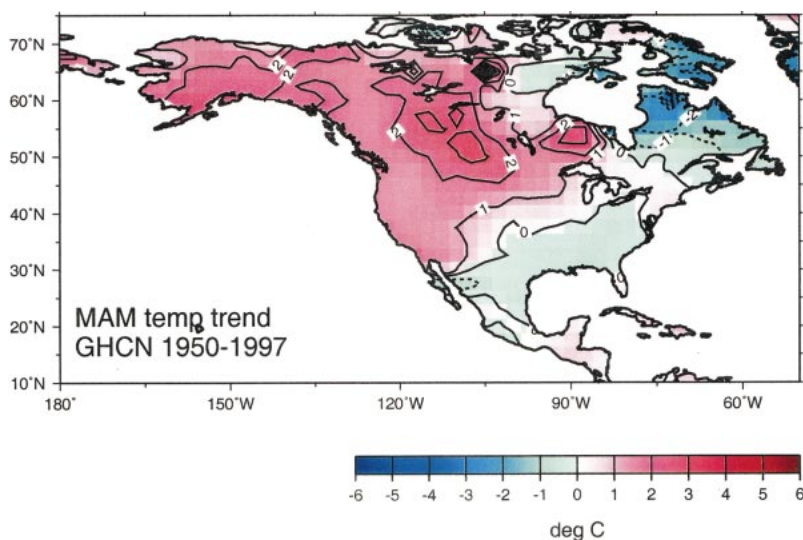


FIG. 1. Linear trend of spring (Mar–May) temperature over North America between 1950 and 1998. Values plotted are the overall change in trend lines (°C) from beginning to end of record.

combined network of lilac phenological observations across the western, northern middle, and northeastern United States shows that many plants in the western and northeastern United States have experienced earlier blooms (by about a week) during the last two decades relative to earlier decades (Schwartz and Reiter 2000). Farther afield, analyses of phenological observations from European botanical gardens during the last few decades indicate that warmer temperatures there have produced advances in spring of approximately 6 days and delays in autumn of about 4–5 days, extending the growing season in Europe by one to two weeks (Menzel and Fabian 1999). In the eastern United States, the influence of a newly developed leaf canopy upon the range of diurnal air temperature, via alterations in the surface energy balance, has been demonstrated using phenological histories and regional meteorological observations (Schwartz and Karl 1990).

In this study, observations of the first bloom of lilac and honeysuckle from the WRPN and observations of the first pulse of spring high-elevation snowmelt from the United States Geological Survey (USGS) stream gauges are examined to understand and illustrate consequences of recent long-term climate variations in the western North America. The timing of the first bloom of the purple common lilac provides a measure of variations of the onset of spring. The availability of phenological data from a companion network of honeysuckle provides for a consistency check with the lilacs, allowing a further test of whether the phenological variability is provoked externally (e.g., by climate fluctuations) rather than by internal biological factors. In addition, an array of daily streamflow records from high-elevation watersheds in the western United States provides a separate measure of spring onset—these mountain streams begin their seasonal flow pulse in response to melting of mountain snowpack. The intent in using these two different kinds of observations is not to infer cause–effect relationships between the two, but rather to examine two very different responses to climate variations. What emerges is a picture of coherent year-to-year fluctuations in the timing of spring throughout the region, reflected in both vegetation and hydrology, and clearly associated with regional temperature anomalies. Furthermore, there is evidence for a substantial trend toward earlier springs during the operation of the two networks, amounting to onsets of spring one to two weeks earlier in recent decades than in previous decades.

Data used, principal component analysis of the WRPN observations, and linkages to temperatures and

streamflow are presented in the next sections, with discussion and conclusions thereafter.

2. Data

In 1957, a network of observers was recruited from locations across the western United States to record the phenology of the purple common lilac to learn more about plant development and its relation to climate variation in the region, especially in relation to plant development for agriculturists in Montana (Caprio 1966). In 1968, a second network was established to record the phenology of honeysuckles; some of these honeysuckle observers were also members of the lilac network. Other regional phenology networks were established in the United States during this same era, but the WRPN provided the most extensive and longest set of data collected (Schwartz 1994).

The WRPN network monitored the timing of key phenological phases of the purple common lilac during the 37 yr from 1957 to 1994, and monitored corresponding phases of two species of honeysuckle from 1968 to 1994 (Caprio et al. 1970; Caprio 1993a; Schwarz 1994). The common purple lilac, *Syringa vulgaris* f. *purpurea* Hort. *Ex Schelle*, is distinguished from many other purple-colored lilacs in that it produces numerous suckers around it that emerge from its roots. The honeysuckles monitored were either (or both) *Lonicera tatarica* cv, “Arnold Red,” and *L. korolkowii* stopf, var. *zebelli*, depending on location (Caprio et al. 1970). Lilacs and honeysuckles were chosen because they both can grow in a variety of soils, elevations, latitudes, and temperature and precipitation regimes, and both are widespread in the United States and beyond. The plants observed in the WRPN were not shaded and were irrigated if needed. Both lilacs and honeysuckle are considered to be accurate indicators of climate because their development responds more to the “thermal” environment than to soil moisture or photoperiod. Thus, the normal increase in spring temperature leads almost directly to an increase in plant development (Caprio 1967).

From an initial set of lilac sites established in Montana in 1956, the networks of both lilac and honeysuckle grew to include sites in 12 western states, with about 2000 observers at the height of the project in the 1970s. Observations ended in 1994. This was a cooperative network, including United States Weather Service cooperative weather observers, government and university forest or agricultural stations, and mem-

bers of local garden clubs. Some observers had only lilac or honeysuckle bushes; some had both. Observers recorded the timing of various phases of lilac and honeysuckle development each year and mailed this information to Montana State University once per year on a single datasheet. The phenological phases displayed important large-scale patterns, for example, generally being more delayed with increased elevation and latitude (Caprio 1966, 1967). After a few years of data were collected, it was clear that a given plant phase's timing changed from year to year in a systematic, regionally coherent pattern (Caprio 1993a).

In this study, we chose to analyze the time of first bloom because the observers most reliably recorded this phenological phase. However, year-to-year variations of other growth phases correlate well with those of first bloom, indicating that first bloom was a good index of spring onset and that this choice probably did not influence the results too much. Correlations between the timing of first bloom and that of other phenological phases all exceed 0.5 and often exceed 0.8 for several representative lilac sites with reasonably complete records (Table 1). Most of our analyses consider a subset of lilac stations, 105 in all, having 20 or more years of data during 1957–94 (Fig. 2a). Elevations of these lilac sites ranged from 2.4 to 2698 m. A complementary set of honeysuckle stations, 87 in all, that have 15 or more years of data during 1968–94 was used to validate the lilac results (Fig. 2b). Elevations of these honeysuckle sites ranged from 15 to 2927 m. Much larger numbers of stations were in operation for

both species, but most have shorter or spotty records, and others were culled to produce a more uniform spatial sample density.

Streamflow records are from the USGS Hydro-Climatic Data Network (HCDN). These were selected because the river basins they represent are relatively uncontaminated by land-use changes and man-made structures that could alter streamflow from its natural characteristics (Slack and Landwehr 1992). In spring or early summer, high-elevation basins throughout the western United States undergo rapid transitions from dormant, low-flow stages to active, high-flow stages, as the snowpack warms and snowmelt commences (Cayan and Peterson 1989). Rather than applying an arbitrary temporal filter to identify the timing of this spring streamflow pulse, a simple algorithm was developed. The algorithm, illustrated in Fig. 3, identifies the day when the cumulative departure from that year's mean flow is most negative, equivalent to finding the day after which most flows are greater than average. Visual inspection of individual hydrographs of rivers dominated by snowmelt runoff showed that this objective scheme accurately reproduces subjective estimates of the beginning of large spring pulses in most high-elevation rivers. Streams were excluded from the analyses presented here if their records did not contain a strong majority (> 70%) of years in which a pulse could be defined between early spring (Julian day 9) and mid-summer (Julian day 208).

This procedure yielded annual time series of the day of year when the first major pulse of spring streamflow, called the "spring pulse" at 110 rivers in the western United States from the Pacific Coast eastward to 105°W (Fig. 2c). These series began in 1948 and ended between 1988 and 1995, depending upon available data.

3. Analyses and results

a. Climatology

First bloom dates of lilacs and honeysuckles vary widely with location and from year to year. In the interior of the western United States, lilac bloom dates on average are delayed by approximately 3 days per degree of latitude, and by 1 day per

TABLE 1. Correlations between times of first bloom and other phenological phases from representative lilacs.

Lilac site			Correlation with first bloom			
Lat	Long	Elev (m)	First bud	All leafed	Peak bloom	Withered
30.56	100.07	671	0.55 (22)	0.67 (22)	0.91 (22)	0.88 (21)
36.36	121.41	18	0.86 (18)	0.97 (16)	0.82 (27)	0.74 (27)
37.21	106.30	2337	0.67 (24)	0.64 (23)	0.80 (32)	0.73 (32)
42.30	112.34	1576	0.50 (20)	0.68 (18)	0.96 (19)	0.86 (18)
45.34	116.50	564	0.66 (19)	0.69 (17)	0.84 (28)	0.77 (29)
48.39	118.14	793	0.56 (21)	0.62 (21)	0.93 (32)	0.79 (29)

Here () is the number of pairs included in analysis.

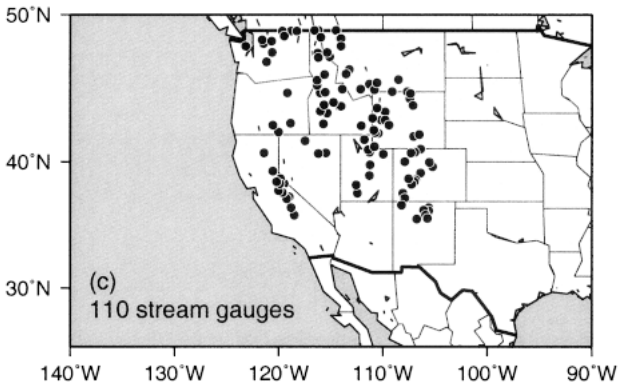
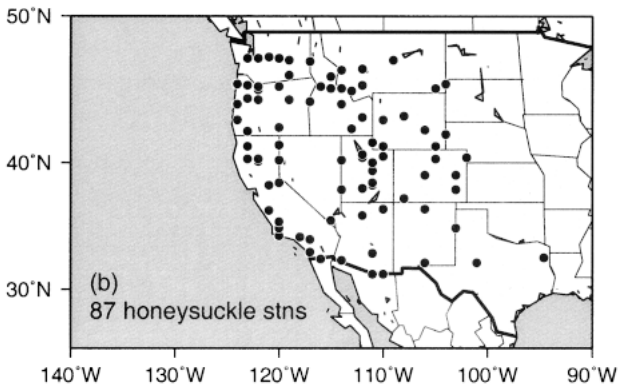
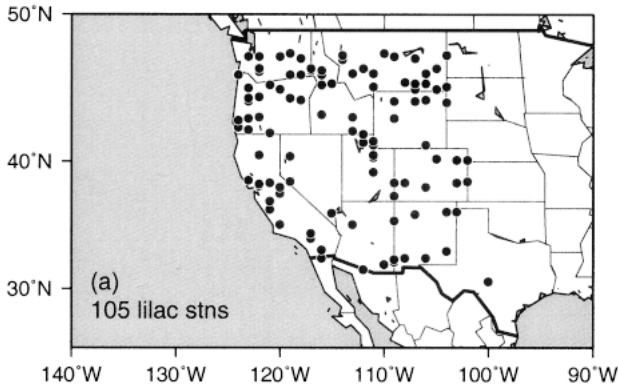


FIG. 2. Locations of (a) lilacs, (b) honeysuckles, and (c) stream gauges used in this study.

30-m increase in elevation (Caprio 1966, 1967). The mean day of lilac first bloom, along with its standard deviation, is mapped in Fig. 4. Average lilac first bloom dates range from mid-March in Arizona and New Mexico to early June in Washington and Montana. Along the West coast, isophanes (lines connecting locations having the same date of occurrence for a given phase of plant development) tend to be oriented south-north, probably because of strong coast-to-inland gra-

dients in temperature and other environmental influences. Some low-elevation sites in California and Arizona exhibit later spring development than nearby higher-elevation sites. This inversion is thought to be caused by an inadequate number or degree of cold winter days at lower elevations, since many plants, including the lilac and honeysuckle, require a cold dormant period to reset their phenological clock (Caprio 1993c). Despite this, inadequate winter chill is not a significant factor at most sites chosen for this study.

As shown by the distribution of all lilac first bloom dates (Fig. 5, top), lilac first blooms occur from the beginning of March to the end of June, with an overall mean in early May and mode in the last half of May. First bloom dates of honeysuckles (Fig. 5, middle), are similarly distributed with an overall mean at the end of April and mode during the last half of May. For comparison, the timing of the spring pulse from snowmelt displays an overall mean in mid-April (Fig. 5, bottom) with most pulses occurring between early March and mid-May. Spring pulse timing is strongly influenced by the elevation and topographic features of a particular watershed, with higher-elevation basins generally having a later pulse.

In the analyses that follow, the long-term average dates of first bloom date or spring pulse at each site were subtracted from each year's observed dates to determine the year-to-year variations of spring onset in the series.

b. Spatial/temporal variability

Standard deviations of lilac first bloom dates for individual plants (Fig. 4) range from 6 days to 18 days, with most having a standard deviation of 8–10 days.

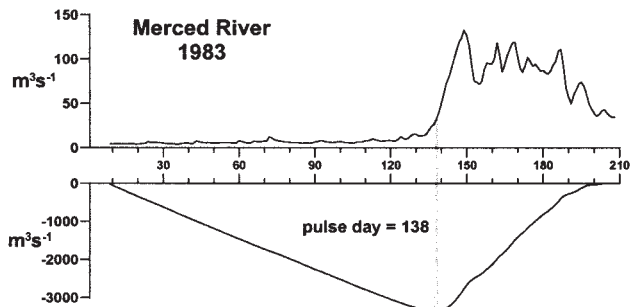


FIG. 3. Daily flows (upper curve) and cumulative departures (lower curve) from the mean flow from Julian day 9–Julian day 208, 1983, of the Merced River (USGS gauge 11264500). On the day when the cumulative departure is minimum, the onset of the spring pulse of streamflow (vertical line) is defined, in this case on Julian day 138.

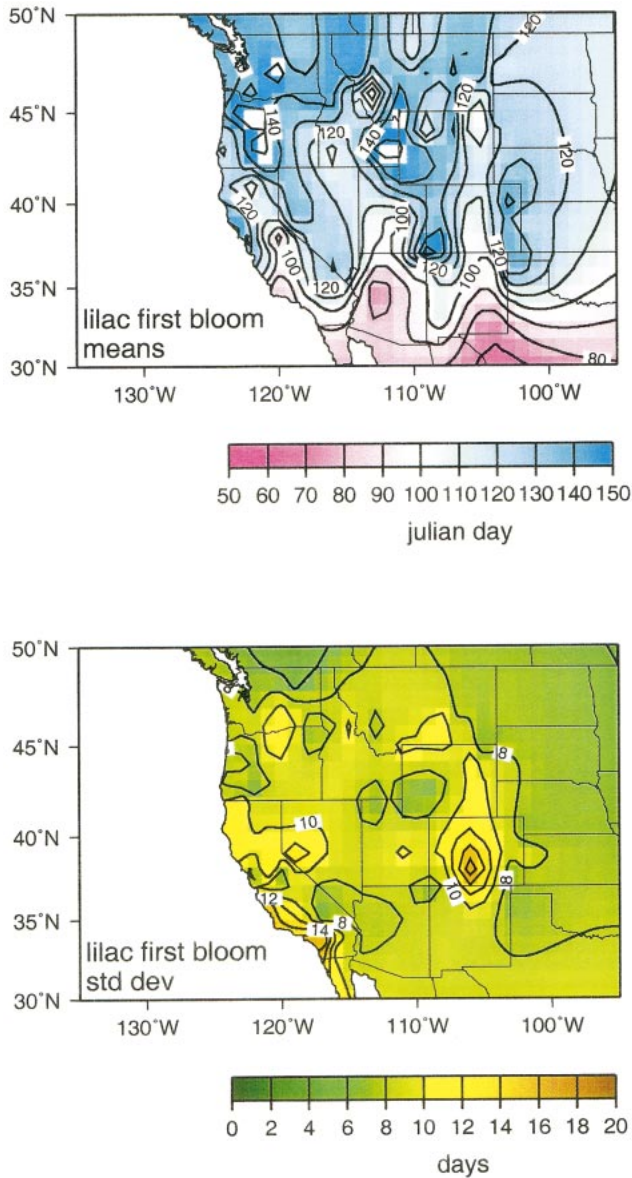


FIG. 4. Mean (top, Julian days) and standard deviation (bottom, days) of the lilac first bloom dates.

During extreme years, lilacs have bloomed more than 20 days later or earlier than their long-term average. Centers of maximum variability are found in California and Colorado. Honeysuckle first bloom timing patterns are very similar to those of the lilac network. For comparison, spring pulse series have standard deviations ranging from 10–20 days.

From the perspective of climate variations, it is of interest to determine whether the lilac and honeysuckle networks record spatially coherent anomalies in the first bloom dates. Significant correlations ($r > 0.35$, $p < 0.05$) are present between nearly 40% of the possible pairs of lilac–lilac and honeysuckle–honeysuckle first

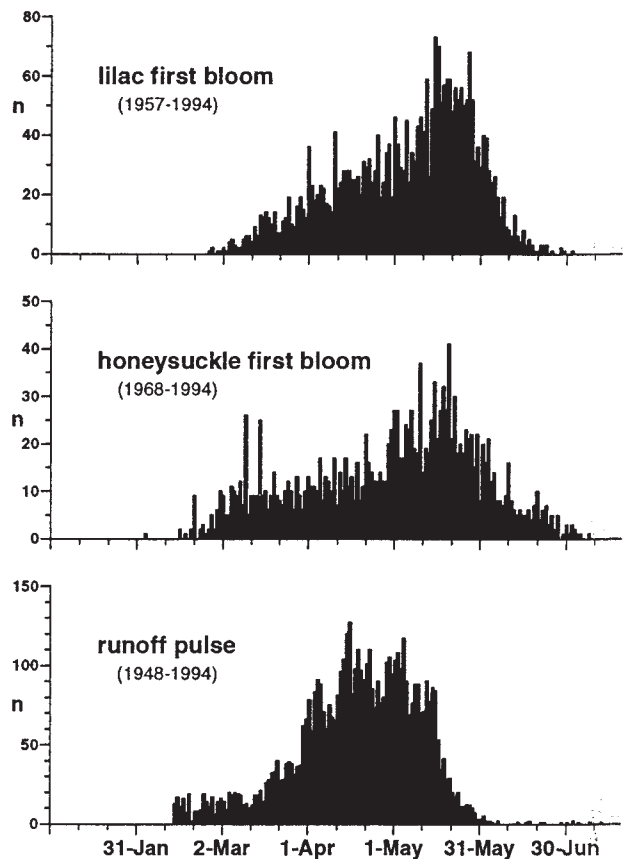


FIG. 5. Distributions of all sites', all years', lilac first bloom dates (top), honeysuckle first bloom dates (middle), and spring pulse dates (lower).

bloom series. These first bloom variations were broken into their dominant patterns by an empirical orthogonal function (EOF) analysis (Davis 1976) of the intersite (but not interspecies) correlations. The EOFs identify the most extensive and influential patterns of year-to-year variability present in the records of the two networks. Results that follow are from the unrotated EOF analysis but are similar to a recombined set of patterns using a Varimax rotation (Richman 1986). We present the unrotated EOFs because they are the most efficient condensation of the variability, and, aside from checks of consistency between lilac and honeysuckle results and in association with spring climate linkages, our emphasis is upon the gravest and most dominant EOF. The first EOFs explain about one-quarter of the variance of the first bloom timing in both networks, while the three leading spatial patterns (Fig. 6) together account for 41% of year-to-year variance in the lilac and 50% in the honeysuckle first bloom set (Table 2).

For both species, the leading EOF represents a broad region of common variability of first bloom tim-

first bloom spatial loadings

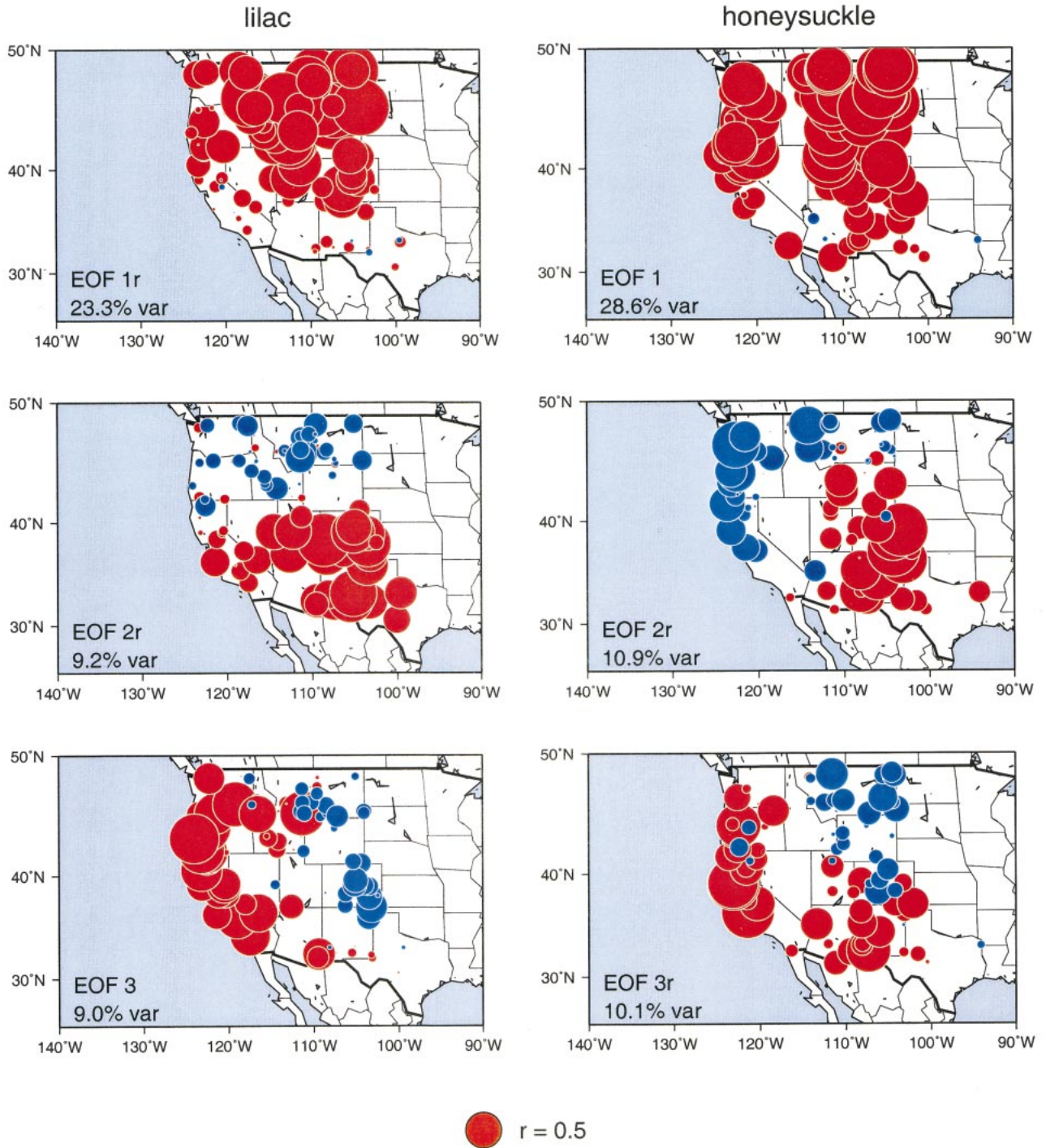


FIG. 6. EOFs 1–3 of lilac first bloom dates (left panels) and of honeysuckle first bloom dates (right panels). EOF weights are expressed as correlations of principal component with the raw time series of lilac and honeysuckle first bloom; red and blue dots represent positive and negative correlations, respectively.

ing over the northern half of the western United States, with strongest weights over Montana, Idaho, and Washington. Although details of the higher EOFs

should not be overinterpreted (Richman 1986), there is a strong resemblance between the lilac and honeysuckle modes. The second EOF of both lilac and hon-

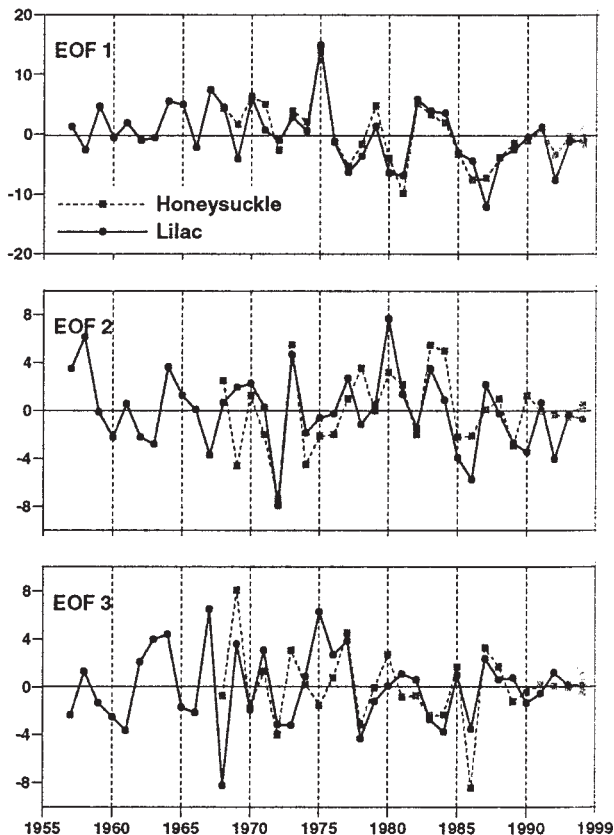


FIG. 7. Principal component series of EOFs 1–3 of lilac first bloom dates (solid), 1957–94, and of honeysuckle first bloom dates (dashed), 1968–94.

eyssuckle includes most of the southern part of the domain, while the third EOF of both species is weighted along the coastal region from Washington southward to California.

In addition to having similar spatial patterns, the yearly variations of the first three EOFs of the lilac and honeysuckle first bloom are remarkably well correlated (Fig. 7). Correlation coefficients relating the time series of the first three lilac and honeysuckle EOFs are 0.91, 0.63, and 0.51, respectively (all p 's < 0.01). The temporal and spatial similarities of the anomalous

bloom fluctuations in the two species suggest that there is a significant component of these variations that is independent of species, presumably reflecting external factors. Thus, interannual fluctuations in spring onset of an individual plant likely are correlated to those of many other plants over broad regional areas.

c. Climate influences

To determine whether, and which, climatic fluctuations are associated with the lilac first bloom variations, composite averages of monthly temperatures and monthly precipitation were constructed for the 12 years with the latest, and 12 years with earliest, first bloom in a given region. This exercise was repeated for each of five regions having strong weightings in the first three EOFs: Montana, Oregon, California, Arizona, and New Mexico. Monthly means of climate division temperature and precipitation (Karl and Knight 1985) were constructed for the November through September period bracketing the springs of the earliest and latest lilac first bloom years. Significance of each division's monthly anomaly composite was judged by whether its Student's t -test value violated the null hypothesis in excess of a 95% confidence level. On the whole, precipitation composites associated with first bloom variations are few and randomly distributed in the study domain. The lack of a precipitation connection may be in part because some lilacs were irrigated. However, this lack of a precipitation link seems to be ubiquitous, even though all of the lilacs were not irrigated. In contrast, there is a consistent association with regional temperature anomalies, as others have described (Caprio 1966, 1967). Associations of representative bloom records with divisional temperatures for lilacs in Montana, Oregon, and New Mexico are shown in Fig. 8. These, plus two other composites for California and Arizona (not shown) exhibit significant temperature anomalies preceding (by one or two months) and during the time of lilac first bloom. Temperature anomalies range from 1° to 2°C for each of the composites. Composite anomalies are significant (at 95% confidence level) for both late and early bloom subsets from Montana and Oregon. These temperature connections are in good agreement with previous reports (Caprio 1966, 1967, 1993d) that anomalous temperatures affect first bloom timing during the two months preceding the bloom. The present analysis finds no consistent link of first bloom timing to temperatures or precipitation during the preceding winter or fall, indicating that the first blooms are mainly indices of spring climate. Curiously, there

TABLE 2. Explained variance (%), EOFs of spring onset indicators.

EOF	Lilac	Honeysuckle	Spring pulse
1	23.3	28.6	38.5
2	9.2	10.9	9.2
3	9.0	10.1	8.3

appears to be a connection to anomalous temperature during subsequent fall months (early bloom associates with anomalously warm temperature in September), but since our focus is upon spring; we leave this for later studies.

To investigate the spatial pattern of anomalous temperatures associated with the bloom variations, the correlations between the leading lilac EOF time series and air temperatures across North America, from the GHCN dataset (Eisheid et al. 1995), were mapped in Fig. 9 (top). Temperature correlations with EOF 1 form a broad pattern of high positive values in the Northwest, symptomatic of an extensive swath of cooling (warming) associated with later (earlier) bloom timing. Indeed, this pattern of high correlations extends across most of the northern United States. Some correlation coefficients are as high as 0.8 ($p < 0.01$). The spatial pattern of this correlation is nearly identical to that of the spring temperature trend (Fig. 1), an item to be discussed later. Incidentally, bloom timing fluctuations in a lilac chronology from Dickinson, North Dakota, that was part of a different phenology network (Schwartz 1994), appear to be very similar to EOF-1 time series, evidently a symptom of this same spring temperature anomaly structure. Extending this exercise to the second and third lilac first bloom EOFs, correlations of spring temperatures with the lilac EOF-2 and EOF-3 time series (Fig. 9, middle and bottom) exhibit positive correlations that closely correspond to the areas of strong weighting in these two EOFs. These maps indicate that these modes reflect somewhat more regionally localized climate forcings, but maintain connections having the same sense (warmer associates with earlier bloom) as EOF 1. Some of the correlation between EOF 1 and temperatures in the same regions as have experienced warming trends in recent decades (Fig. 1) may be due to the trend that is also evident in the EOF-1 time series (Fig. 7). In order to quantify the contribution of year-to-year temperature and bloom variations to correlations in Fig. 9, correlations between time series of spring temperature anomalies centered over the interior Northwest and the EOF-1 time series were computed for raw and detrended versions of the series. The temperature series used was constructed by averaging temperature anomalies from U.S. divisional temperatures (Karl and Knight 1985) from eastern Washington, Idaho, western Montana, and western Wyoming. The correlations of unfiltered series is 0.78 ($p < 0.01$). This correlation is reduced, when the linear trend is removed from each of the two series, but only to 0.74 ($p < 0.01$). Thus, bloom tim-

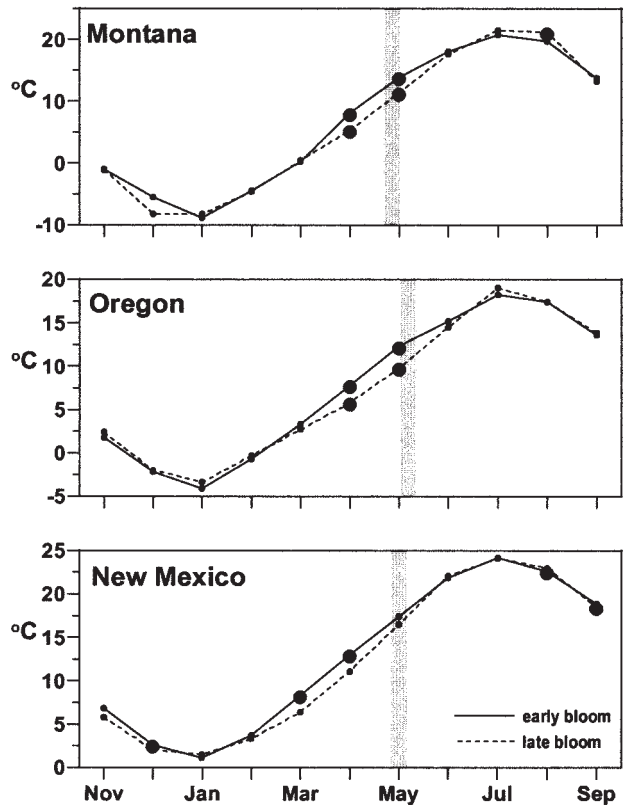


FIG. 8. Composite monthly temperatures ($^{\circ}\text{C}$) from subsets of 12 yr each with anomalously early (solid) and late (dashed) lilac first bloom dates in Montana, Oregon, and New Mexico. Composite anomalies exceeding 5% significance level are shown as bold dots. Mean first bloom date (± 1 std dev) indicated by shaded vertical line. Temperature is from the climate division that includes the respective lilac site.

ing is as related to the interannual temperature fluctuations as to the low-frequency secular variations.

Given the strength and spatial scale of these temperature associations, it is not surprising to find that bloom timing changes have a strong connection to North American and North Pacific atmospheric circulations. This connection can be illustrated by correlations of lilac bloom EOF-1 series with Northern Hemisphere spring 700-mb height anomalies (Fig. 10, upper). Early bloom cases are marked by a pattern with massive ridges of high pressure over North America, centered over Manitoba, Canada, and the Dakotas. This pattern yields anomalous southerly flows, high-tropospheric heights, and subsidence, and makes the west warmer than normal. In contrast, late blooms associate with negative 700-mb height anomalies over the western United States, a pattern that would produce more clouds and cooler temperatures there. Furthermore, the anomalous spring bloom cases are teleconnected to the midlatitude storm tracks over the

lilac first bloom EOFs vs spring Tair (1957-1994)

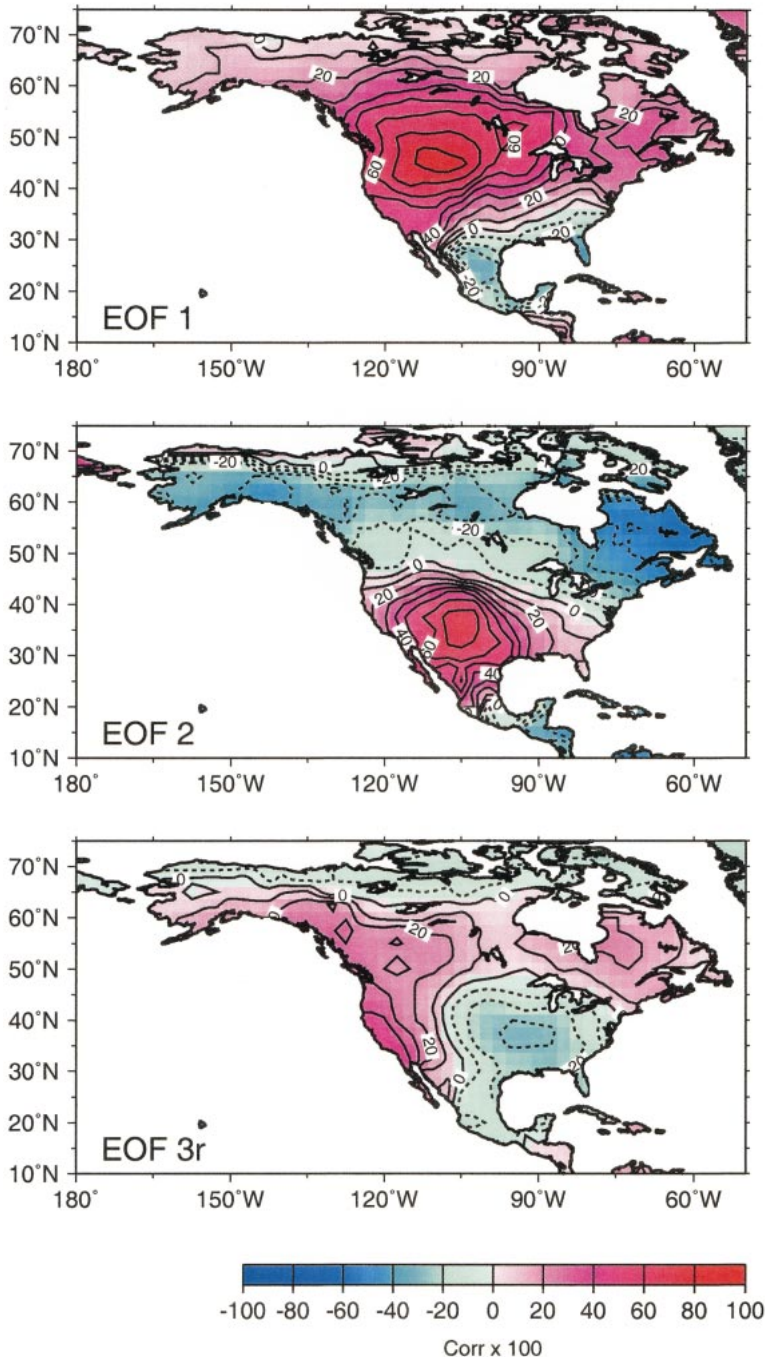


FIG. 9. Correlations (%) of spring (Mar–May) GHCN temperature anomalies over North America with lilac EOFs 1, 2, and 3.

North Pacific, especially for the early first bloom cases with their associated broad deepened Aleutian lows. Changes in cloudiness associated with the circulation anomalies play a significant role in spring. Elsewhere, Otterman et al. (2000) have found that in northern

Europe, the influence in springtime of insolation on continental temperatures begins to overwhelm the effect of warm oceanic air advection (which dominates during winter).

The link to the North Pacific is also suggested, though not too strongly, by correlations of the lilac bloom EOF-1 time series with April sea surface temperatures (SST) anomalies over the Pacific (Fig. 10, lower). These correlations show that earlier spring bloom has been accompanied by a band of positive (warm) SST anomalies throughout the eastern North Pacific. The opposite phase of this SST pattern prevails during springs having late first blooms. The extension of the anomalous SST pattern in an arc from south of the Aleutians into the tropical Pacific, and the reversal to opposite phase anomalies in the central North Pacific, resembles the deep Aleutian low (El Niño-like) phase of the Pacific Decadal oscillation (PDO; Mantua et al. 1997) or North Pacific oscillation pattern (Gershunov et al. 1999). The correlation between lilac EOF first bloom and the April PDO series is 0.48 and significant ($p < 0.01$), albeit not strong. Consistent with the SST pattern, the 700-mb height correlation pattern resembles the Pacific–North American (PNA) pattern (Barnston and Livezey 1987), which is generally associated with such PDO variations. Correlations between lilac bloom EOF 1 and the February–March–April PNA series is 0.41 ($p < 0.01$), and between lilac bloom EOF 1 and April PNA is 0.58 ($p < 0.01$). These correlations may be modest because the PNA is mostly a winter atmospheric mode; in the transition from winter to summer, the frequency and amplitude of PNA patterns diminish and other atmospheric circulation modes become more prominent (Barnston and Livezey 1987). Another possibility is that these circulation patterns represent influences that more strongly involve terrestrial processes than the upstream atmospheric circulation or Pacific Ocean

lilac EOF 1 Correlations

influences. It is noteworthy that the strongest correlations with 700-mb height anomalies are over northern North America, not the North Pacific.

4. Links to spring runoff

If lilacs and honeysuckles (and ecosystems, in general) respond to fluctuations in spring climate it seems likely that other measures in North America would exhibit corresponding variations. Anomalously warm or cool weather in a given year would also be expected to affect other biological (e.g., Myneni et al. 1997) and physical systems of the western United States. Of practical concern (Roos 1991), western snowmelt-driven rivers exhibit substantial variability in spring-runoff timing (Fig. 5), and thus, like lilacs, delay or advance their timing as the region has cooled or warmed from year to year (Aguado et al. 1992; Dettinger and Cayan 1995). But how closely related are the biological and hydrologic variations in spring onset? To answer this question, lilac first bloom dates were compared with year-to-year variations of spring pulse dates in a network of snowmelt-influenced watersheds from the western United States.

As suspected, there is noticeable correspondence between the timing of spring green up (as indexed by lilac first blooms) and the onset of spring-snowmelt runoff in western North America. Correlations between the annual series of lilac first bloom dates and spring pulse dates at representative rivers (Clark Fork in the Northern Rockies in western Montana, Merced in the southern Sierra Nevada Mountains in California, and Rio Ojo in the southern Rocky Mountains in northern New Mexico) illustrate this connection. Each stream was well correlated ($r > 0.5$, $p < 0.01$) with a broad regional swath of lilac sites (not shown).

Rather than illustrating these connections on a river-by-river basis, an EOF analysis of the standard-

ized spring pulse dates was conducted using a set of 110 stream gauges with well-defined records spring pulses and records from 1948 to 1995. Missing values were filled with the mean value of a particular stream's spring pulse record. The first three spring pulse EOFs are broad-scale features accounting for approximately 56% of the variance (Table 2), indicating that there is substantial coherence in the year-to-year variations of timing of spring-snowmelt runoff in the region. Spring pulse EOF 1 (Fig. 11, top) accounts for

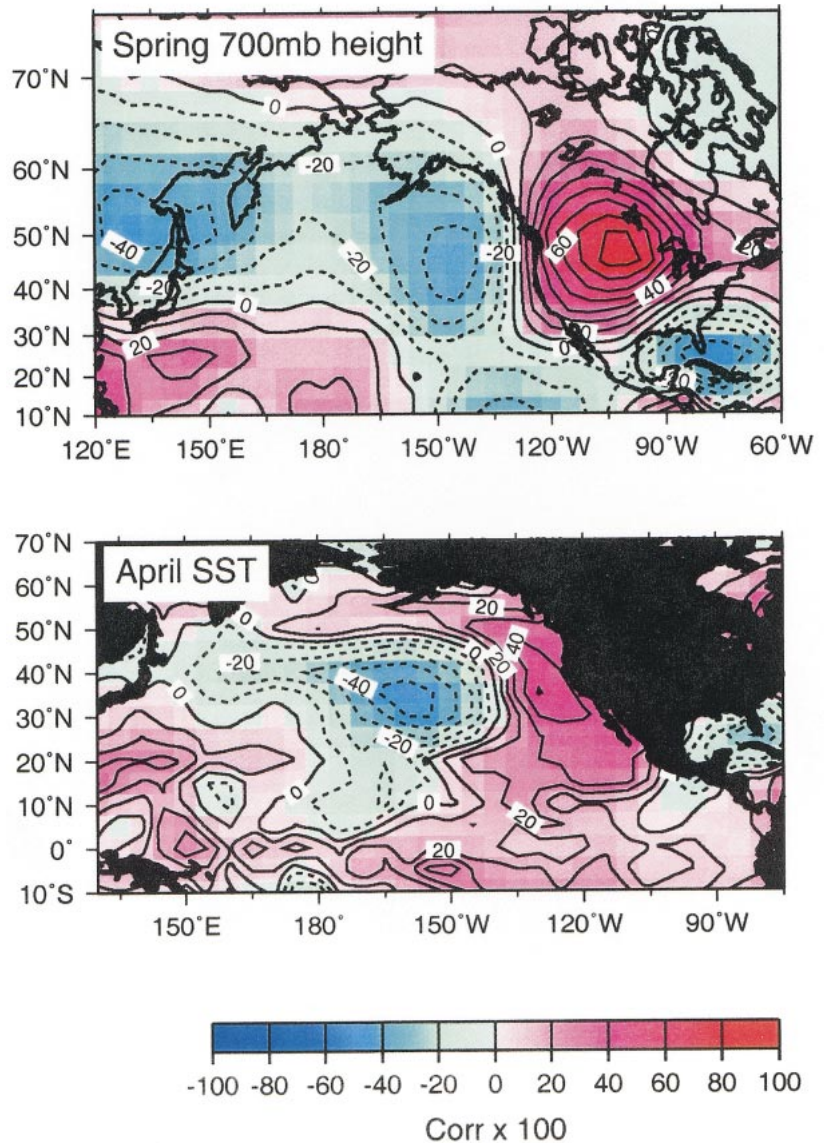


FIG. 10. Correlation (%) of lilac first bloom principal component with spring (Mar–May) Northern Hemisphere 700-mb height anomalies (top), and with Apr SST anomalies (bottom).

38% of the total variance, and expresses timing fluctuations of streams in most of the Northwest, the central and Northern Rockies, and to some extent the Sierra Nevada in California. Associated with EOF 1 is a trend toward earlier spring values (Fig. 11, bottom). Correspondence between the time series of spring pulse EOF 1 and that of lilac first bloom EOF 1 is quite high ($r = 0.78, p < 0.01$). Further, spring pulse timing has a significant link to anomalous spring temperature: the correlation between the spring pulse EOF 1 and the interior Northwest spring temperature series is 0.55 ($p < 0.01$).

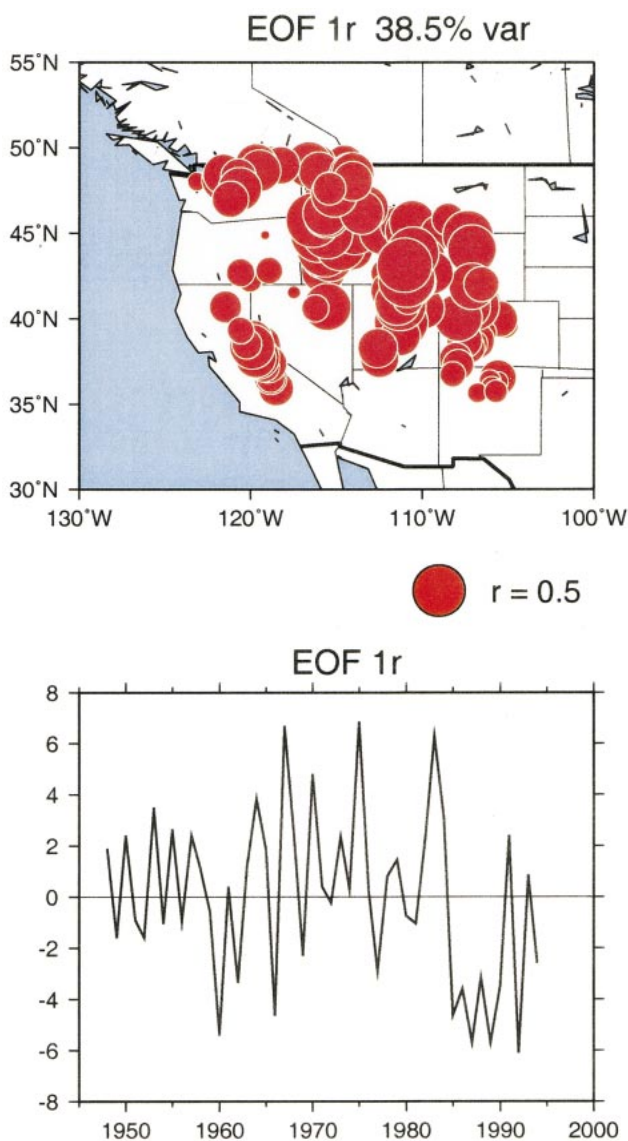


FIG. 11. EOF 1 of anomalous spring pulse dates of streamflow: spatial patterns (top); and principal component series (1948–94; bottom). EOF weights are expressed as correlations between their principal component and each site's raw spring pulse dates; red dots represent positive and, respectively.

5. An advance in the onset of spring

All three spring indicators—lilacs, honeysuckles, and streamflow (Figs. 7, 11, and 12)—exhibit trends toward earlier spring timing since the mid-1970s. For insight into this change, spring conditions associated with the most extreme year in the lilac and honeysuckle record were examined. Inspection of all spring onset dates from the entire set of lilac bloom, honeysuckle bloom, and spring pulse data (Fig. 12, top and middle) indicates that the years with latest bloom are 1964, 1967, and 1975, and the years with earliest bloom are 1986, 1987, and 1992. Thus, years with latest bloom occurred nearly exclusively in the first half of the record while nearly all years with earliest bloom occurred in the second half of the record after the mid-1970s. Temperatures during these extreme years (not shown) are characterized by anomalously cool and warm springs, respectively, across large parts of west-

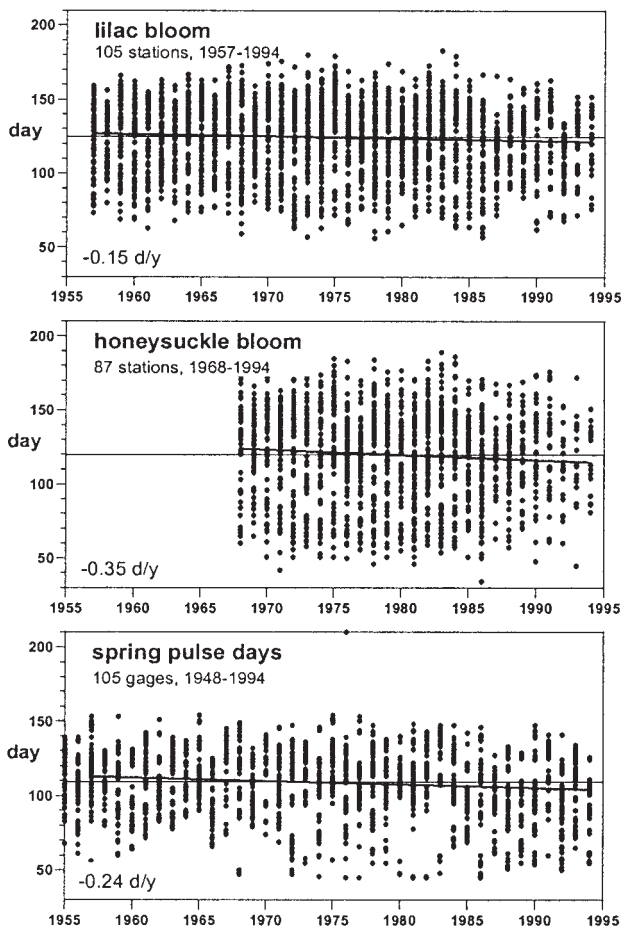


FIG. 12. Aggregate of all lilac first bloom dates (top), honeysuckle first bloom dates (middle), and spring pulse dates (bottom). Linear-regression trend line is included in each.

ern North America, using either U.S. divisional temperatures (Karl and Knight 1985) or GHCN gridded temperature anomalies (Eisheid et al. 1995).

The series of lilac and honeysuckle first bloom dates and the series of spring pulse dates all indicate that spring has tended to come earlier during the second half of the record. The average bloom-date trends have amounted to advances of about 7.5 days 38 yr^{-1} (2 days decade^{-1}) in lilacs and about 10 days 27 yr^{-1} (3.8 days decade^{-1}) in honeysuckle. Some of the larger honeysuckle trend is due to a shorter record length since most of the trend occurred after the 1960s in both. These bloom trends are paralleled by trends and year-to-year variations of the aggregate spring pulse dates (Fig. 12, bottom). The trend in spring pulse dates has amounted to an advance of about 2 days decade^{-1} over the (1957–94) period. These spring pulse timing trends are probably just another perspective of changes described by previous studies wherein several rivers in the western United States have experienced, during recent decades, a diminished proportion of the year's discharge that occurs within the spring and summer snowmelt season (Roos 1991; Aguado et al. 1992; Wahl 1992; Dettinger and Cayan 1995).

The proximal driver of these trends is clearly the spring air temperature, with snowmelt runoff and vegetation responding similarly to the warming over the last two decades. Mean spring temperature within the interior western United States increased by about

1.7°C from 1948 to 1995, as shown in Fig. 13. For comparison, April PDO series is also plotted in Fig. 13, and indicates the tendency for the cool central and western North Pacific SSTs (positive PDO) states that took hold in the mid-1970s to accompany warmer and earlier springs. Assuming the secular trends in lilac bloom and spring temperatures are linked, the response in first bloom date is an advance of 4.5 days per degree Celsius of spring mean temperature at typical sites in the coastal and interior northwestern United States (Table 3). Notably, the magnitude of this response to the trend in temperature is consistent with the first bloom response to short period temperature fluctuations. For example, for the typical lilac sites in Table 3, the detrended lilac and mean spring temperature series are also significantly correlated, and the detrended series yield highly significant ($p < 0.05$) regression coefficients of -4.3 to -5.4 days per degree Celsius anomaly of spring mean temperature. Thus, the responses of first bloom to trends and to interannual temperature fluctuations have been very similar. This similarity suggests that the warming trends are sufficient to explain the hastening spring blooms in recent decades.

6. Discussion

Records of the times of first bloom of lilacs and honeysuckles, along with the time of the first major

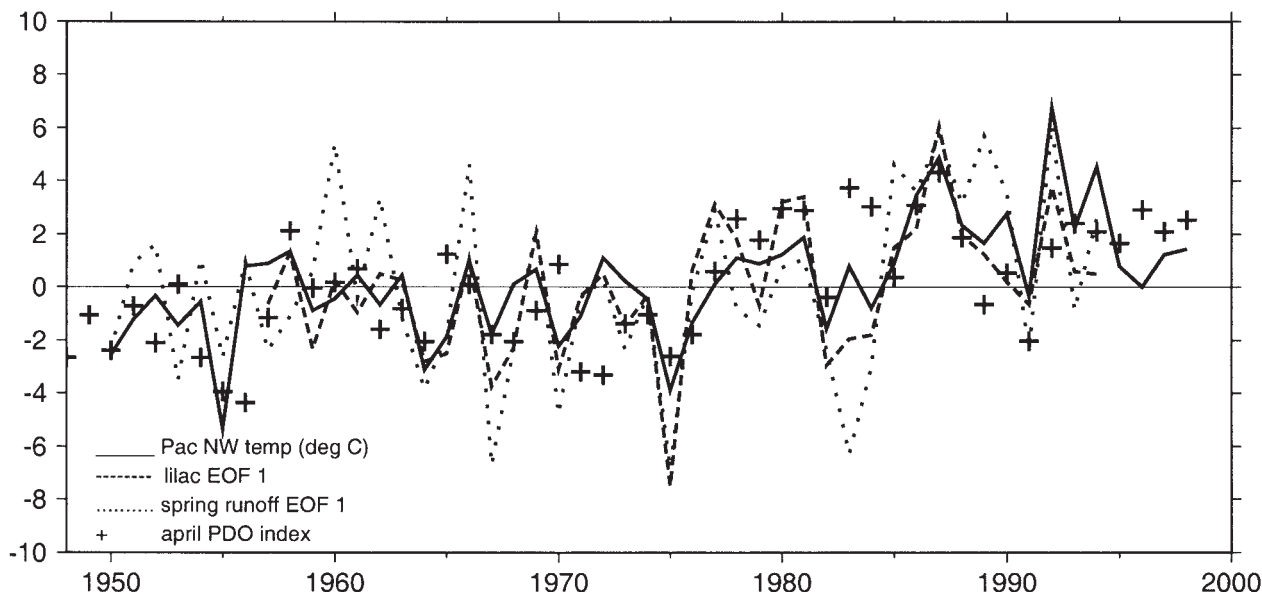


FIG. 13. Time history of spring (Mar–May) temperature anomalies (solid, °C) averaged over the interior northwestern United States, EOF 1 of lilac first bloom date anomalies (dashes), and EOF 1 of runoff spring pulse date anomalies (dots). Apr PDO (crosses) is also shown. Temperature is the average of eastern Washington, Idaho, western Montana, and western Wyoming divisional values.

TABLE 3. Trends and correlations of selected lilac first bloom date series with spring temperature.

Lat (°N)	Long (°W)	Elev (m)	Mean bloom (Julian day)	Std dev bloom (days)	Bloom trend (day yr ⁻¹)	Bloom- temp corr (unfiltered)	Bloom- temp corr (detrended)	Bloom- temp regression (unfiltered; day °C ⁻¹)	Bloom- temp regression (detrended; day °C ⁻¹)
45.5	104.1	43	137	8.3	-0.11*	-0.55*	-0.56*	-4.3	-5.1
48.1	117.0	61	116	11.3	-0.58*	-0.79*	-0.66*	-7.9	-6.4
48.4	104.0	793	145	6.9	-0.19*	-0.70*	-0.66*	-4.6	-4.8

Significance levels: * for $p < 0.01$.

spring pulse in snow-fed streamflow, provide consistent indications of the effects of spring climate variability in the western United States from nearly four decades since the late 1950s. Springtime temperature variations are the strongest determinants of the phenological and hydrological fluctuations. The first bloom date variations are coherent across regions the size of several states and are replicated in both lilacs and honeysuckles. Spring pulse timing variations also exhibit regional-scale patterns that are well correlated (spatially and temporally) with the bloom timing dates. In turn, the bloom and pulse timing fluctuations are correlated with anomalous spring temperatures in the sense that the blooms and snowmelt pulses occur later when springs are cool and earlier when springs are warm. The regional scales of the plant and streamflow timing variations reflect large regional patterns of spring temperature anomalies.

As important as their spatial structures are the temporal fluctuations exhibited by the spring ecological and hydrological timing changes. Superimposed upon the interannual variations in spring onset, which amount to differences of one–three weeks, is a detectable shift toward earlier spring, with a net change of nearly the same magnitude. Spring temperatures over western North America have increased by 1°–3°C since the late 1970s, and this is reflected in bloom dates and spring-snowmelt timing. Bloom dates and spring pulses occurred 5–10 days earlier in the last half of the record than they did in the first half. The trend toward warmer spring temperatures in North America is about as large as has occurred in winter, but the spring warming extends southward into the western half of the United States, whereas the winter warming has been more confined to Alaska and Canada. Not surprisingly, beyond the western U.S. region examined here, there is strong evidence that trends toward earlier snowmelt

and earlier spring plant development extend into western Canada (Moore and McKendry 1996; Luckman 1998; Beaubien and Johnson 1994), and eastward into the prairie states and perhaps even the northeastern United States (Schwartz and Reiter 2000).

Perhaps the most tantalizing question that arises from these observations is, what has caused the warming and resulting advance in spring timing? One interpretation is that these changes are simple natural climate variability. The transition to a high pressure regime during winter months that set in over western North America coincided with the late 1970s shift in Pacific–North American winter climate that is understood to be one element of the Pacific Decadal oscillation (Mantua et al. 1997; Gershunov et al. 1999). However, a surprising feature of the spring changes seen here is that their associated atmospheric circulation anomalies appear to be more strongly seated over the northern North American landmass than they are in the upstream North Pacific region (Fig. 10). This might suggest an alternative explanation for the warming, involving the terrestrial land surface. It is well established that spring snow cover in northern North America has receded in recent decades and there is some evidence that this feeds back positively to produce warmer spring temperatures (Groisman et al. 1994). Presumably this would lead to other regional effects. cursory examination of the lilac spring bloom timing in comparison to interannual variations in North American snow cover since 1966 (courtesy of D. Robinson, Rutgers University) finds broad regional correlations of western bloom dates with snow cover extent across the North American snow boundary region.

Whether these changes are symptoms of global change is possible but uncertain. The plant and snow cover datasets analyzed here all begin in the 1950s or 1960s. As a result, their periods of record are centered

on a single realization of the PDO. With such short records, we are unable to distinguish between a long-term trend and less than one “cycle” of an interdecadal climate oscillation. In light of this limitation, continuation of these specialized networks is particularly important: recent variations of North Pacific climate suggest that the PDO may have recently shifted from its positive (El Niño–like) phase to its negative (La Niña–like) phase. If so, continued observations would help to determine whether recent earlier springs have reflected the PDO or some even longer-term (possibly human initiated) trend.

The effectiveness of the phenological and hydrological observations in recording spring climate variability is reason for continued monitoring and analysis. Clearly, this study would not be possible were it not for the histories provided by some very special regional monitoring programs. Long-term quantitative time series that record how vegetation responds to climate are rare. Such data will be needed as ground truth for remote-sensed estimates of vegetation characteristics (White et al. 2000). Phenological data also have direct applications to agriculture, ecosystem modeling and management, and dendroclimatology. It is worth noting that the western regional phenology network, established by Caprio and colleagues in 1957, was maintained for almost four decades over the western United States on the basis of “low-tech” reporting practices carried out by volunteer observers. Observations by the WRPN ended in 1994 (shortly after Caprio retired). If this network were to be reinstated, it must happen quickly before all of its long-term lilac and honeysuckle bushes, and thus the phenological baselines, are lost. The simple, inexpensive methods employed suggest that a reinstatement could be achieved if a few committed individuals and the right institutional home could be identified.

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